Emission standards for heavy-duty diesel engines have become significantly more stringent throughout the last 20 years and continue towards zero emissions levels in the future. Modern direct-injected diesels include well-developed combustion systems that have electronically controlled injection systems and robust turbochargers. These technological advancements enable heavy-duty engine manufacturers to meet emission standards through an adjustment in injection timing by using a small array of sensors in concert with the engine control module (ECM). Standards targeted for 2002 and 2007 will require the inclusion of external devices and associated sensors that will create additional degrees of freedom for the ECM and thus a larger sensor array in comparison to current diesel engines. This article outlines the potential impact, within the next seven years, of these emission standards on control strategies for heavy-duty engines and the associated sensors under “warmed up” conditions.

Modern Heavy-Duty Engines

The typical truck engine today includes a state-of-the-art turbocharger, intercooler, and an electronically controlled injection system that is governed to prevent excessive smoke production during transient operation. In this system, fuel delivery is limited throughout a step load change in throttle position to maintain a minimal air-fuel ratio while meeting the driver’s demand for torque response. This tradeoff between performance and emissions has been addressed through the development of electronically controlled, high-pressure injection systems that readily allow for injection timing changes [3]. In particular, engine manufacturers have controlled tailpipe emissions of particulate matter (PM) by retarding injection timing to control the peak temperatures within the cylinder while maintaining proper atomization through higher injection pressure.

The Heart of the Engine

These modern injection systems currently use cam or hydraulic actuation with electronic control through a high-speed fuel or oil valve. The Hydraulically actuated, Electronically controlled Unit Injector (HEUI) system employs high-pressure lube oil (280-350 bar) for generating necessary fuel injection pressure through a special intensifier piston arrangement (Fig. 1). Essentially, high-pressure lube oil forces a piston downward and compresses a fuel charge which in turn...
reaches injection pressures between three and five times the lube oil pressure (650 to 1700 bar). Subsequently, pressurized fuel flows through internal injector passages and ultimately lifts a needle that allows the fuel to be injected into the cylinder. An electronically controlled, high-speed poppet valve located upstream of the intensifier piston arrangement is primarily responsible for injection timing through appropriate opening and closing cycles. One advantage of this type of injection system is that timing is independent of engine speed, but two associated disadvantages are the possible cross contamination of lube oil and diesel fuel and the required power to operate the high pressure, lube oil pump(s).

The other commonly used injection system is the electronic unit injector (EUI). It relies on cam actuation (Fig. 2). Again, an intensifier piston arrangement generates the necessary injection pressures, but cam motion is used to multiply the fuel pressure instead of lube oil. The EUI system can generate much higher peak injection pressures (2100 bar) than the HEUI system, but depends directly on the engine speed through its camshaft lobe design and thus is not as robust as its hydraulically actuated counterpart. The HEUI system allows for flexibility in the number of injections and overall injection rate per engine firing cycle while the EUI system is only capable of multiple injections at low engine speed given the limitation on cam lobe design and the associated force of the injector push tube. The EUI system also typically yields a triangular-like injection rate profile in comparison to the HEUI system, which can mimic other injection rate profiles such as a “top hat” or square pulse.

**Certification Process**

The current procedure for certifying heavy-duty diesel engines is a transient federal test procedure (FTP) engine dynamometer cycle that has been approved by the U.S. Environmental Protection Agency (EPA). This cycle comprises a number of step load and speed changes that supposedly represent typical driving cycles for this class of vehicle application [4]. As shown in Table 1 [1], [4], between 1990 and 1998 the EPA mandated that nitrous oxides (NOx) and PM would be reduced by 33% and 83%. Thus, current heavy-duty engines meet the 1998 standard of 4 g/bhp-hr of NOx and 0.10 g/bhp-hr of PM. The 2004 standard (which must be met by October of 2002 due to the Consent Decree [4]) calls for another 40% reduction in NOx emissions while the recently approved 2007 standard mandates an additional 90% reduction in both NOx and PM below 2004 levels. Additionally, heavy-duty manufacturers must also certify engines for the 2004 standards and beyond under the FTP transient cycle with the extra stipulation that emission levels must not exceed a certain peak level at a given cycle operating point. This additional constraint is aimed at preventing engine manufacturers from heavily weighing emission levels at a narrow range of engine speed and load.

**Current Engine Control Strategy**

Today’s heavy-duty engines are certified under the 1998 standards predominately by in-cylinder control over the combustion event through proper modification to injection timing. Fig. 3 shows that engine calibrators use engine speed and position and intake manifold absolute pressure (MAP) as the primary control variables for determining injection timing. Using this data, a two-dimensional lookup table is employed for determining the start of injection based on turbocharger state and engine speed. The secondary sensors include coolant temperature for differentiation between cold and warm condi-

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**Fig. 1.** HEUI type injector.
tions, intake manifold absolute temperature (MAT), and throttle position (which represents driver demand).

