STUDY ON

EMISSION CONTROL TECHNOLOGY FOR HEAVY-DUTY VEHICLES

FINAL REPORT

VOLUME 3

DEVELOPMENT OF ON BOARD DIAGNOSTICS SYSTEMS

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1 EXECUTIVE SUMMARY

To ensure the early detection of malfunctioning emission control components an on board diagnostics (OBD) system is to be introduced into the EU legislation for heavy duty engines. Ideally emissions should be measured in the vehicle exhaust, however this is unlikely to be feasible in the near-term because the sensors are neither available nor proven to be robust and durable for truck applications. Thus the functionality of the critical systems, that is EGR, fuel injection and DPF and SCR devices will have to, in general, be monitored indirectly.

DPFs can be monitored by measuring the pressure differential across the filter and the exhaust gas flow. These measurements will also be necessary for controlling the filter regeneration strategy. Additionally, temperature sensors should detect overheating which could damage the filter.

For SCR both the exhaust temperature -required to control the urea injection- and the level of the urea in the tank have to be monitored. To detect other potential malfunctions such as inadequate urea dosing and damage to the catalyst, the use of NO_x and ammonia (NH_3) sensors seem to be the best approach. Although SCR is a robust technology, the monitoring of the system is very critical. These sensors are not in series production for truck applications, their durability is unproven, and they are likely to be expensive.

The general functionality of the fuel injection system may be monitored by measuring the regularity of the angular velocity of the crankshaft. The necessary sensors are available and have a good performance at engine speeds below 1500 rpm. Other possibilities include the use of wideband lambda and air mass sensors or map-based monitoring of the exhaust gas temperature of each cylinder. The availability and the long-term stability of the sensors are unproven.

Monitoring of EGR systems could use EGR valve, mass flow, wideband lambda, temperature or NO_x sensors. Again, the availability and long-term stability of the sensors are open issues. Today's temperature sensors are, additionally, rather slow, and thus could only detect permanent errors.
The signals from the sensors have to be processed via a CAN-Bus in the engine control unit (ECU). An exhaust gas after treatment system control unit (EGAS CU) will be necessary for DPF and SCR, and the OBD will add additional functions and complexity to the electronic system. The OBD system has to store the emission related faults, and routines have to be developed to trigger the malfunction indicator (MI). The stored information could also be used for inspection and maintenance at the service organisation.

Although the electronic system is complex, it will, most likely, not be a very critical part in the OBD system. ECU manufacturers could offer standard functions for OBD purposes, which have to be filled with the routines developed by the engine manufacturers. The latter will require a lot of research to develop a reliable system, which accurately detects malfunctions that result in emissions above the threshold values, but without a high risk of activating the MI wrongly.

Given all the uncertainties, the OBD requirement in the legislation should only describe the principles and key elements. The development of a specific OBD testing plan with the manufacturers to prove the system for type approval, is recommended. This has to include the test cycles, the threshold levels and, in particular, a list of faults which have to be simulated and detected during the OBD test. Finally, procedures need to be developed as to how these faults should be simulated in modern HD engines.

2 INTRODUCTION

Today's Heavy Duty Vehicles (HDV), are known to have well regulated emissions. This is possible due to the robust and durable nature of the vehicles components and systems. However, the main driver for this durability is not emissions regulation but the customers desire to see the useful and reliable life of an HDV reach one million kilometres.

Increasingly stringent emission limits for HDVs in 2005 and 2008 will require more sophisticated emissions control technologies. These technologies may include, flexible high-pressure fuel injection systems, exhaust gas recirculation (EGR), Particulate Filters, NO_x adsorbers and advanced engine and vehicle control systems. The use of such advanced technologies will obviously create the risk of emissions becoming uncontrolled if one of the components within a system fails to work correctly or an operator fails to comply with the maintenance regime of the system

A solution to this problem would be the installation of on-board diagnostics, or OBD. A proposal by the Commission for HDV-OBD contains the following elements:

- OBD-monitoring of the engine plus any downstream emission control system, applicable to new diesel engines from the 1st of October 2005 (Euro4)
- OBD-monitoring of the engine, plus any downstream emission control system, with extension to the vehicle system; diagnostic interface between the ECU and other vehicle electronic systems that provide input to or receive an output from the ECU applicable to new vehicles with diesel engines from 1st October 2008 (Euro5).
- OBD-monitoring functionality: For 2005 propose to monitor NO_x adsorbers and PM traps only for:
    - Total functional failure
    - Removal or replacement of systems
    - Lack of reagent for Selective Catalytic Reduction (SCR)
    - Electrical failure of SCR actuators
    - Major breakdown of NO_x adsorber
    - Major breakdown of PM trap
    - Complete melted filter
    - Completely clogged filter

However, there is a problem with the introduction of OBD on heavy-duty vehicles, namely the current lack of suitable sensors. These sensors are being developed but are commercially available. OBD technology does exist for light duty vehicles (LDV), but it is unlikely to be adopted on HDVs. The primary reason for this is the unsuitability of LDV emission control technology when applied to HDVs, increased load regime and the operator's vehicle durability expectations. More sophisticated solutions e.g. model based OBD approaches need to be discussed to overcome the current lack of appropriate sensors.

2.1 OBJECTIVES

This report gives an overview of the potential malfunctions of future HDV emission control technologies and the methods for monitoring the proper function of the emission control devices. It also lists and describes the transducers and sensors required for this task, and discusses the availability and durability of these devices within the time frame specified.

It should be noted at this point, that nearly all critical components, especially sensors required for HDV applications, are still being developed and are consequently subject to restrictive commercial confidentiality measures imposed by the manufacturers.

2.2 BACKGROUND

OBD was introduced for European gasoline fuelled passenger cars and light duty trucks in 2001. The same will be required for diesel cars and light duty trucks by 2003. The U.S. has proposed that vehicles with a maximum weight of 14,000 lbs (6,350 kg) be fitted with OBD by 2004. The European commission has proposed regulations for HDV-OBD to be in place by 2005 (Draft Proposal for Heavy-Duty Vehicle OBD amending DIRECTIVE 88/77/EEC) and has asked this consortium to review this proposal and to give recommendations for HDV-OBD solutions.

3 APPROACH

This study commenced with a detailed literature review from which a gap analysis was conducted. A series of expert interviews and workshops were organised to scrutinise the report and to fill any remaining gaps.

The work programme was structured as follows:

1. Review of OBD regulations for light duty vehicles
2. Definition of critical emission control components for HDV
3. Description of possible OBD strategies for monitoring those components
4. Description of the necessary equipment for analysing collected data
5. Comparison of the needs from (4) and the available components
6. Description of necessary improvements for current sensors to be applicable to OBD in HDV
7. Compile information on the ongoing research in the field of (6) and on potential results (expected reliability, accuracy, costs, etc.)

Additional research was carried out by asking a number of manufacturers, service agents and experts in this field for their views on the specifications and possible costs for equipment needed for HDV OBD. However, many components are not near production and little technical information and specifications for this equipment including durability and accuracy are available. Consequently, a logical assessment of the implementation costs is difficult.

4 ON BOARD DIAGNOSTICS (OBD) - GENERAL

To assist in the discussion of HDV OBD, an explanation of current OBD terminology is given in Annex I (see 14.1).

In recent years the electronic systems in trucks has become state-of-the-art. Due to the variety of truck applications the variety of truck control units has exceeded that applied to standard passenger cars. The future introduction of active exhaust gas after treatment devices (EGAS) will increase this number of control systems and will consequently add to their complexity.

This also introduces the need for effective Inspection and Maintenance (I/M) programs to assure emission compliance over the vehicles lifetime. Electronic OBD will be an essential part of these I/M programs.

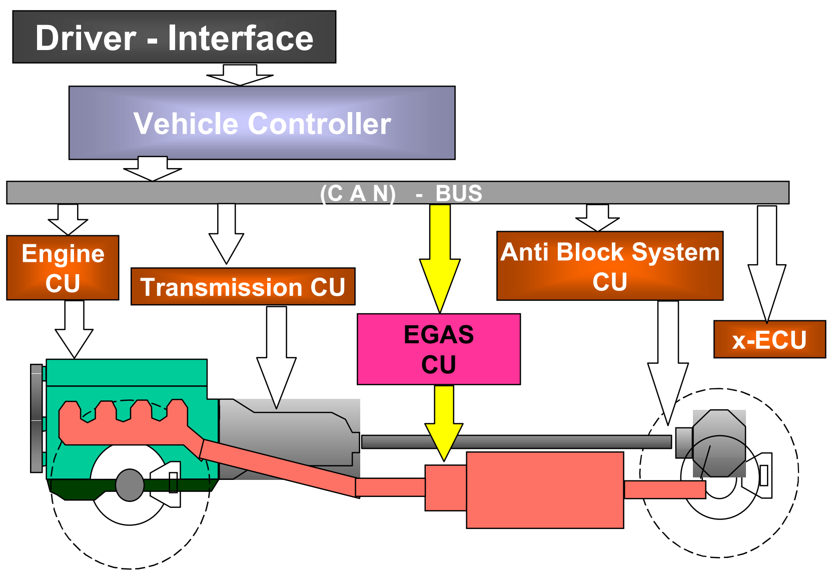

Figure 1: Modern Control Architecture in Trucks

The exhaust emissions of a vehicle will be controlled primarily by the engines control unit (ECU) and exhaust gas after treatment control (EGAS CU). These two control units determine the combined operating strategies of the engine and after treatment devices.

