Diesel Engine Emissions Reduction (DEER) Conference 2003
August 24 - 28, 2003
Newport, Rhode Island

Put Paper Number Here

VARIABLE CHARGE MOTION FOR 2007- 2010 DIESEL ENGINES

Josef Maier/AVL Powertrain Engineering, Inc.

ABSTRACT

The use of direct injection diesel engines in US heavy duty pick-up truck applications is becoming increasingly popular with over 250,000 produced in 2002. The high torque density and greatly improved fuel consumption offer distinct advantages to the end user. 2007 and 2010 emissions legislation will present another set of technical and product cost challenges to this type of powertrain. The introduction of efficient aftertreatment systems is mandatory to the success of these engines but optimization of engine-out emissions is also a critical element. Much has been written on the improvements in modern fuel systems which offer great flexibility for the direct introduction of fuel into the cylinder. This paper presents complementary technologies which allow improved air/fuel mixing processes by the additional flexibility of variable in-cylinder charge motion. This approach is particularly applicable to pick-up truck engines, which require high BMEP levels across a wide engine speed range to offer the driveability demanded by the consumer. Design solutions for 2 valve and 4 valve engines are presented along with the potential emissions and fuel consumption benefits.

INTRODUCTION

Due to increasingly stringent emission limits for heavy duty truck engines (Fig.1) it becomes more challenging to find the right compromise between conflicting targets like exhaust emissions, fuel consumption, costs (production as well as development) and customer demand.

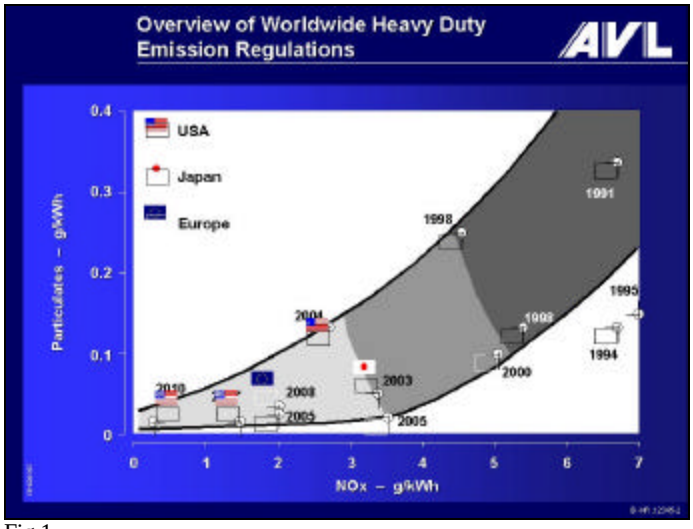

Fig.1

Due to the nature of the test cycles used to determine emissions of a truck (heavy duty transient cycle, 13 mode test) it is necessary to optimize the entire engine map with regard to exhaust emissions. Fig. 2 shows the operating points of a steady state simulation of the heavy duty transient cycle. The diameter of the points indicates the time operating under these conditions and therefore it becomes quite clear that due to the exhaust gas volume at high speed and high load, the areas of rated power and as high torque are very important in this test. In any case it is required to have a lot of flexibility of all the emission related features and controls especially if we talk about truck engines with rated speeds up to 3500 RPM.

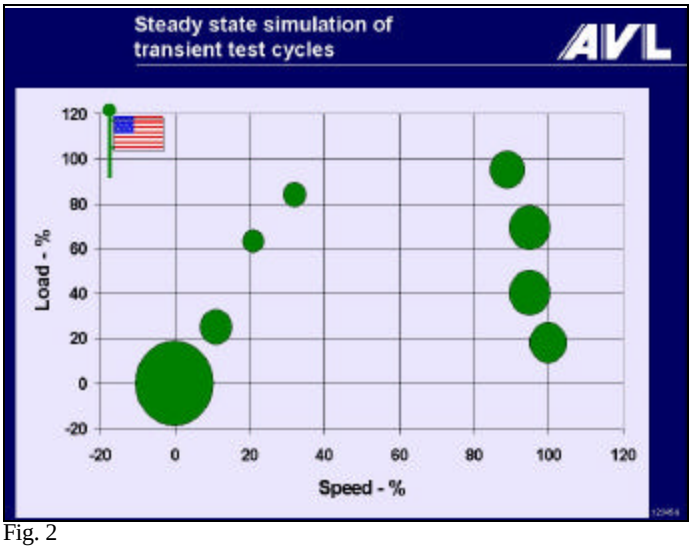

Fig. 2

Additionally to meet 2007/2010 emission limits, some form of exhaust gas aftertreatment will be required. According to our experience the following features will be required to achieve these limits:

? Advanced fuel systems
? Cooled EGR
? Particulate filter
? NOx aftertreatment
? Oxidation catalyst
? Advanced control strategies
? Alternative combustion?