During a step load increase from an initial idle condition, both fueling rate and engine speed must simultaneously increase to meet the demanded throttle position without generating excessive smoke. To meet this smoke limiting criteria, injection timing is initially advanced because of the initial decrease in cylinder air-fuel ratio associated with the turbocharger dynamic response, i.e., the required increase in fueling rate “leads” the associated increase in inducted air. This strategy allows the in-cylinder charge to take on a more homogeneous burn and thus control emitted smoke as the engine speed increases. Eventually, the advanced timing will result in larger in-cylinder pressure rise and peak temperature as the turbocharger speeds up with the resultant production of NOx. Thus, as the boost pressure (intake manifold) continues to rise, injection timing must be retarded (for controlling peak cylinder temperature) without generating smoke and NOx while providing necessary driver demanded torque. Ultimately, the engine calibrator determines the number of entries in the MAP-engine speed lookup table based on smoke limiting operation, NOx production, fuel economy response, and torque response under the constraint of the FTP transient cycle. Again, today’s engines meet the 1998 standards through careful calibration based on the appropriate lookup table resolution of two dimensions.

Future Heavy-Duty Engines

The next generation of emission standards becomes effective October 2002 and calls for a 40% reduction in NOx emissions. To date, it appears engine manufacturers will not be able to meet this requirement by simply adjusting injection timing without a major fuel economy penalty. Instead, manufacturers must rely on some combination of “cooled” recirculated exhaust gas (EGR), injection timing changes, and possibly a passive NOx catalytic device [2]. Additionally, it is anticipated that many engine manufacturers will introduce variable geometry turbochargers (VGT) into 2003 model year engines, given the potential improvement in overall performance associated with wide band turbines. As shown in Fig. 3, such engines will require a number of additional sensors and control loops beyond those associated with meeting the 1998 standards. In particular, exhaust MAP, VGT blade position, and EGR valve position sensors will be critical for enabling the use of EGR as a strategy for meeting the 2004 standards.

From a very simple perspective, the exhaust MAP must maintain a minimal value exceeding the intake MAP to ensure proper EGR flow direction. During steady-state operation, the VGT blade and EGR valve positions must be adjusted to ensure adequate exhaust MAP for delivering the proper EGR flow rate required at a particular engine operating condition. It is also possible that EGR flow rate may be indirectly measured and controlled using some type of exhaust specie measurement such as that provided by either a carbon dioxide or an oxygen sensor. Additionally, an exhaust MAT sensor could be used both to determine required EGR cooling if variable speed coolant pumps are employed in 2002 engines and as a potential diagnostic for a passive NOx catalytic device.

Transient operation as defined by the FTP cycle presents major challenges for engine calibrators aiming to meet the 2002 standards. For example, a step load transient introduces additional difficulties beyond associated turbocharger lag issues of current engines. At idle, the engine will be operating at a substantially high level of EGR (roughly 50%) and thus will have an exhaust, EGR, and intake system that will contain a substantial amount of exhaust products. At initial throttle position demand, the VGT must be adjusted to provide both a higher level of boost and the necessary exhaust pressure for purging each cylinder and the induction system of EGR while increasing in-cylinder oxygen concentration to ensure necessary combustion behavior. In the meantime, the injected fuel quantity must increase to provide the desired torque response with the stipu-

![Fig. 2. EUI type injector.](image)

Table 1. EPA Heavy-Duty Diesel Truck Engine Standards in Units of g/bhp-hr.

<table>
<thead>
<tr>
<th>Year</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>10.7</td>
<td>0.60</td>
</tr>
<tr>
<td>1990</td>
<td>6.0</td>
<td>0.60</td>
</tr>
<tr>
<td>1991</td>
<td>5.0</td>
<td>0.25</td>
</tr>
<tr>
<td>1994</td>
<td>5.0</td>
<td>0.10</td>
</tr>
<tr>
<td>1998</td>
<td>4.0</td>
<td>0.10</td>
</tr>
<tr>
<td>2004¹</td>
<td>2004¹</td>
<td>0.10</td>
</tr>
<tr>
<td>2007²</td>
<td>0.2</td>
<td>0.01</td>
</tr>
</tbody>
</table>

NOx — nitrous oxides; PM — particulate matter

¹Consent Decree requires October, 2002 compliance
²Includes low sulfur fuel requirement of 15 ppm
lation of minimal smoke generation. In general, excessive amounts of EGR will tend to decrease the effective in-cylinder oxygen concentration through the displacement of fresh air charge and thus will tend to generate smoke at lower injected quantities in comparison to an engine without EGR. The net result of this initial transient response is that the EGR mass trapped in the engine system must be purged without generation of smoke while delivering acceptable torque response. The solution to this complex transient problem will incorporate precise VGT blade and EGR valve position control in parallel with careful selection of injection timing and duration.