Today's control systems employ a number of sensors and actuators that fulfil the complex control tasks and each system performs an internal diagnosis system check that exceeds any current legal requirement. The major motivation for this internal system check is engine, after treatment and vehicle protection. The results of these internal checks could be transferred to the OBD system. If this is not sufficient the OBD system could use separate sensors and software to detect emission failures. Wherever appropriate sensor technology is not available, e.g. particulate sensor, emission device models could be introduced to calculate and predict device performance.

The planned mandatory introduction of a common OBD on trucks requires the installation of a new electronic system with functions that are designed to detect failures in the engine and exhaust after treatment system.

The OBD system must indicate the failure of an emission control component or system when that failure results in an increase in emissions above pre-described thresholds and when there has been a major functional failure of the control system.

OBD systems currently installed in passenger cars consist of:

- Emission control system - ECS could be located inside the vehicle controller or within the ECU or stand-alone.
- Specific sensors additional to those required for operation.
- Malfunction Indicator / Malfunction Indicator Light (MI / MIL).
- Standardised diagnostic data link connector.

Within the ECS, the engine and after treatment conditions are stored as an event when an emission related fault is detected. Consequently, vehicle operational restrictions might be triggered such as reduced speeds and torque from the engine. These are called limp home functions.

The malfunction indicator (MI) is a visual, or audible indicator that clearly informs the driver that a vehicle non-compliance event or malfunction of an emissions related component connected to the OBD system has occurred. The MIL actuation is strictly regulated and is subject to location and illumination conventions.

The diagnostic link connector is normally standardised by a service organisation; however, a standard convention would be desirable.

5 COMPARISON OF OBD REGULATIONS

US EPA and the California Air Resources Board (CARB). The EC proposed a directive concerning OBD on heavy-duty vehicles for 2005. In the USA HDV-OBD (for vehicles with < 14,000 lbs (6350kg) GVWR) is proposed and the CARB has proposed regulations for passenger cars, light duty and medium duty vehicles.

Table 1

Comparison of OBD regulations				
		EU	**USA**	**CARB**
Title of existing or proposed regulation		Draft proposal for Heavy-Duty Vehicle OBD amending directive 88/77/EC, as last amended by commission directive 2001/27/EC	ENVIRONMENTAL PROTECTION AGENCY 40 CFR Parts 85 and 86 § 86.1806-04 On-board diagnostics.	Modifications to Malfunction and Diagnostic System Requirements for 2003 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines (OBD II), Section 1968.2, Title 13, California Code Regulations
OBD regulation comes into force	**Cars** **Light duty** **Heavy duty**	- - 2005	2004 – 40% of projected sales 2005 – 60%, 2006 – 80 % 2007 – 100%	2003 (passenger cars, light duty and medium duty vehicles)
Components to be monitored (listed for diesel only)		- catalytic converter, - deNOx system, - particulate trap, - fuel-injection system, - combined deNOx-particulate filter system - other components, the failure of which may result in emissions exceeding the limits	- catalytic converter, - particulate trap, - lack of cylinder combustion - oxygen sensor - other emission control systems, the failure of which may result in emissions exceeding the limits - other emission-related power train systems	- catalyst system - misfire occurring continuously in one or more cylinders - secondary air system - electronic fuel system components - oxygen sensors - EGR system - positive crankcase ventilation - engine cooling system - cold start emission reduction strategy - PM trap (MY 2005) - other emission control device
Malfunction indicator (MI or MIL)		The OBD system must incorporate a malfunction indicator readily perceivable to the vehicle operator.	The MIL must illuminate and remain illuminated when any fault is detected and verified, or whenever the engine control enters a default.	If a malfunction has been detected and a pending fault code is presently stored, the MIL shall illuminate
Limits		NOx: 7 g/kWh PM: 0,1 g/kWh	1,5 * the applicable emission standard (for NMHC, CO, NOx or PM)	1.5 * the applicable FTP standards. (for NMHC, NOx or PM) some special limits, e.g. misfiring: malfunction when one or more cylinders are continuously misfiring

Comparison of OBD regulations			
	EU	**USA**	**CARB**
MIL deactivation	After three subsequent sequential driving cycles with no malfunction	After three subsequent sequential driving cycles with no malfunction	After three subsequent sequential driving cycles with no malfunction
Fault code storage	- The OBD system must record code(s) indicating the status of the emission-control system. - A fault code must be stored for any detected and verified malfunction causing MI activation and must identify the malfunctioning system or component as uniquely as possible.	- The OBD system shall record and store diagnostic trouble codes and diagnostic readiness codes indicating the status of the emission control system. - The stored diagnostic trouble code must identify the malfunctioning system or component as uniquely as possible.	- if a malfunction has been detected a pending fault code must be stored
Exceptions **(disablement of OBD system)**	- low fuel level (<20% of capacity) - during operation of an auxiliary control device - when operational safety or limp-home strategies are activated. - active power take-off unit - during periodic regeneration of an emission control system	- if evaluation would result in a risk to safety or failure of systems or components. - during operation of a power take-off unit such as a dump bed, snow plow blade, or aerial bucket, etc	- below twenty degrees Fahrenheit (20°F) - at elevations above 8000 feet above sea level - fuel level is 15 percent or less - Power Take-Off (PTO) units
Failure modes to be tested	- Test cycle: ESC with preconditioning - replacement of any catalyst with a deteriorated or defective catalyst - replacement of a deNOx system with a deteriorated or defective deNox system or electronic simulation - total removal of the particulate filter or replacement with a defective particulate filter - disconnection of any fuelling system electronic fuel quantity and timing actuator - Electrical disconnection of any other emission-related component	- replacement of a catalyst or particulate trap with a deteriorated or defective catalyst or trap, or an electronic simulation of such - an engine misfire condition is induced - replacement of the oxygen sensor a deteriorated or defective sensor - a malfunction condition is induced in any emission-related power train system or component - a malfunction condition is induced in an electronic emission-related power train system or component	- the manufacturer shall perform single-fault testing based on the applicable FTP-test cycle with the components/systems. set at their malfunction criteria limits as determined by the manufacturer for meeting the requirements.

The US-EPA didn't extend the OBD requirements beyond the 14,000 pound (6,350 kg) range. Many potential issues associated with applying OBD requirements to > 14,000 lbs GVWR (6,350 kg) applications that are not similar to smaller vehicles. For example, trucks this large (> 14,000 lbs or 6,350 kg) tend to be equipped with power take-off units that are operable a substantial portion of the time. Both CARB and EPA regulations currently allow disablement of most OBD monitors during power take-off unit operation. It makes little sense to require a sophisticated OBD system on a vehicle if it's allowed to remain disabled during essentially its entire operation due to the power take-off unit. Another such issue is the lack of vertical integration in the heavy-duty industry, particularly in the > 14,000 pound (6,350 kg) GVWR classes. This lack of vertical integration creates increased difficulty associated with bringing together engine, transmission, chassis and safety related diagnostics because so many different manufactures are involved in creating the end product. The EPA will gather further information and work closely with interested parties to develop proposed OBD requirements for such engines. [1]

5.1 US FACT FINDING TOUR

As part of this study, the US EPA and American truck manufacturers were visited and asked for their opinions on the future development of the HDV industry, emissions control strategies and the possibilities for OBD. The information is summarised below:

In the US, vehicles in the size range 8,500 to 14,000 lbs (3,856 to 6,350 kg) can be vehicle or engine certified. CARB requires these vehicles to have OBD and the EPA is introducing similar Federal requirements. It was thought that OBD would be incorporated into the 2007 heavy-duty diesel engine regulations. However, this did not occur. The EPA is looking closely at the EU experience before progressing with this and is keen to co-operate with the European Commission on this issue.

Caterpillar argues that because the profit margins for their product are small, the introduction of OBD would be too costly and consequently OBD requirement for Euro IV might drive the company out of the market. Cummins and Detroit Diesel Corporation (DDC) recognise that OBD is likely to happen in the US, but is currently in its infancy.

In the US and EU, different communication protocols are used. Also within the US, light and heavy-duty engines use different protocols. Cummins would like to standardise on the US HD communication protocols in the EU (see chapter 9).

It is likely that NO_x sensors will be required for $DeNO_x$ devices. However, it is unlikely that PM sensors that have been proved to be very durable will be required for oxidation catalysts. For DPF it may be considered sufficient to monitor for major malfunction rather than monitor PM directly.

Any future on-board monitoring (OBM) i.e. the in-vehicle measurement of exhaust emissions using dedicated sensors will also require OBD which will enable the driver to know that there has been a pollution episode and the reason why.

Currently there are no Inspection and Maintenance (I/M), requirements for heavy-duty vehicles in the US. The EPA envisages that once ODB is implemented in HDTV's, this might lead the way to I/M.

6 OVERVIEW ON OBD REQUIREMENTS

The OBD system must indicate the failure of an emission control component or system when that failure results in increased emissions above set thresholds and on the occurrence of a major functional failure.