I put a question mark on alternative combustion because according to today's knowledge' it will not be possible to cover the whole engine map with an alternative combustion system. Conventional diesel combustion will be necessary at least for the higher load and speed range.

If we have a closer look at the engines and vehicles on the market forced to comply with the heavy duty emission limits, we immediately realize the huge engine range and operating conditions we have to deal with.

? Displacement / Cyl.	0.7 – 3.0 Liter
? Rated Engine Speed	1800 –3500 RPM
? BMEP Max.	15 – 23 Bar
? Spec. Power	40 – 60 hp/L
? Durability Required	300 – 1000 K Miles
? Vehicle Mass	8.500 – 150.000 lb

Just looking at these few specifications it becomes very obvious that we have to apply different technologies for different applications even if they have to be certified with the same test procedures.

As mentioned above, especially for the emission limits in 2007 / 2010, it will be required to use exhaust gas aftertreatment but unlike those systems used in gasoline engines, diesel aftertreatment systems have to be regenerated from time to time. Regeneration frequency influences fuel consumption as well as the long term efficiency of the aftertreatment system (deterioration) and is mainly determined by the pure size of the catalytic converters and filters, fuel quality and engine out emissions. Due to the fact that the size of the aftertreatment system determines to a great extent the costs and also gives a packaging issue, it is clear that for a good system performance, the lowest possible engine out emissions are mandatory.

This paper will concentrate on engine out emissions improvement especially NOx and particulate or better NOx particulate trade off with focus on variable charge motion (swirl). Besides a proper base engine design, the following features are required to achieve the lowest NOx and Particulate levels:

? High pressure fully flexible fuel system
? Cooled EGR
? Variable charge motion
? Alternative combustion?

Alternative combustion again with a question mark as explained above. Nevertheless I want to start with a short explanation of alternative combustion and then continue with the other bullet points to finally have a more in detailed look at variable charge motion.

ALTERNATIVE COMBUSTION

Fig. 3 shows the NOx and soot formation of diesel combustion dependent on local flame temperature and air excess ratio as well as areas where conventional and possible alternative combustion systems are located.

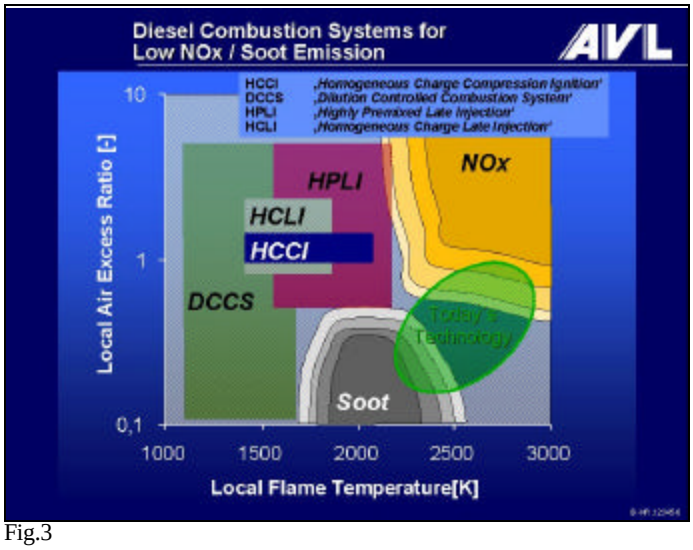

Fig.3

According to our experience, HPLI and HCLI combustion systems are very promising to be applied in a diesel engine. Both systems have a great potential in reducing NOx as well as particulates. With our research engine at 1500 RPM and 4 bar imep we measured 0.011 g/kWh particulate and 0.071 g/kWh NOx emission with HCLI combustion, but as mentioned earlier both systems are limited especially with regard to load. Fig. 4 shows what we have achieved so far and even if we assume some further potential it is obvious at least for the near future that we can not cover the whole operating range required. With that regard it looks a bit better in the light duty and passenger car arena because these vehicles are operated to a great extent in the low load and speed range in their duty cycle as well as in real life. But there is another opportunity for alternative combustion and that is the regeneration of the aftertreatment system. HPLI combustion for instance leads at the same operating condition to much lower NOx and particulate emissions but also to significantly higher exhaust temperatures compared to conventional diesel combustion.

This effect can help to initiate regeneration of the aftertreatment system.