After this initial portion of the step load transient, the manifold and EGR system will be purged and the engine will continue its response to throttle position demand by closing the EGR valve. This action minimizes exhaust gas flow while adjusting the VGT blade position to shorten the turbocharger lag. VGT response is more robust in comparison to a standard turbocharger but must meet an exhaust manifold pressure requirement that will degrade its performance. Regardless, the final engine calibration table will include injection timing strategy, EGR valve position, and VGT blade position requiring a significant increase in calibration time in comparison to current engines. This should be apparent given the use of additional VGT/EGR position control signals and utilization of additional sensors beyond current engine systems.

The mandate to reduce NOx and PM production by 90% between 2002 and 2007 requires highly effective after-treatment devices for the exhaust.

**Projection of 2007 Impact on Engine Calibration**

The mandate for heavy-duty engines to reduce NOx and PM production by 90% between 2002 and 2007 will require highly effective after-treatment devices for the exhaust. At a minimum, active devices will be required for NOx reduction and possibly for PM reduction. It is also feasible that both active and passive devices will be used as after-treatment devices for addressing either pollutant. If these devices can provide at least a 90% reduction in tailpipe emissions, then these engines will not include EGR. As shown in Fig. 3, the number of required sensors

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**Fig. 3.** Projected engine control strategy for heavy-duty engines.
and control blocks will significantly increase beyond today’s engines. Some type of filter device is required for PM reduction and thus some type of pressure restriction measurement will be necessary to determine the state of this device if it is an active element. For example, catalytic or regenerative PM filters are currently under investigation as potential devices for 2007 engines. These filters must convert the PM to a benign substance over a defined warranty period. These filters could use some means such as electrostatic discharge, microwave regeneration, or chemical reduction that is actuated by either a flow restriction sensor or a pollutant accumulation sensor.

Other important sensors will include VGT blade position, exhaust MAP, exhaust species, and various exhaust MATs. The sensors for exhaust species will monitor the state of the exhaust gas to decide how and when to energize an active device for either PM and NOx reduction. For example, based on today’s technology, a trap or urea-reductant device will be used for tailpipe NOx reduction. The objective of either device is to convert NOx to benevolent chemical forms such as nitrogen and oxygen. The trap essentially adsorbs NOx into a special substrate with eventual desorption (into a benevolent chemical form) through the introduction of some reductant such as unburned hydrocarbons, i.e., gaseous diesel fuel. Conversely, the urea-reductant system introduces urea into the exhaust stream to convert NOx directly to a more benevolent chemical form. Either device will require exhaust species and temperature sensors to determine proper metering of the reductant (diesel fuel or urea). If the NOx reduction strategy includes an additional passive device downstream of the active analog, then exhaust MATs will also be important for determining the state of this passive device with eventual feedback towards determining the reductant metering strategy.

The VGT blade position and injection timing strategies will depend on the conversion efficiency of both the PM and NOx reduction devices. Essentially, calibrators will have more flexibility in meeting fuel economy and torque specifications if these devices achieve efficiencies exceeding 90%. For example, injection timing may be advanced over a longer period of time during a transient as the VGT speeds up if calibrators use the after-treatment devices for controlling both smoke and NOx production. Conversely, if these devices are less than 90% efficient, either injection timing will be modified at the cost of fuel economy or EGR will be introduced as a NOx control mechanism with the additional transient issues outlined earlier in this article.

Regardless of which after-treatment technologies become integral members in these engine systems, calibration tables will become increasingly complex because of the control of these active devices, injection timing and duration, and VGT blade position.

**Summary**

Future heavy-duty diesel engines will incorporate additional sensors for meeting impending emission standards in comparison to today’s engines. In particular, the 2002 standards will be met with utilization of “cooled” EGR which requires the inclusion of additional sensors for properly metering EGR while minimizing smoke production in parallel with meeting demanded torque. The resulting calibration will be substantially more complex. The 2007 standards will require active after-treatment devices for meeting the mandated 90% reduction in PM and NOx. Again, various sensors will be required to monitor the state of these devices in parallel with ensuring customer needs are met, i.e., fuel economy and torque. In the end, engine calibration will require an order of magnitude increase in effort by calibrators to meet these stringent 2007 standards in comparison to today’s engines.

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**References**


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