To detect malfunctions relevant to the emissions behaviour of the vehicle, two different approaches can be taken into consideration:

- Direct measurement of the emissions at the tailpipe
- Indirect method by monitoring parameters that would change as a result of a malfunction. For example, pressures, temperatures and engine speed. This data would be inputted into to an advanced model for calculating the emission behaviour.

The first approach would require accurate and reliable sensors for NO_x, CO, HC and PM that are not currently available for in service monitoring and are also expected to be expensive. Furthermore, sensor calibration and the ageing of the sensor over time can have a significant effect on the accuracy of this method. Consequently, OBD in passenger cars is based on the latter method and is believed to be the short-term.

This method would require reliable, simple sensors on one hand and a sophisticated strategy to check the signals against complex models on the other hand. The model software needs to be implemented in the OBD controller or subsystem controller.

In case of using the direct method of analysing tail pipe emissions and reporting that the emissions have exceeded the pre-described limit, there is little opportunity to isolate the reason for the non-compliance. The indirect method provides a better chance to detect the reason and location of the fault and therefore provides valuable maintenance information at the same time.

In practice it is most likely that the OBD systems will utilise a combination of the direct and indirect method.

The definition of parameters to be measured and how the signals are processed is usually driven by the operational requirements of the respective system. In some cases the use of dedicated additional OBD sensors will be necessary and the additional sensor inputs need to be implemented into the respective control system or into the supervisory OBD control unit.

7 EMISSION CONTROL SYSTEMS

Emission control systems need to be defined, the possible malfunctions and failures described and the effect of their failure on emissions quantified. Also the sensors that could be used for OBD are described. The following emission control systems will be considered:

- Diesel Particulate Filters (DPF)
- NO_x adsorbers
- Fuel supply and Injection systems
- Exhaust Gas Recirculation (EGR) systems
- Selective Catalytic Reduction

The working principles of these exhaust emission control systems are described in greater detail in Volume1 "Survey of Future Emission Control Techniques".

Obviously, the first sequence in any OBD system is the identification of the unit being monitored and that the unit is installed correctly. For example, has the particulate filter been removed? Secondly, an interrogation of the electrical integrity of the sensor circuits would be required.

7.1 DIESEL PARTICULATE FILTER (DPF)

There are different systems to reduce particulate matter (PM) emissions.

- Continuously Regenerating Trap (CRT™, Johnson Matthey)
- Fuel-Born Catalysed Filter
- Fuel Burner Regenerating Trap
- Catalysed Diesel Particulate Filter (CDPF, "CSF" catalysed soot filter)

7.1.1 Continuously Regenerating Trap (CRT™, Johnson Matthey)

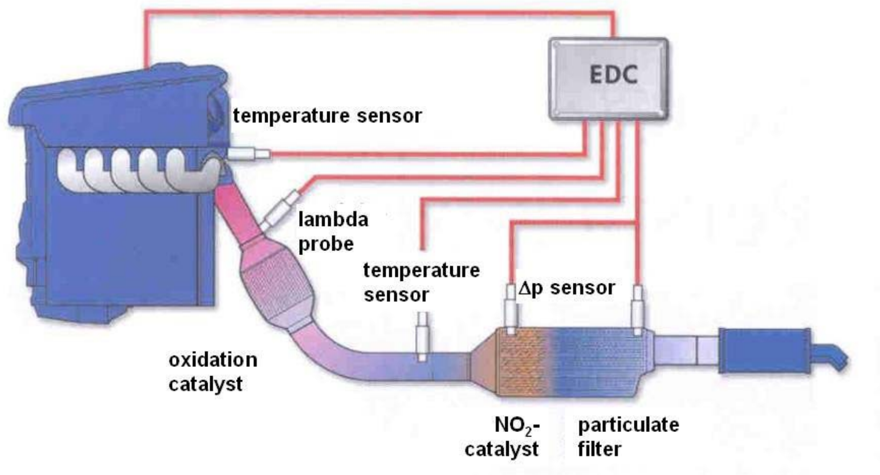

Figure 2: Continuously Regenerating Filter

Critical parts and malfunctions:

This technology requires temperatures above 300°C to start the filter regeneration process. Refuse trucks or city busses may not achieve this temperature with the possibility of regeneration not occurring and would result in the filter rapidly becoming blocked. Additional systems for active regeneration are then needed. Electrical or fuel burner heaters could be used to overcome these issues.

The loading of the filter with particulate matter is an important issue. An overloading by only 3-4 grams per litre filter volume causes a rise in regeneration temperature in the order of 300-400°C.
Ashes, derived from lubricating oil additives can accumulate on the filter over lifetime and will melt at high temperatures (>1100°C) during regeneration. The ashes can react with the filter substrate and clog the filter permanently (glazing effect). Therefore the loading rate and temperature of the filter has to be monitored accurately to prevent overheating and damage to the filter.

7.1.2 Fuel-Born Catalysed Filter

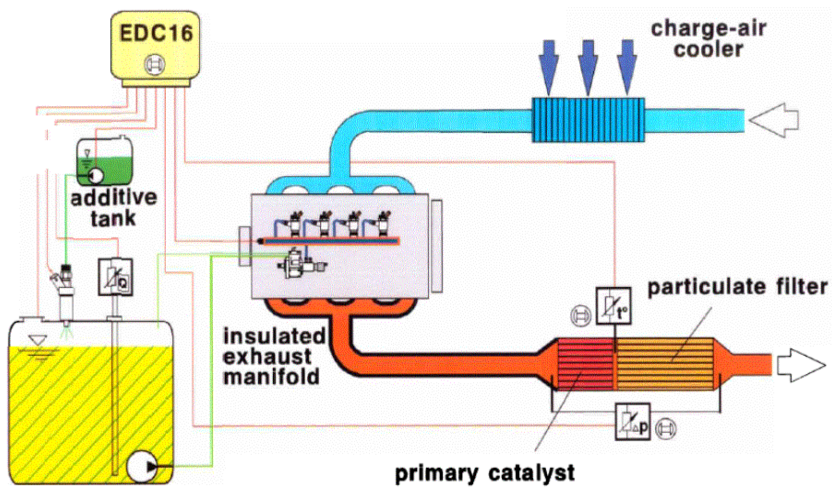

Figure 3: Fuel-Born Catalysed Filter
(Source: Bosch)

An additive is used to reduce the soot ignition temperature and is introduced into the fuel system after refuelling in proportion to the fuel on-board the vehicle.

Additives currently used are cerium, iron and strontium. Tests with copper have not been successful due to the formation of chlorine compounds and dioxin.

Critical parts and malfunctions:

Faults that are specific to this system are most likely to occur in the additive supply system, e.g. wrong dosing caused by a defective level gauge in the tank or a defective dosing unit. Too high additive concentrations is not believed to be a problem; too little could lead to delayed regeneration and overheating during the regeneration process. Segregation in the additive tank is not an issue during vehicle operation, but could be a concern during long vehicle inactivity.

7.1.3 Fuel Burner Regenerating Filter

A fuel burner is used to obtain the temperature that is necessary for the soot ignition. (Figure 4)

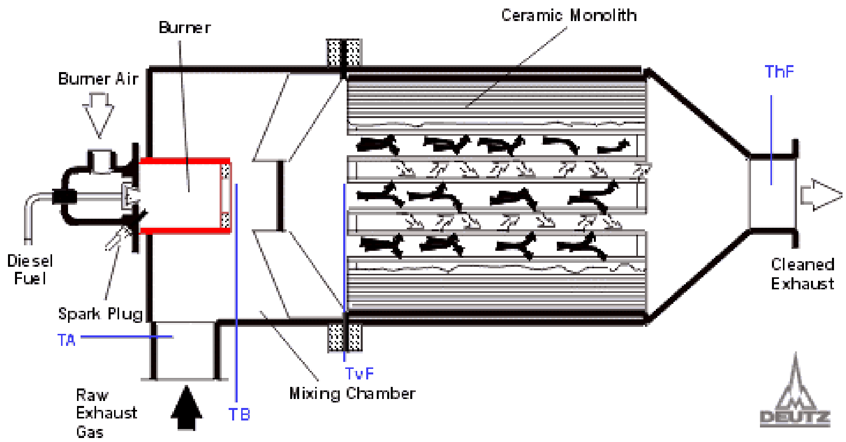

Figure 4: Fuel Burner Regenerating Filter
(Source: Deutz)

In additional to the CRT, this system includes the following: pressured air supply, a fuel supply for the burner, ignition system.

Critical parts and malfunctions:

Possible faults of this system in addition to those of a standard DPF could be the burner not igniting correctly or the quality of combustion being bad. The reasons for poor ignition and burning could be a bad spark plug, a clogged nozzle or a fault in the fuel or air supply. The may have the side effect of increasing HC emissions markedly.

7.1.4 Catalysed Diesel Particulate Filter (CDPF)

This process involves applying catalytic material directly to the filter material that will reduce the soot oxidation temperature to approximately 300°C.

7.1.5 Diesel Particulate Filters - Detection of the malfunctions

DPFs, require direct monitoring of particle emissions that could be achieved with a soot sensor. The increasingly stringent regulations are creating difficulties in measuring particulate emissions within dedicated laboratories and are therefore a great challenge to detect particulate emissions produced by the vehicle in use.