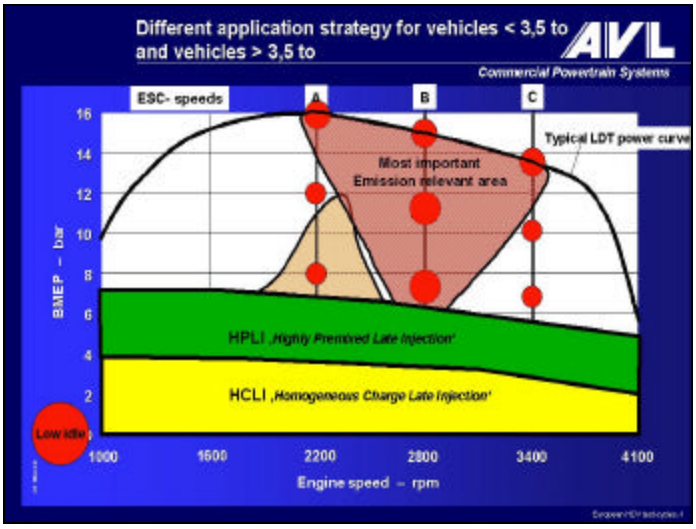

Fig.4

HIGH PRESSURE FULLY FLEXIBLE FUEL SYSTEM

To achieve the lowest possible engine NOx and particulate values it is required to look for an EGR tolerant combustion system. Besides all the geometric data of the combustion bowl and the injection nozzles, the fuel injection pressure has a major influence on EGR tolerance. Fig. 5 shows NOx and soot trade off dependent on EGR rate and injection pressure. The investigation was carried out on an AVL single cylinder research engine, 2 liter displacement, 1500 RPM, 15 bar BMEP. As expected a higher injection pressure leads to higher NOx emission at a constant injection timing but it can be compensated with a higher EGR rate and due to the reduced sensitivity of the smoke emission with high injection pressure, we achieve a much better overall result.

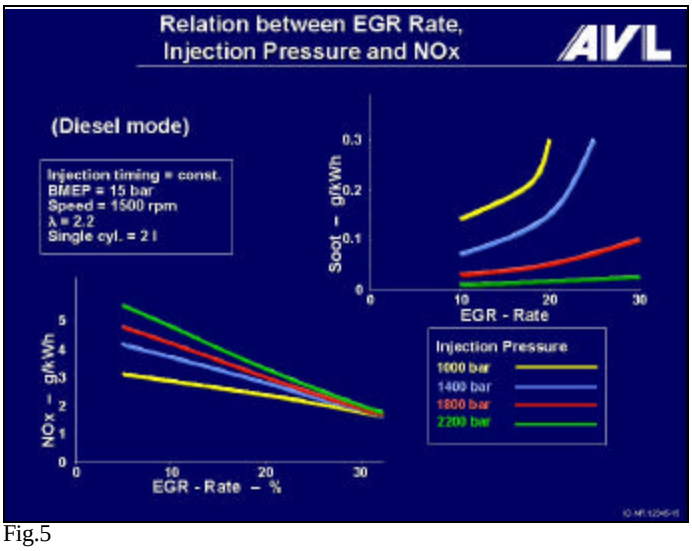

Fig.5

High injection pressure is just one required feature of advanced fuel systems, flexibility is also very important. Flexibility means that the injection pressure can be chosen independent from speed and load as well as the possibility of multiple injection events. Fig. 6 shows the effect of different injection events on engine behavior. Multiple injections influence not only emissions but also noise and may even be necessary to match the requirements of an aftertreatment system.

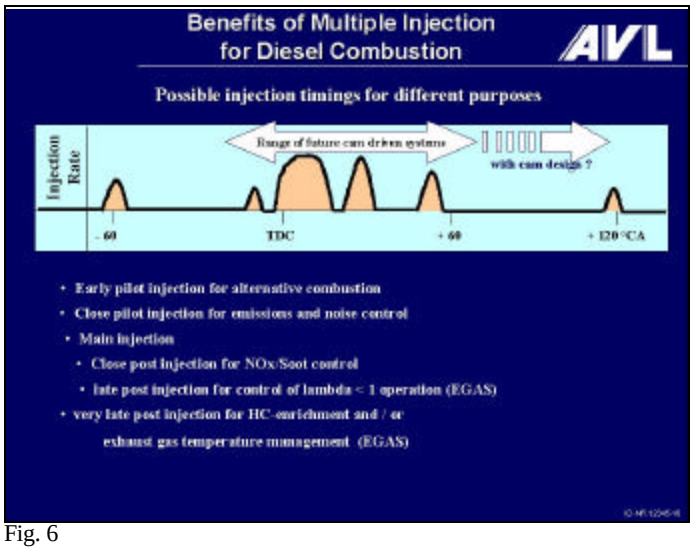

Fig. 6

COOLED EGR

There are two major measures to reduce engine out NOx emission on an engine with conventional diesel combustion:

? Retarded start of injection
? EGR

Both methods have their drawbacks. Retarded start of injection delays combustion and therefore increases fuel consumption. EGR reduces combustion temperatures and air fuel ratios and causes an increase of smoke. Fig 7 demonstrates the NOx improvement potential of EGR versus retarded start of injection and the influence on fuel consumption. It can be seen that with constant timing, fuel consumption is penalized with increased EGR rate, what is explainable due to the slower combustion, but the effect is much less than with timing retardation and therefore the improvement potential significantly higher.

