Using Engine Cycle Simulation In Truck Engine Development

By Dr. Joachim Weiss

Cycle simulation has played an increasing role in engine development. Using tools such as the Hiroyau jet combustion model, which is integrated into the commercial 1-D simulation code GT-POWER by Gamma Technologies, it allows for the prediction of in-cylinder diesel combustion and of the emission of nitrous oxides. These tools were employed to study engine design alternatives, allowing MAN Nutzfahrzeuge to meet the upcoming Euro 4 emissions limits with a tolerable increase in fuel consumption. The optimization is based on high EGR rates that require two-stage turbocharging for obtaining sufficient air-fuel ratios.

As there are many possible engine design options, simulation supports the preselection of promising variants. In this way cycle simulation can help to find the best solution, saving money and time by finding the best solution and reducing engine testing.

Euro 4 is the next step of emission legislation which will take effect in 2005. It requires that the emission limits for nitrous oxides and particulate matter be sharply reduced: NO\textsubscript{x} to 3.5 g/kWh and particulate matter (PM) to 0.02 g/kWh, compared to the Euro 3 limits of 5.0 and 0.10, respectively. One of the most promising directions is to employ large rates of exhaust gas recirculation (EGR), coupled with advanced turbocharging.

The main factors for reducing in-cylinder NO\textsubscript{x} emissions are: injection timing, injection rate shape, charge-air temperature and charge composition, especially higher portions of carbon dioxide supplied by EGR. Regarding PM, up to certain EGR rates an increase in soot emission can be almost avoided if the air-fuel ratio is at least kept constant or raised up to a required value. Therefore, in this work air-fuel ratios were at first adjusted by engine tests to meet the targeted level of PM emission and then taken as boundary conditions within the further calculations.

To keep the extremely low PM emission under mass production conditions, the use of a so-called PM-Kat (Particulate Matter Diminishing Catalyst) is envisaged. This system consists of a platinum oxidation catalyst and metallic catalyst substrates with open

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Fig. 1. A schematic of a high-pressure EGR system with flutter valves.

Fig. 2. NO\textsubscript{x} emissions of basic engine in ESC (+ Test, o GT-POWER)
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continued on page 44
There are several basic arrangements for EGR. One widely used is the high-pressure loop (Fig. 1), which has the advantage of avoiding compressor and intercooler soiling. Though the high charge-air pressures that will be necessary for Euro 4 are not likely to be achieved by single-stage turbocharging, it must be considered because it offers a simpler and cheaper alternative. The positions of the calculated ESC operation points within the compressor map can be viewed in Fig 3.

To obtain high air-fuel ratios with large EGR, one needs high charge pressures, which can be reasonably realized only by two-stage turbocharging (concept B). Four variants of this concept were considered:

B1 – Basic variant with an intercooler, EGR cooler and a single-entry high-pressure turbine (Fig. 4).

B2 – The same as B1, but with a twin-entry turbine and no intercooler.

B3 – The same as B1, but with no intercooler.

B4 – The same as B3, but with nothing but internal EGR, realized by early exhaust valve closing.

In variant A, the fluttering reed valves decrease the usable exhaust energy. This can be avoided by taking the exhaust gas from the LP turbine outlet and recirculating it to the LP compressor inlet. To overcome the pressure loss of the EGR cooler, an exhaust throttle has to be implemented to increase the backpressure (variant C1). A negative is the soiling mentioned above, which will have to be...
dealt with. Another possibility here is to delete the EGR cooler and use the cooling potential of the air cooler (variant C2) and now the PM-Kat should generate a sufficient backpressure so that no throttle will be needed.

Another concept is to take the EGR from the exit from the high-pressure turbine and supplying it to the low-pressure compressor, as illustrated in Fig. 5. This concept (D) does not require an exhaust throttle.

Apart from the targeted NOx emission and the air-fuel ratio mentioned, there were two other parameters whose limits were not to be exceeded: cylinder pressure had to be lower than 2900 psi (200 bar) and exhaust gas temperature was not allowed to rise above 1292°F (700°C). The injection mass was kept constant at every operation point and the first step when evaluating the results was to examine whether the specified torques could be achieved at full load.

It was found that variants A, B3 and B4 produce a substantially smaller torque at lower speeds than the others. While this might be expected for the one-stage turbocharged engine (A), the two-stage variants without intercooler (B3, B4) showed that one needs the intercooler and that internal EGR generation is less effective than external.

The compressor maps of each variant were selected with a view to positioning the ESC operation points in map areas of high efficiency. This was another objective of this work, to preselect the compressors for later engine test.

To achieve meaningful comparisons, the EGR rates also had to be adjusted to similar values and they ranged from...
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about 28 percent at low loads to about 15 percent at high loads. Exceptions were variant A, which could not generate sufficient EGR rates because of the one-stage turbocharging, and variant C2 (LPL without EGR cooler) where because of the missing throttle the EGR rates could not be varied arbitrarily and remained constant at about 18 percent. In every case and variant the level of NOX was set to 5.20 g/kWh to maintain sufficient reserves for transient operation.

Fuel consumption results are seen in Fig. 6. Variant A turns out to be an acceptable alternative for a lower rated engine, because its cycle fuel consumption is not extraordinarily high. With two-stage turbocharging, the lowest fuel consumptions can be obtained with variants B1, B2 and D. Charge-air intercooling seems to be necessary in terms of efficiency (variant B1 compared with B3), but it might be less important by use of a twin entry turbine (B2 compared with B1). The result of B4 indicates that internal EGR is not efficient under the boundary conditions considered here. Also EGR cooling does not appear essential in every case, as seen from comparison of variants C1 and C2. Based on the BSFC results, engine tests with both high- and medium-pressure EGR loop (variants B1, B2, D) are recommended.

It has been shown that GT-POWER cycle simulation is able to yield reliable results concerning the engine behavior. With the jet model, fairly safe predictions on NOX can be obtained, even at varying injection timing and EGR rate. As a result, truck engine development has at its disposal a tool for the preselection of different solutions to meet the Euro 4 emissions limits. This will be achievable by optimizing the engine to low emissions and additional use of the so-called PM-Kat aftertreatment system. For obtaining EGR rates higher than 20 percent at acceptable air-fuel ratios, two-stage turbocharging will be essential for high rated engines. In the majority of cases, variants with an EGR cooler and intercooler are advantageous. Further tests, in which the transient behavior too will be investigated, will subject this result to closer scrutiny.