There have been attempts to develop a soot sensor, but these are not yet commercially available for vehicles. It is considered unlikely that they will be available in the 2005 timescale. [1] [2] [3]

Indirect monitoring can be achieved by measuring the drop in pressure across the filter. The drop in pressure between the input and the output of the filter is used to assess the quantity of soot in the particulate filter. However, this pressure difference fluctuates with engine speed and load conditions. Pressure sensors are also sensitive to soot fouling and gas condensation. [3]

The actual flow rate of the exhaust gas needs to be considered (see Figure 5) and can be determined by a model created from engine test bed measurements or by measuring the intake airflow and the exhaust gas temperature.

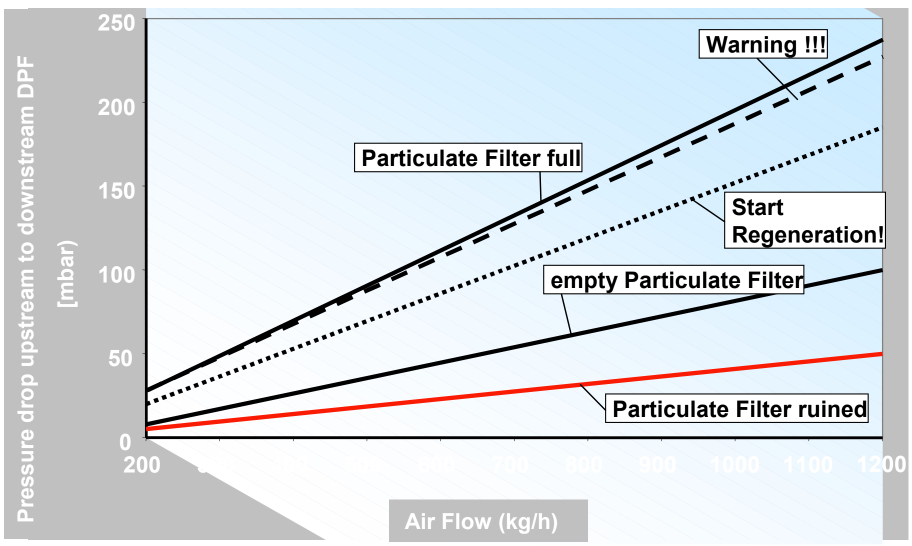

Figure 5: Particulate filter loading model

The principal problem with airflow sensors is guaranteeing their accuracy over a useful life span. Heating the film surface cannot easily clean hot-film sensors. This is because of the incorporated electronics that would rapidly be damaged at the required temperatures.

The fouling of the sensor surface causes a different heat transfer coefficient and consequently, a deviation of the measured values. Presently, for a light-duty vehicle lifetime of 12000km, an accuracy of 3 to 5% can be guaranteed. At present, no sensor manufacturer offers an airflow sensor for heavy-duty application, however this is not considered an insurmountable problem.

Another possible solution for determining the exhaust mass-flow rate is the calculation of the inlet air mass, using boost pressure and a boost temperature sensor as a function of density, engine displacement, absorption ratio, and the injected fuel quantity. If EGR is used, an EGR mass flow sensor must determine the EGR mass flow. Such sensors are in development but will not be production before 2005.

To monitor the correct functioning of the oxidation catalyst and to protect the filter against overheating, an additional three temperature sensors would be required to detect an increase in temperature over the catalyst, a sensor should be mounted upstream and downstream of the oxidation catalyst. The third is placed downstream of the particulate filter to detect excessive temperatures resulting from the regeneration.

Additional requirements for fuel born catalysed filter:

Filters that require a fuel born catalyst have to have the correct catalyst-dosing regime monitored. Initially, the level in the tank is monitored by the fluid level indicator and will give a warning signal at a defined low level. The direct method to monitor the correct dosing of the additive could be to measure the concentration of the additive in the fuel. Measuring the electrical conductivity of the fluid could achieve this but there are no suitable sensors identified at this time.

An easy, but not accurate method to monitor the correct fuel dosing is to check the additive consumption and compare it with a known consumption figure for the driven kilometres.

An important point is the use of the right regulated additive and how to detect non-compliance. The use of unregulated additives, such as those that contain cooper, can extend the regeneration period and consequently reduce fuel consumption. To prevent this misuse, the sensor system would detect all unregulated additives, but at this time there are no sensors known which are capable of achieving this.

Additional requirements for DPF with fuel burner:

The correct function of a fuel burner DPF is dependant on the correct ignition and burning of the fuel. Faults can be caused by a clogged nozzle or incorrect air supply. The easiest way to monitor the ignition and combustion would be the use of a temperature sensor sited in the burner. A second but more complex and expensive method is the use of an optical sensor that detects the light of the burner combined with CO sensors, which are currently not available.

7.2 NO_X ADSORBERS

There are two known after treatment systems to reduce NO_x emissions.

- Selective Catalytic Reduction (SCR)
- DeNO_x (Lean NO_x) Catalyst

7.2.1 Selective Catalytic Reduction (SCR)

Figure 6 shows the principle of the SCR Catalyst.

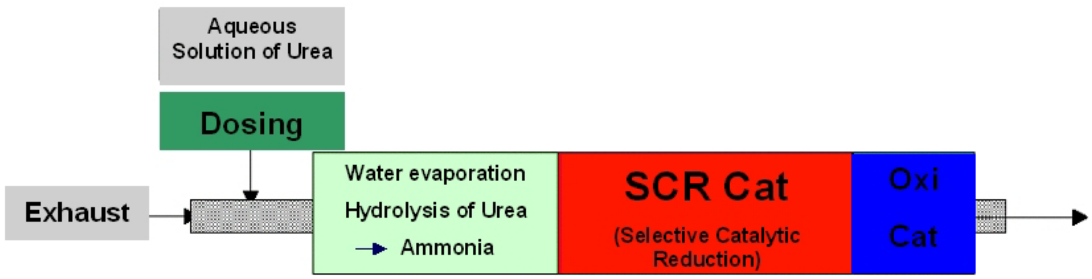

Figure 6: Principle of the SCR Catalyst
(Source: PUREM)

Urea is dissolved in water and is injected in the exhaust gas stream and hydrolyses CO_2 and NH_3. The ammonia is used as NO_x reductant producing N_2 and water.

The SCR catalyst is a honeycomb catalyst made of ceramic material in which the ammonia is stored. An oxidation catalyst downstream the SCR catalyst can be used to prevent ammonia from passing through to atmosphere, (ammonia slip).

Critical parts and malfunctions:

The urea injection starts at a defined exhaust temperature and engine speed, normally at 150°C, and is controlled by a temperature sensor. Engines running a considerable time at idle speed, e.g. in city busses, will have problems reaching the required temperature, especially in winter. An Inadequate, broken reactant tank will result in the malfunction of the SCR system and may result in overdosing of NH_3. This would produce serious environmental consequences called ammonia slip. There are no vehicle performance penalties when the reactant tank is empty. Monitoring of the reactant level in the tank is crucial for compliance.

7.2.2 DeNO$_x$ (Lean NO$_x$) Catalyst

The DeNOx catalyst stores NO$_x$ as nitrate during lean operation and releases the NO$_x$ under rich conditions where the NO_2 is reduced by the hydrocarbons.

For heavy duty-vehicles applications a large catalyst volume is needed which could be several times the cylinder capacity and therefore this system is unlikely to be used.

Critical parts and malfunctions:

This system is extremely sensitive to sulphur, even when using low-sulphur fuels. This requires the catalyst to be cleaned of sulphur every 10–15 hours of operation. This is achieved by raising the catalyst temperature to over 600^{o}C by introducing fuel to the catalyst directly via injection into the exhaust or the engine. However, these high temperatures, especially under oxidizing conditions can cause the catalytic material to melt and recrystallise randomly across the catalysts ceramic monolith, permanently decreasing the NO$_x$ adsorber performance.

Proper NO$_x$ adsorber function requires extensive functionalities implemented in the ECU using both NO$_x$ adsorber and a raw emission models. These models can be built from physical data or models based on simple emission maps. The models and the controllers require a NO$_x$ sensor to determine NO$_x$ breakthrough and the state of ageing and sulphur poisoning of the adsorber. These models can also be incorporated into OBD functions

7.2.3 NO$_x$ adsorbers - Detection of the malfunctions

The most effective method to monitor the effectiveness of the NO$_x$ adsorber is to monitor the levels of NO$_x$. A NO$_x$ sensor downstream from the SCR-catalyst used for closed-loop NO$_x$ control could be used together with a NO$_x$ sensor upstream of the SCR-catalyst. The rate of NO$_x$ conversion could then be calculated and the condition of the catalyst assessed.

NO$_x$ sensors are available for passenger cars but are still considered expensive. However, there is a major difficulty in implementing the malfunction strategy described above using current NO$_x$ sensor technology, namely, they respond to ammonia as well as to NO$_x$ which is clearly undesirable in a system in which both ammonia and NO$_x$ will be present. Further developments in sensor technology and system integration are likely to be required before an effective NO$_x$ monitoring system is available. [2]

The cross sensitivity of the NO$_x$ sensor to NH3 mentioned above is another point at the SCR system. The NO$_x$ sensor downstream the SCR would detect the NO$_x$ reduction but also a possible NH_3 breakthrough. A high level at this sensor would show that there is a fault in the system but not if there is too much NO$_x$ or undesirable NH_3 emissions. Many tests would be necessary to define signal levels for every possible fault of the SCR system or the NH_3 dosing.