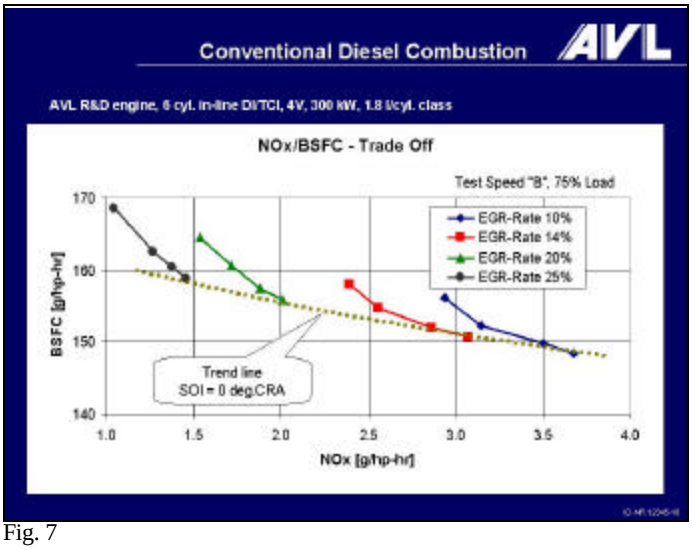

Fig. 7

Fig. 8 shows, measured on the same engine, the NOx soot trade off for different EGR rates dependent on injection timing. It is an interesting fact that the soot emission improves with retarding the timing at least to a certain extent especially at higher EGR rates although with a negative impact on fuel consumption.

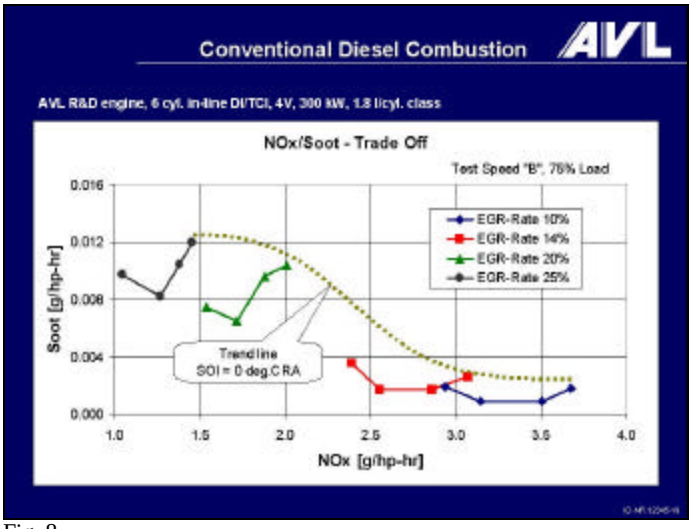

Fig. 8

VARIABLE CHARGE MOTION

It is well known that swirl assisted diesel combustion systems should have variable swirl levels dependent on load and speed. That is true for conventional fuel systems with load and speed dependent injection pressure but also for advanced common rail systems where we have the freedom to choose the most appropriate injection pressure almost independent from the operating conditions. Fig. 9 shows the smoke emission of a medium duty truck engine measured at two different speeds and loads with two different swirl levels. We see a tremendous increase of smoke at 3000 RPM and full load (double the smoke number) just by increasing the swirl number from 1.7 to 2.0. By reducing speed and load to about 2000 RPM and 50% load the trend is reversed and we get better results with the higher swirl number.

Shown swirl numbers in this paper are always evaluated with the paddle wheel method.

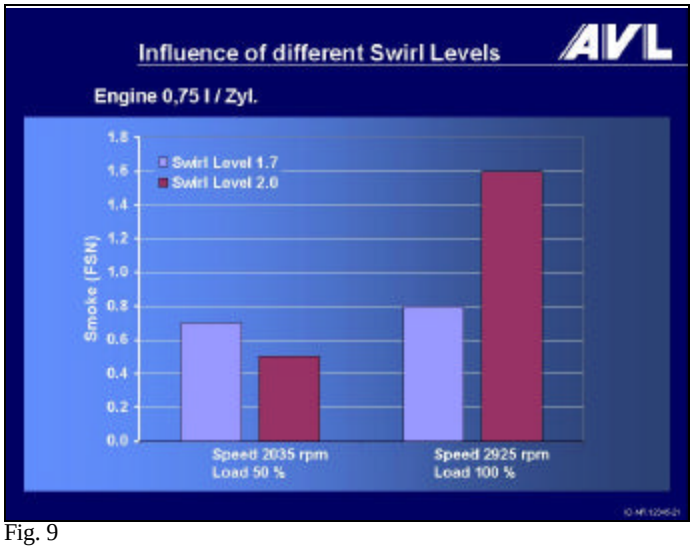

Fig. 9

The question is how to achieve variable swirl efficiently and reliably. It is obvious with a 4 valve concept with one swirl port and one filling port. In a proper arrangement the filling port will destroy to a certain extent the swirl created by the swirl port. If we now close the filling port we will increase the swirl number significantly. That is easily done with a port deactivation valve and is currently seen in production in Europe on passenger car engines. This method has one downside, by increasing the swirl (closing one port entirely) the flow capacity will obviously be reduced substantially and therefore the volumetric efficiency. That is not a problem if we need high swirl numbers just at low speed and load but if we want to go to higher loads even at low speeds we need a proper volumetric efficiency not to penalize soot emission due to a low air fuel ratio. On the other hand especially on turbo charged engines, a big exhaust gas volume stream is appreciated under all operating conditions to improve load response.

AVL has developed a split port concept where we can vary the swirl number and still keep good volumetric efficiency values. Split port means that one port is divided with a cast in wall and together with the right arrangement of the second port you get a high swirl if you just close 50 % of the cross section of one port. Fig. 10 shows the influence on volumetric efficiency of two different 4valve port concepts.

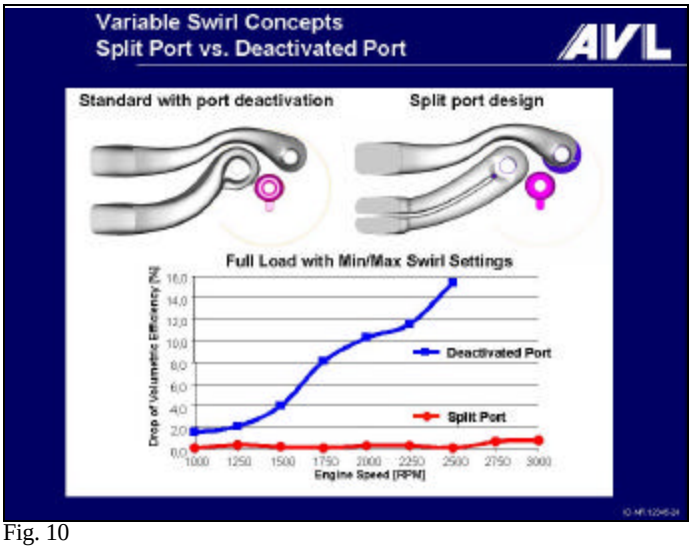

Fig. 10

The comparison shows the dramatic improvement of volumetric efficiency with a split port design especially at higher speeds with just minor implication on the overall head design. How that can be transformed into improvement of engine out emissions is shown in Fig. 11. based on a 0.5 L/cyl. TCI engine with a common rail fuel injection system.

Fig. 11

At 1500 RPM and 4.1 bar BMEP the smoke - NOx trade off is shown with 2 different swirl levels, created with a split intake port. The plott shows the NOx improvement potential due to the much higher EGR tolerance.

Fig. 12 and 13 give an impression how the high swirl operating range with a split port concept can be extended compared to a conventional system just due to the higher volumetric efficiency. That will help significantly to reduce emissions in the heavy duty transient cycle (reduced particulates) but also gives a better transient response of the turbocharging system due to the higher exhaust flow caused by the split port as well as due to the lower smoke dependent air / fuel ratios possible using a higher swirl level.