US truck manufacturers believe that the NO_x sensor technique for direct NO_x measurement of reduction catalysts will not be in production by the 2004 model year and these sensors are expected to be very expensive. [1]

To detect incorrect NH_3 dosing and reactant tank level, a sensor together with a basic model and distance driven could be used. This however, this is not considered sufficiently accurate.

7.3 LOW PRESSURE FUEL SYSTEM

The task of the low-pressure fuel system is to store the fuel and guarantee the correct fuel supply to the injection systems.

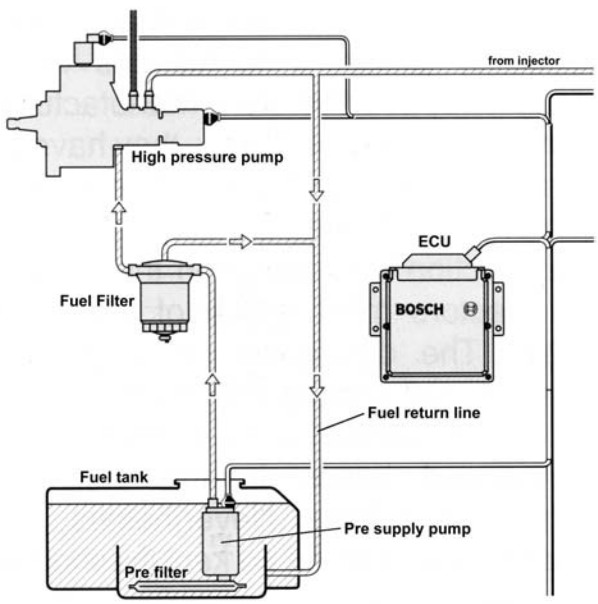

Figure 7: Low pressure circuit of a CR injection system
(Source: Bosch)

Possible faults in the fuelling system:

- Breakdown of the fuel pump
- Leakage in the tank or tubing
- Fault of the level sensor
- A clogged fuel filter

7.4 INJECTION SYSTEMS

The following injection systems are commonly used in HDV engines.

- Distributor Injection Pump
- Electronic Unit Injector (EUI) + Electronic Unit Pump (EUP)
- Common Rail

7.4.1 Distributor Injection Pump

The subsystems of the distributor injection pump system that could have an effect upon the vehicles emissions are, the pump, line, nozzle, sensors and electronics. In Table 2 critical parts and possible malfunctions of these subsystems are described and the influence on emissions is assessed.

Table 2

Critical Parts and Malfunctions of the Distributor Injection Pump		
		Influence on emissions
Pump	Defective injection timing device	+ + +
	Wear/dirt or leaking electromagnetic valve => increased leakage	+ + +
	Defective pre-supply pump/leaking housing/leaking pressure holding valve	+ + +
Line	Leaking screw => lower pressure, less injection rate	+
	Crack in the line => total break of the line => engine breakdown	0
Nozzle	Defective needle-travel sensor => wrong timing	+ + +
	Bursting of the nozzle	+ + +
	Coking of the nozzle	+
	Seizing of the needle (open) => engine break down	0
	Spring breakage => engine break down	0
	Leakage in nozzle holder	+
	Seat wear and seat fouling	+
Electronics Sensors	Engine-camshaft rotational speed => inexact start of injection	++
	Defective air flow sensor	+ + +
	Cooling water temperature sensor (e.g. False cold start)*	++
	Fuel temperature sensor	+

0 …… no influence on emissions +++ … high influence on emissions

*'False cold-start' means that the cooling temperature sensor suggests a temperature that would stimulate the engine control to initiate cold start conditions. (e.g. different injection timing to reach operating temperature faster)

7.4.2 Electronic Unit Injector (EUI) + Electronic Unit Pump (EUP)

Electronic Unit Injector (EUI) systems combine the fuel injection pump, the injector, and a solenoid valve into one unit. These unit injectors are located in the cylinder head above the combustion chamber. The EUI is driven by a rocker arm, which is in turn driven by the engine camshaft.

Switching the integrated solenoid valve actuates injection. The closing point of the bypass valve marks the beginning of fuel delivery and the duration of closing determines the fuel quantity.

Table 3 describes the critical parts and malfunctions of the EUI and EUP and their influence on emissions.

Table 3

Critical Parts and Malfunctions of the EUI and EUP		
		Influence on emissions
Pump	Leakage in pump	+
	Return-flow restriction seized open	+ + +
	Wear/dirt => increased leakage	+ +
	Electromagnetic valve inexact	+ + +
	Defective pre-supply pump/leaking line/leaking pressure holding valve/ closed fuel filter	+
Line	Leaking screw => lower pressure, less injection rate	+ +
	Crack in the line => total break of the line => engine break down	0
Nozzle	Bursting of the nozzle	+ +
	Coking of the nozzle	+ + +
	Seizing of the needle (open) => engine break down	0
	Spring breakage => engine break down	0
	Leakage in nozzle holder	+
	Seat wear and fouling	+
Electronics Sensors	Engine-camshaft rotational speed => inexact start of injection	+ +
	Defective air flow sensor	+ + +
	Cooling water temperature sensor (e.g. False cold start)*	+ +
	Fuel temperature	+

0 …… no influence on emissions +++ … high influence on emissions

*‘False cold-start’ means that the cooling temperature sensor suggests a temperature that would stimulate the engine control to initiate cold start conditions. (e.g. different injection timing to reach operating temperature faster)

7.4.3 Common Rail Injection system

Figure 8 shows the schematic picture of a common rail system and the control system.

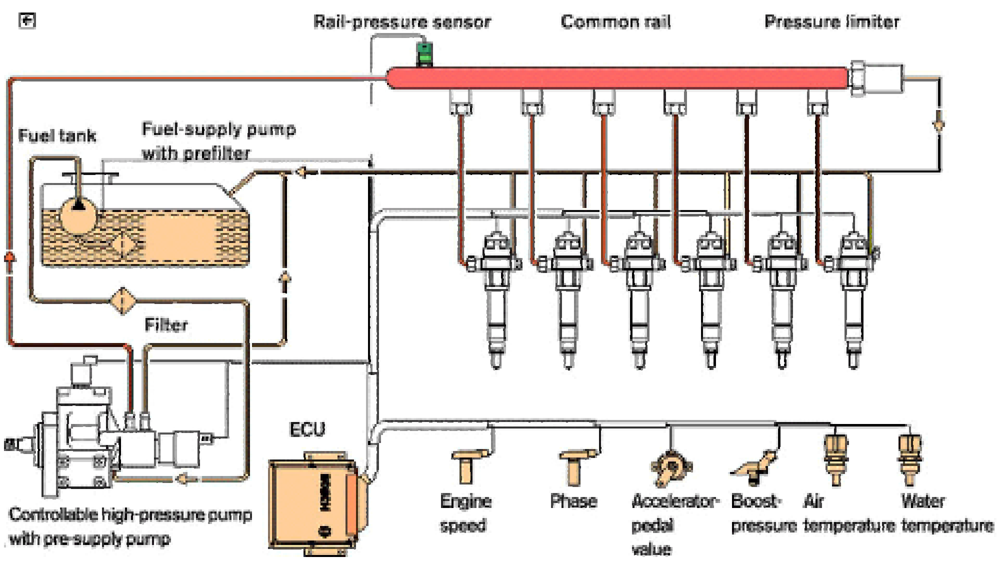

Figure 8: Common Rail
(Source: Bosch)

Table 4 shows the critical components and malfunctions of the Common Rail system and their influence on emissions.

Table 4

Critical Components and Malfunctions of the Common Rail Injection System		
		Influence on emissions
Injector	Needle stays open => cylinder is filled with fuel => engine breakdown	0
	Fouled nozzle-needle seat => small leakage	+ + +
	Fouled inlet or return flow throttle => different opening and closing speed	+ +
	Nozzle spring fatigue => higher injection rate	+ +
	Electromagnetic valve spring breakage => engine breakdown	+
	Electromagnetic valve defect => no injection	0
	Leaking electromagnetic valve	+ + +
	Injector return flow – wrong pressure	+
	Bursting of the nozzle	+ + +
	Coking of the nozzle	+
	Seizing of the needle (open) => engine break down	0
Line	Leakage – rail pressure is not reached => fault indication	0
	Crack of the line => total break of the line => engine break down	0
Rail	Flow limiter response => one cylinder is switched off	+
	Pressure limiting valve defect	+ +
High-pressure pump	Too much or too little amount is delivered => system detects that	0
Electronics Sensors	Engine-camshaft rotational speed => inexact start of injection	+ +
	Defective air flow sensor	+ + +
	Cooling water temperature sensor (e.g. False cold start)*	+ +
	Fuel temperature	0
	Rail pressure sensor (wrong indication)	+ + +

0 …… no influence on emissions +++ … high influence on emissions

*'False cold-start' means that the cooling temperature sensor suggests a temperature that would stimulate the engine control to initiate cold start conditions. (e.g. different injection timing to reach operating temperature faster)

7.4.4 Injection Systems - Detection of the Malfunctions

An incorrect injection rate can be calculated using a wideband lambda sensor and an air-mass sensor, from which the collected data is compared to the required fuel quantity. However, the lambda probe also indicates problems within the air intake system and EGR system. These effects could compound each other.