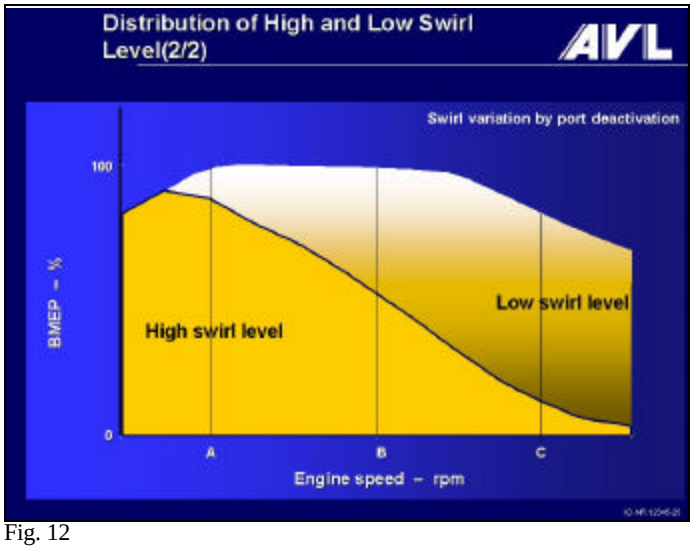

Fig. 12

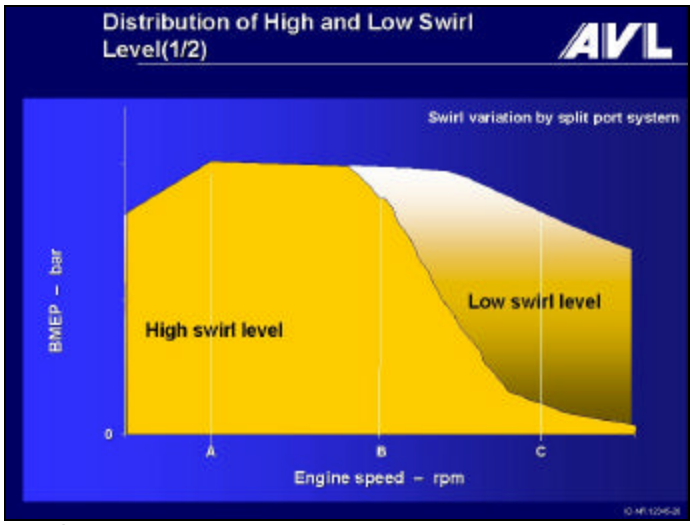

Fig. 13

Fig 14 shows the relation of swirl and mean flow capacity of typical AVL 4-valve port design compared with a conventional variable port concept closing step by step one port and a split port concept, doing the same. Again as shown before for the same swirl variation we can see the much better performance of the split port concept with regard to flow capacity. These results were obtained on an AVL flow bench measured with the paddle wheel method.

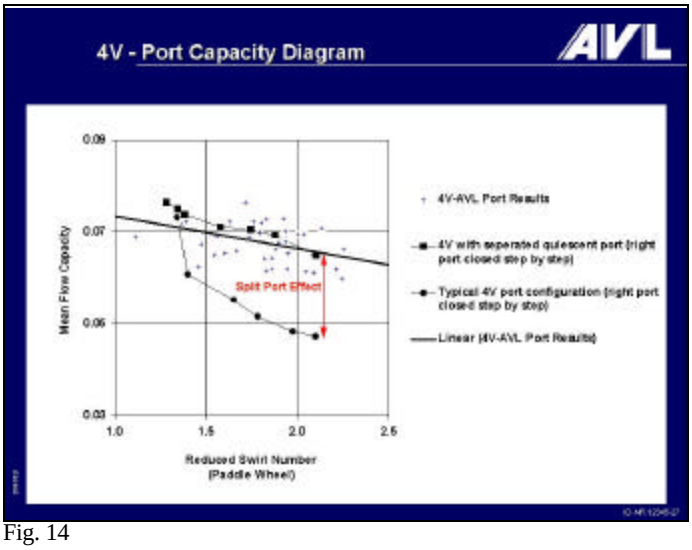

Fig. 14

With a 0.5 L/cyl. Engine, split port concept, high swirl 3.2 and low swirl 1.2 swirl number, we could reduce NOx and Particulate emissions by 30 % in the FTP cycle and increase the low end torque between 1000 to 1500 RPM by 12 %. In addition, load response was significantly improved due to improved EGR tolerance (less particulate at lower air/fuel ratios). The trend for "high speed" heavy duty engine will be very similar.

Fig. 15, 16, 17, show some different port concepts for 4-valve engines. Flow results for all these configurations are similar, which concept to choose is also dependent on the overall head concept, water jacket as well as valve train concept.