A different approach to detecting injection malfunctioning is map based monitoring of the exhaust temperature at each cylinder. Either by measuring the exhaust gas temperature downstream of the exhaust manifold with one very fast exhaust gas temperature sensor, or measuring the temperature at each outlet port with separate temperature sensors. This would allow a fault in a single cylinder to be detected. Temperature sensors with very short response times have recognised durability problems.

Another approach is analysing the angular accelerations of the flywheel. If there were a fault of the injection system in one cylinder, variations of engine accelerations would occur. This technique would work well at idle and at low engine speeds but would have problems at higher engine speeds.

The varying start of injection caused by a change in injection pressure or wear of the nozzle is monitored by a control loop with a needle travel sensor.

7.5 EXHAUST GAS RECIRCULATION (EGR)

EGR is used to reduce NO_x emissions by recirculating a proportion of the exhaust gas back into the combustion cylinder. This reduces the oxygen available in the cylinder for combustion and creates lower peak temperatures that inhibit the formation NO_x.

There are different principles of exhaust gas recirculation.

- External High Pressure EGR
- External Low Pressure EGR
- Internal EGR

7.5.1 High pressure EGR

Exhaust gas is diverted back into the intake manifold from the exhaust manifold under pressure from the combustion cylinder. For cooling the exhaust gas an EGR cooler is used. (Figure 9)

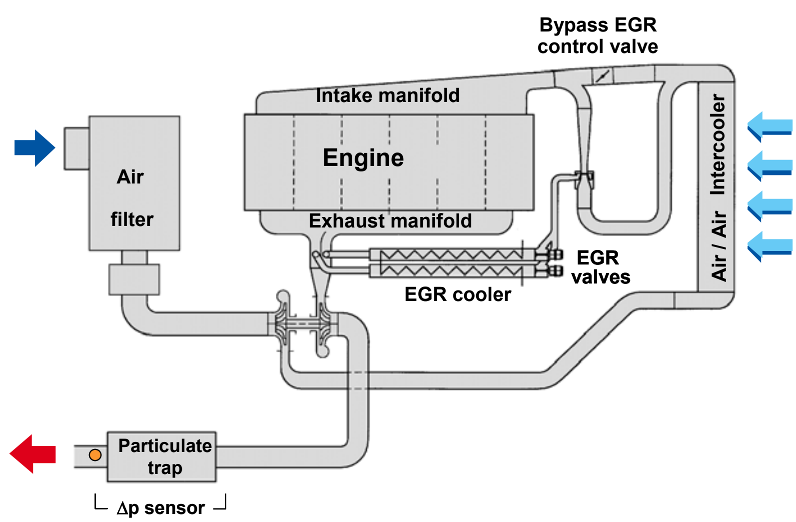

Figure 9: High pressure EGR
(Source: AVL)

7.5.2 Low pressure EGR

The low pressure EGR re-routes the exhaust gas from after the turbocharger and particulate filter to the fresh airflow before the turbocharger. (Figure 10)

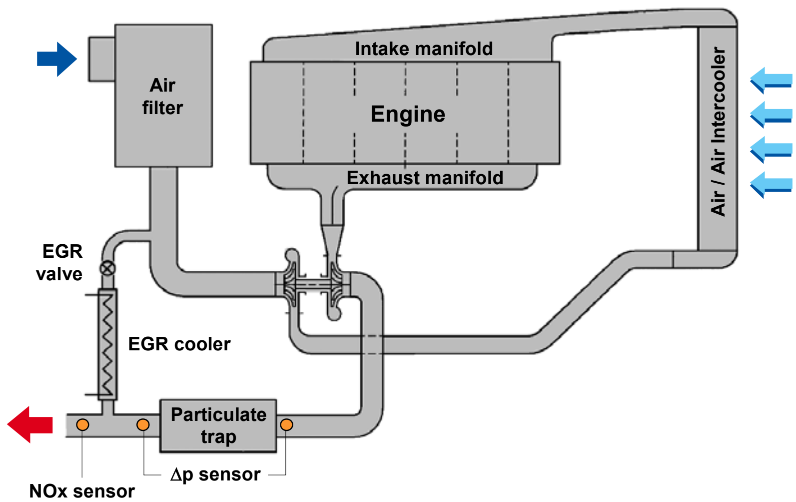

Figure 10: Low pressure EGR
(Source: AVL)

7.5.3 Internal EGR

An overlapping opening of the exhaust and the intake valve results in a mixture of fresh air and exhaust gas in the cylinder. (Figure 11)

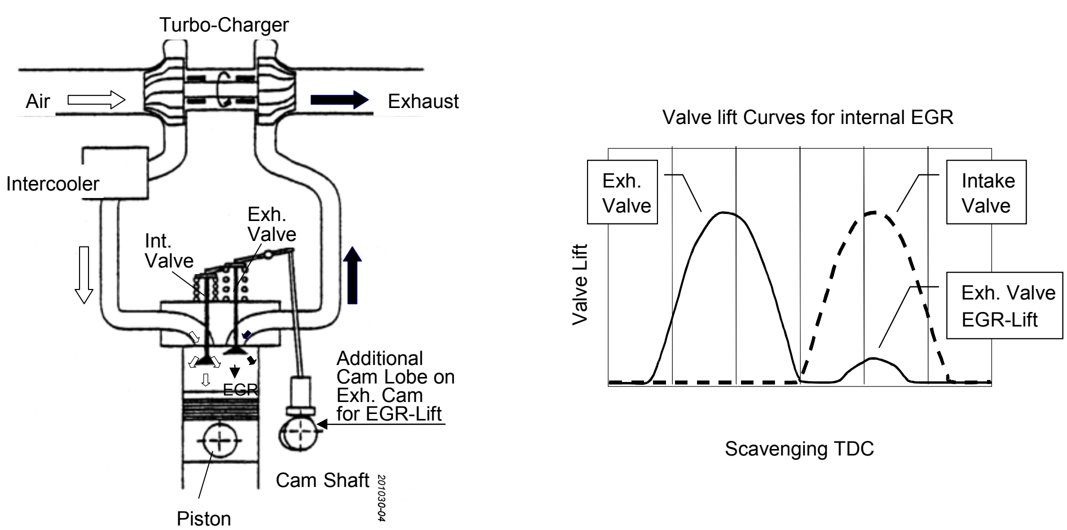

Figure 11: Internal EGR)
(Source: Hino Motors Limited

7.5.4 Exhaust Gas Recirculation - Possible Malfunctions and their detection

Table 5

EGR- Possible faults and their influence on emissions	
Seized EGR valve	+++
Defective intake manifold throttle	+++
Leaking EGR cooler (water injection)	+
Leaking EGR-line	++
Defective fresh air flow sensor (= control variable)	++

\+ …… low influence on emissions +++ … high influence on emissions

Direct emission measurement:

The rate of EGR has a big influence on NO_x emissions. Therefore, a NO_x sensor within the exhaust will detect faults in the EGR system comparing the measured values with engine map based models.

Indirect methods:

Temperature sensors are too slow for dynamic conditions, but could be used to detect a sticking EGR valve. A valve that has become permanently closed could be detected by mounting a temperature sensor directly within the EGR system. By locating the sensor in the intake system (after the EGR connection), a valve that has become permanently open could be detected through observing rising temperatures in the intake system. A more logical solution to identify stuck valves would be to incorporate a position transducer into the valve itself. Few actuators can offer this facility

Most vehicle control systems shut off EGR in the case of a malfunction to protect the engine. A temperature sensor could also be used to detect faults in the EGR cooler, again by comparison with a map-based model.

The EGR mass flow could be monitored with a flow sensor located after the EGR cooler measuring the pressure drop over the EGR valve.

8 SUMMARY OBD

Table 6 gives an overview of methods for detecting changes in the function of Emission Control System Components.

Table 6

Methods for Detecting Changes in the Function of Emission Control Systems			
Component/System	**Impact on Emissions**	**Detection**	**Sensors**
Fuel injection system	Low to high (Various malfunctions possible)	- Needle movement and/or - Constant engine velocity and/or - Exhaust temperature and/or - Lambda measurement	- Needle travel sensor - Speed sensor (pick-up) - Fast temperature sensors - Accurate Lambda sensor
Exhaust Gas Recirculation	High (valves and control)	- Temperature measurement and/or - Lambda measurement and/or - Flow measurement	- Temperature sensor - Fast and accurate lambda-sensor - Exhaust hot mass flow sensor
Particulate trap	High (bad regeneration, melting, physical damage,..)	- Pressure and temperature before and after the trap, model based check with exhaust mass flow	- Pressure sensor - Temperature sensor Exhaust hot mass flow sensor
NO_x adsorber	High (bad regeneration, melting, physical damage,..)	- NO_x measurement and - NH_3 measurement	- NO_x sensor - NH_3 sensor
All	All	- Emission measurement at the tailpipe	- Emission sensors for NO_x, PM, CO, HC

Although the composition of exhaust gas have been measured within a laboratory environment for many years using predominately gas analysers, only a small number of the sensors available on market fulfil the requirements for automotive applications. The general requirements for automotive applications are, low cost, small, ruggedness, accuracy and especially in case of HDV, durability.