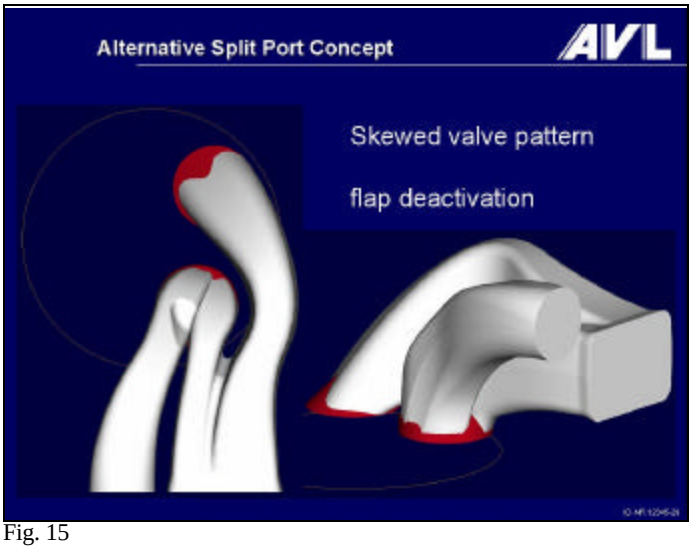

Fig. 15

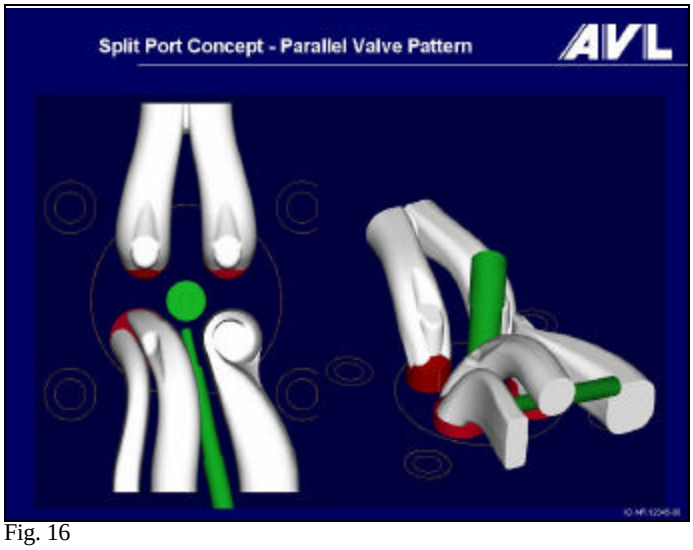

Fig. 16

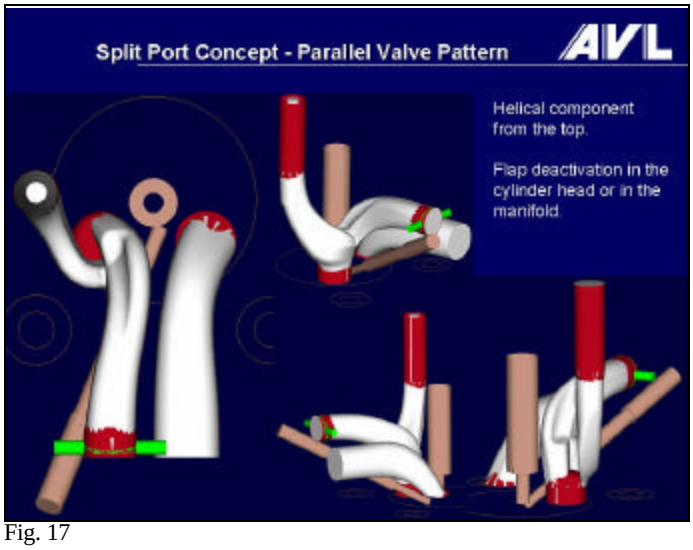

Fig. 17

Another advantage of the split port concept is the possibility to introduce variable swirl not just together with 3 or 4-valve cylinder heads, it can also be applied to 2-valve concepts with similar results. Fig. 18 shows a low swirl helical port with a cast in separation wall. Closing one part of the port again leads to significant increase of the swirl number. A different concept is shown in Fig. 19 where a helix is designed around a quiescent port. The achieved swirl and mean flow capacity numbers of the ports shown compared with conventional 2 and 4-valve configurations are displayed in Fig. 20.