It can be assumed that the electronic systems (controller, harness, connectors etc) fulfil the reliability and durability requirements, but the reliability of OBD systems is strongly connected to the reliability of the sensors used. Historical evidence suggests that sensors currently used in passenger car applications must be further improved to fulfil the more demanding requirements of commercial vehicles. A direct transfer of passenger car sensors is not feasible. It may be possibly too possible to change sensors at service intervals, but this would increase maintenance costs significantly.

On one hand, the use of OBD systems will help to identify faults faster and will consequently save repair costs and vehicle downtime. However, the sensors will have to be checked as part of a standard vehicle service regime, staff will require considerable extra training and these additional cost may negate the advantages described above.

All these issues result in a considerable effort and extra costs to both the manufacturer and the vehicle operator. Any OBD system has to be designed to enable the customer to benefit from extended service intervals and minimized downtime. [4]

Currently, specific information about sensors, which are in development, is commercially restricted and difficult to obtain. Cost prediction information, especially for a high production numbers, has proved impossible to obtain.

Table 7, shows an overview on the sensors needed and their availability, durability and accuracy. Although there is little or no information available, the author has attempted to compare the cost effect of HDV OBD sensors to existing systems. However, this has to be considered a conservative estimation ranging from no additional costs (marked with “0”) to high additional costs (marked with “+++”).

Table 7

Sensors for detecting changes in the function of components relevant for the emission level				
Sensor	**Availability**	**Durability**	**Accuracy**	**Costs**
Needle lift sensor	In series production	Good	Good	+
Speed sensor for angular velocity	In series production	Good	Good below 1500 rpm	0
Exhaust hot mass flow sensor	Pre series	Open	Good	++
Pressure				
In Injection system (e.g. rail pressure)	In series production	Good	Good	0
For particle trap	In series production	Critical	Critical long term stability	++
Temperature				
For EGR	Pre series for HDV	Open	Good	+
For exhaust gas (fast)	Pre series for HDV	Critical if fast response is needed	Good	+
For particle trap	Pre series for HDV	Open	Sufficient	+
Lambda Sensor (wide band)				
For EGR	Yes	Needs to be improved	Low at high Lambda	++
For NO_x adsorber control	Yes	Needs to be improved	Low at high Lambda	++

Sensors for detecting changes in the function of components relevant for the emission level				
Sensor	**Availability**	**Durability**	**Accuracy**	**Costs**
Emission sensors				
NO_x sensor	Yes	Needs to be improved	Needs to be improved	+++
CO-sensor	Open	Open	Open	+++
HC-sensor	Open	Open	Open	+++
PM sensor	Open	Open	Open	+++
NH_3 sensor	Open	Open	Open	+++

A list of sensor manufacturers and information of the sensors offered from these companies is given in Annex II (see 14.2).

9 FAULT STORAGE AND ENHANCED FUNCTION OF OBD

In addition to the detection of malfunctions and non-compliance to emissions limits, the OBD system has to have the capability of storing collected information and allow interrogation enabling the fault to be located and the reason for the fault to be identified. The following is a description of the fault storage functions extracted from the US EPA regulation § 86.099–17.

OBD systems should be designed to be able to record and store in computer memory diagnostic trouble codes and diagnostic readiness codes indicating the status of the emission control system. These codes shall be available through the standardized data link connector. A diagnostic trouble code shall identify the malfunctioning system or component as uniquely as possible and should be stored for any detected and verified malfunction causing MIL illumination.

Separate status codes, or readiness codes, shall be stored in computer memory to identify correctly functioning emission control systems and those emission control systems which require further vehicle operation to complete proper diagnostic evaluation.

Upon determination of the first malfunction of any component or system, ‘‘freeze frame’’ engine conditions present at the time shall be stored in computer memory. Stored engine conditions shall include, but are not limited to: engine speed, open or closed loop operation, fuel system commands, coolant temperature, calculated load value, fuel pressure, vehicle speed, air flow rate, and intake manifold pressure if the information needed to determine these conditions is available to the computer. For freeze frame storage, the manufacturer shall include the most appropriate set of conditions to facilitate effective repairs.

Access to the data required shall be available through a standardized data link connector and shall be unrestricted and not require any access codes or devices that are only available from the manufacturer (OBD standardisation).

OBD Standardisation

Generally the aim of OBD standardisation is to allow independent or "free" vehicle service agents unrestricted access to the stored OBD data. Therefore the connection interface between the vehicle system and the diagnostic tool must be standardised and meet all the requirements of ISO 15031-3 (Road vehicles - Communication between vehicle and external test equipment for emission-related diagnostics).

ISO 15031 rules out the possibility of communication between vehicle systems and diagnostic tools. Four ways are currently available:

- Serial link using vehicle voltage level according ISO 9141-2
- Keyword 2000 protocol according ISO 14230
- SAE J1850 (already obsolete)
- CAN Bus according ISO DIS 15765-4 (not yet in use, but currently prepared)

In Europe, a working group exist engaged in preparing a new ISO regulation (ISO 15765). European truck manufacturers prefer ISO 15765 and it is expected that this will be adopted by all EU member states.

ISO 15031 includes the technical specifications and solutions that are required by CARB, EPA, and EU and for future inclusion by Japan. For passenger cars and heavy-duty vehicles, the 15031 standards now have been extended to that required by MY 2005.

Although the diagnostic system has to recognise all protocols of the ISO 15031, European manufacturers would prefer the diagnostic connector currently used in light-duty vehicles. This would allow one common connection across a wide range of commercial vehicle types. The US manufacturers object on the point of durability and vehicle systems voltage differences and consequently, would prefer to have a different connector for heavy-duty vehicles.

The basic difference between ISO standards and SAE J1939 is the use of a different data format. SAE J1939 also uses a different diagnostic connector and protocol. An ISO 15031-4 equivalent external test equipment specification as part of the SAE J1939 does not exist. Neither SAE nor ISO intend to develop a diagnostic scan tool specification based on J1939.

At the ISO working group many points are in discussion at the moment and changes of the proposed ISO standard are made permanently.

A further difference between ISO and SAE standardisation is demonstrated by SAE standards being issued by a consortium of manufacturers (OEMs) and can be changed quickly if desired by the SAE members. International ISO standards require the involvement of authorities, national standardisation agencies and this process causes to the agreement and implementation of any changes. Therefore, the truck industry prefers using SAE standards. It should also be noted that there is little motivation for the OEMs to allow access to their diagnostic data frames to independent service stations that are seen as competitors to the authorised dealers and repair shops.

Enhanced OBD functions for heavy-duty vehicles

There are a number of possibilities that would enhance functionality of heavy-duty vehicle OBD. One could be to store a record of the most regularly used areas of the engine operational map (perhaps together with an appropriate weighting), to generate a specific multi-point emission cycle. Such a map could be used for in-use conformity testing and deliver valuable statistical information for the design of new test cycles and procedures. A second could be a rolling record of emission events established over a limited number of “key-on” events that could be accessed through a standard diagnostic connector.

Another issue that requires consideration is related to fault code storage and the handling of subsequent actions that occur after an emissions control system fault is detected and the MI activated. The commission will have to decide if an immediate action is required or if another course of action is required.

When the MI is activated, the objective should be to encourage the vehicles driver to stop at the next authorised service agent for remedial action as soon as possible. This could be achieved by immediately reducing power. However, this action could prove to be dangerous whilst driving on public roads. A better solution would be to alter the engine control to produce the best possible emissions behaviour whilst still suffering from the fault (special limp home maps). This could lead to poor fuel consumption, which in itself is an incentive to proceed to the service agent as soon as possible.

It has also been proposed that fines could be imposed if there are long periods between MI activation and the visit to the service agent. In the EU proposal, it is included that a record be kept of the operational hours between MI activation and fault rectification. The problem with this solution is, how and who shall perform the checks. Many large fleet organisations have their own service departments, will repair their own vehicles and may not submit any non-compliance reports. Also, independent service agents may not be keen to report their customers for fear of losing business. The only regulated solution would be to require police or government officials to conduct random and periodic checks similar to those currently conducted on maximum allowable driving hours.

10 ON-BOARD MONITORING (OBM)

OBD, as a method of monitoring the functionality of emissions control systems, would be a useful tool if all the issues previously described were addressed. An alternative to OBD is On Board Monitoring, OBM, which would measure exhaust emissions at the tailpipe.

An OBM system must have a number of operational characteristics in order to be practical for in-use testing. The system must be reliable, measure the levels of certain exhaust constituents, be repeatable and correlate with measurements that have been obtained from laboratory tests. In addition, it must be expected that such a system would function accurately over a wide range of ambient conditions including altitude.