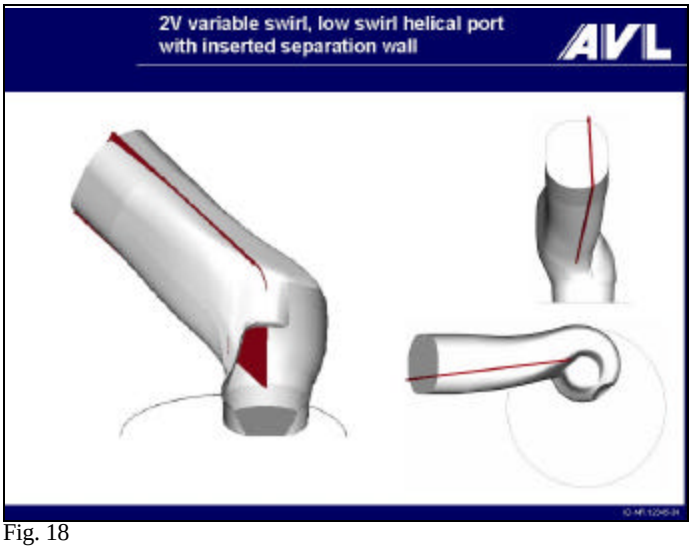

Fig. 18

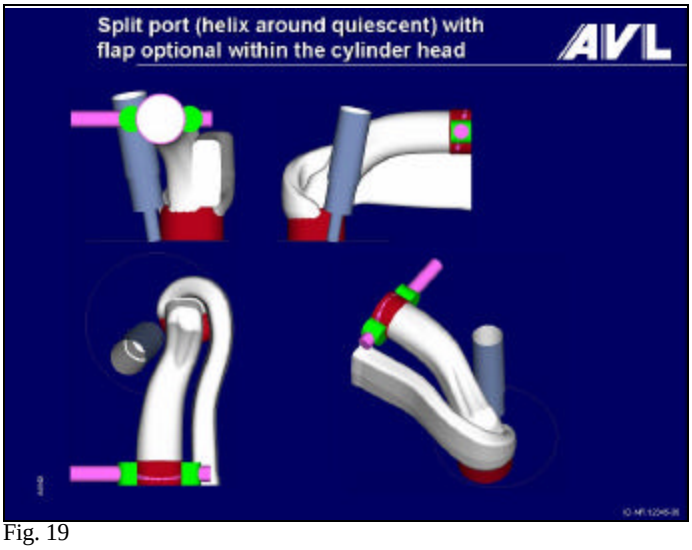

Fig. 19

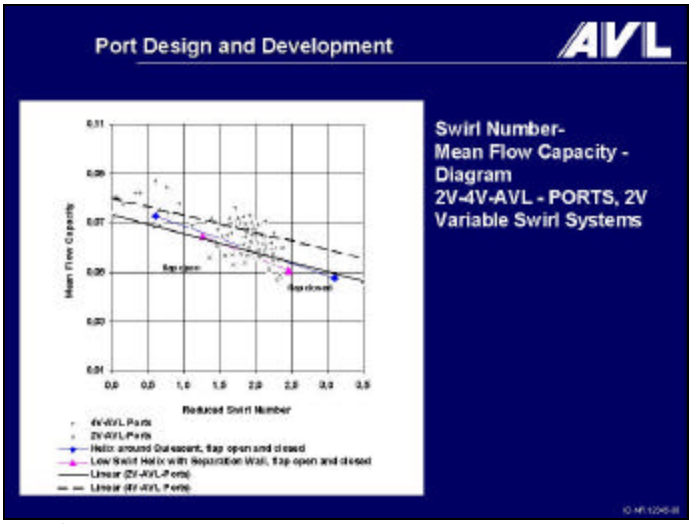

Fig. 20

CONCLUSIONS

To achieve 2007/2010 heavy duty emission levels it will not be enough just to add an aftertreatment system to an existing engine configuration. It will require a very close look at the fuel system, EGR and the charging system. Flexibility of these systems will be required to cover the whole load and speed range to be compliant with the legislation but also to fulfill customer requirements like performance, fuel consumption and reliability. All these objectives must be accomplished at a reasonable cost level. Variable swirl is one of the features that can help to achieve these goals. As shown above, there is a big potential to improve the Particulate - NOx trade off as well as the low end torque with variable swirl. With the special AVL split port design it can be applied to 2-, 3-, or 4-valve engines with moderate cost implications. To achieve the best solution though it has to be seen and developed together with all the other combustion related parameters and features like base engine design, combustion bowl geometry, fuel injection, charging system, EGR and aftertreatment system. Just in understanding and optimizing all these parameters as a system will lead to a compliant and robust product. Variable swirl especially with a split port design can be a major enabler to achieve that goal, especially in the high speed heavy duty arena.

REFERENCES

1. Weißbäck, M., Csato, J., Glensvig, M., Sams, T., und Herzog, P., “Dieselmotoren: - Ein Ansatz für den zukünftigen Pkw-Dieselmotor,” MTZ 9/2003
2. Moser, F.X., Sams, T., Dreisbach, R., “Heavy Duty Diesel Engines to Meet Japanese NLTR,” JSAE 20035425
3. Moser, F.X., Fraidl, G., Mundorff, F., Herzog, P., “Development directions for passenger car and commercial vehicle engines,” SIAT 2003
4. Wünsche, P., Glanz, R., “Vier Ventile für den PKW Dieselmotor mit direkter Einspritzung,” Tagung Mehrventiltechnik Essen, 24.02.94
5. Glanz, R., “Differentielle Erfassung von Tumble-Strömungsfeldern,” MTZ I/2000, 61. Jahrgang, Januar 2000
6. Laimboeck, F.J., Glanz, R., Modre, E., Rothbauer R.J., “AVL Approach for Small 4-Stroke Cylinderhead-, Port- and Combustion Chamber Layout,” SAE 1999013344
7. Bohac, S.V., Landfahrer, K., “Effects of Pulsating Flow on Exhaust Port Flow Coefficients,” SAE 1999010214