The motivation for developing an on-board exhaust measuring system was to create a system for making emission measurements under real world driving conditions. Various systems were developed in the 1980's and employed in inspection and maintenance (I/M) programs. These were based on existing laboratory technology. [5]

In 1998, West Virginia University (WVU) started development of a mobile emissions measuring system (MEMS), for US truck manufacturers. However, due to the problems of determining HC and CO, with the existing technology, they concentrated on CO_2 and NO_x emissions. [6]

The US-EPA has also developed an on-board emission measurement system called ROVER (Real Time On-road Vehicle Emission Reporter). This system and the MEMS of WVU, derives the engine power from the torque data available on the vehicle CAN-bus. The ROVER developers found that there were considerable differences with the accuracy of the torque data between different truck brands. Similar to MEMS, ROVER also uses emission flow measurements to convert the analysed emissions expressed as percentages to grams. This flow measurement has significant inaccuracies because most flow meters only give accurate values when the exhaust gas flow is laminar. The use of flow meters is reasonable for long overhead exhaust pipes as seen on many US trucks but on European trucks, this layout is uncommon and consequently the use of a flow meter is not recommended for EU mobile emission measurement systems. [7]

The Flemish Institute for Technological Research (VITO) has developed a further mobile measuring system. This system has the capability of measuring of real world particulate mass. Vito's On-the-road Emission and energy Measurement-system (VOEM) does not use the emissions flow to calculate grams from the analysed emission percentages. The VOEM methodology is based on the mass balance over the engine and the measured concentration of the emissions. For in-use compliance testing of heavy-duty vehicles, Vito is developing a new system called VOEM-suitcase.[8]

The system developed by the Wissenschaftliche Werkstätte für Umweltmeßtechnik (WWU, Hamburg) is believed to be small enough to easily fit within the vehicle without compromising accuracy.

There is currently no data available on the durability of this devices and it is not expected that such systems will be ready for production until 2010.

Truck manufacturers, however have objections to using emission analysers within the vehicle. They are concerned by the costs and the lack of information on system reliability. They know by experience how sensitive emission measurement systems are in the protected environment of laboratory and it is uncertain how these systems can cope with the difficult road conditions.

Instead of using in-vehicles gas analyser systems, a preferable solution might be to use emission individual sensors e.g. NO_x, HC sensors. These are smaller, easier to handle and calibrate and will be less expensive. A few manufacturers are currently developing such sensors. However, the limited market potential is limiting the speed of their development.

In general, OBM should not be regarded as a replacement for OBD but as an enhancement. The OBM system continuously measures the vehicles emissions and the measured values are compared with stored nominal values for a specific driving condition. Therefore the important requirement for such a system is not absolute accuracy but the reproducibility. [5]

11 CONCLUSIONS

To meet the future Euro4 and Euro5 emission limits, new emission technologies such as Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR), Diesel Particle Filters (DPF) and $DeNO_x$ catalysts are required. Together with the introduction of these technologies, OBD will most likely become mandatory to assure vehicle compliance with legislation over lifetime.

Some of these emission systems need active control, while others need passive monitoring systems to protect the engine. All these systems are equipped with sensors and/or actuators that will perform internal diagnosis for operational control. Most of these signals can be processed without creating problems to the OBD system (freeze frame data).

For proper function and control, additional sensors, measuring directly the relevant emissions components, would be desirable or at least recommended. Most of these sensors are not currently available for HDV applications and it is uncertain if these sensors will be in series production before 2005. Sensors measuring the emission species directly are just in the initial stages of development, with the exception of the NOx sensor, which is already used today in passenger cars. However, further development work is necessary before it can be applied to HDVs.

Presently, to overcome the emissions sensor shortcomings, the control and monitoring of the emission devices will be based on internal software models, describing the current status of the emission device. Signals from standard sensors can be used as inputs to those models and therefore the status and behaviour of the system can be calculated. From this internal simulation messages can be transferred to the OBD system.

All these issues result in a considerable effort and extra cost. Therefore, these systems have to be designed to give longer service intervals and minimised stop periods resulting in greater benefits to the customer.

The OBD system must be designed, constructed and installed in the vehicle to enable the identification of deterioration and malfunctions over the entire life of the engine. Some natural deterioration will occur and has to be accepted, however, an appropriate durability period needs to be achieved. Currently, no reliable data to determine such durability periods is available.

Currently, the manufacturers have not demonstrated a system and there is no clear picture of what a truck OBD system will look like. Therefore only speculations about the reliability of OBD systems can be made.

It can be assumed that the electronic systems controller, harness, connectors etc. fulfil the reliability and durability requirements. The reliability of OBD systems is strongly connected to the reliability of the sensors. These sensors are either in development or only recently in service. Consequently, reliable data on long-term performance over HDV lifetimes are not available.

The concept of a complete exhaust emission-monitoring system based on emission analysers in a heavy-duty vehicle is currently rejected by the truck industry. Such systems have not proven to be durable and reliable over the expected lifetime of a truck and are very expensive. Furthermore the maintenance and calibration of such systems are not feasible in field application.

Developing a system to monitor emissions with sensors would be a better solution but there are no suitable sensors available at the present and it is uncertain when such sensors will be ready for series production.

12 RECOMMENDATIONS

Integration I/M programs

OBD and Inspection/Maintenance programs should be considered as the system to ensure emission compliance as well as engine protection.

The introduction of OBD could also generate additional benefits for the end user that could negate some of the additional costs of such systems.

Before finalising the text of the EU Directive talks and expert hearings should be held with maintenance experts of big fleets or OEM organisations.

Standardisation

The policy expressed in the EU proposal to force standardisation for connectors, data format, freeze frame data etc. should be retained. The general introduction of ISO standards should be accelerated and not diluted by long transitional periods, for example, by moving from SAE J1939. Most of the systems are being designed now. It would be no additional effort to commence with ISO at the beginning.

Type Approval

The general intentions of the Draft Proposal seem feasible. However, the details of some of the paragraphs covering the functional aspects could be reconsidered.

The current directive proposes to use the standard type approval ESC test cycle for approval. The phases of approval are:

- Simulating the malfunction of a component in the engine management or emission control system
- Preconditioning of the OBD system with the simulated malfunctions over a number of test cycles
- Operating the engine with a simulated malfunction over ESC test cycle and measuring emissions
- Determining whether the OBD system reacts to the simulated malfunction and indicates malfunction in an appropriate manner

The fault simulation using SCR as an example should be carried out by:

- Replacing components that are aged, defective or damaged
- Lack of reagent (i.e. Urea) for the selective catalytic reduction (SCR) system
- Electrical failure of any SCR actuator
- Major breakdown of a NO_x trap system

The exact procedure of how to test OBD could not be as comprehensive as intended. This proposal does not include easy to perform tests such as:

- Disconnecting sensors and actuators
- Simulating wrong sensor signals (signal tampered by an electric device)
- Simulating faulty tank / storage signals

It can be anticipated that the internal diagnosis of a SCR system also takes care of such faults.

The same applies to the testing of particulate filters. In order to test these systems, replacing the filter with one pre-prepared to the detailed specification of the faults to be expected. This includes the specification of “clogged”, “broken”, “melted” etc. However, the test should not allow engine-operating conditions that will allow the diesel particulate filter substrate to melt considerably. Such a procedure could lead to a major damage to the engine.

As an example, the clogged filter could be described as a filter that has only 30% of the nominal flow or 1.5 times the nominal allowable exhaust gas backpressure. A major crack could be represented by a very small backpressure related to an orifice in the filter substrate.

Generally, it might be appropriate to propose only some generic procedures and let the manufacturer, in co-operation with the certifying authority, to establish a specific “OBD test plan” for a specific emission control and OBD system.

Since the functionality of the control systems is likely to be more difficult to realise under transient engine conditions than for steady-state tests and since some faults may have much higher effects on the emission levels under transient conditions, it is recommended to extend the OBD type approval to a transient test cycle, e.g. ETC at least in the second phase of OBD regulations when more experience is available.

Thresholds

Determination of OBD thresholds is also critical. There is little practical experience with real life faults, especially on the exhaust after treatment systems. These prototype systems have not undergone much field-testing and only little experience has been reported so far.

In the proposal, thresholds were derived from the emission limits by simple multiplication, for example, 1.2 x emission limit or 30% plus. Such threshold values are just an estimate that represents a postulation from a legislative point of view. A future well “engineered” solution should consider the effect of real-life failures and should adjust the thresholds accordingly. Therefore, extensive testing on emissions test beds as well as in the vehicle will be required to develop a feel for the appropriate threshold settings.

It is too early to decide on clear and justified thresholds until sufficient experience with the new systems has been collected.

EU Support

Currently the industry is struggling to achieve the required HDV emission limits, whilst assuring system robustness and preparing the new emission technologies for series production.

The parallel development of OBD means that whenever the emission devices undergo change or design variation, the OBD functions will need to be changed as well and a lot of "fault" testing will need to be carried out.

Therefore, it is recommended that support be given to any pre-competitive research program that aims to develop generic tools and helps to shorten the development time of new diagnostic and OBD functions.

EU Monitoring

As the development of HDV power train cannot be regarded as settled, further monitoring of emission, OBD approaches and sensor development for OBD and OBM has to be performed.

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14 LIST OF ABBREVIATIONS – ACRONYMS

A

AUTh	Aristotle University of Thessaloniki

C

CAN	Controller Area Network
CARB	California Air Resources Board
CDPF	Catalysed Diesel Particulate Filter
CFR	Code of Federal Regulations
CO	Carbon monoxide
COP	Conformity of Production
CRT	Continuously Regenerating Trap
CVS	Constant Volume Sampler

D

DDC	Detroit Diesel Corporation
DFC	Diagnostic Fault Code
DG ENTR	Directory General ENTeRprise
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DPNR	Diesel Particulate NO_x Reduction

E

EC	European Community
ECS	Emission Control System
ECU	Engine Control Unit
EDC	European Driving Cycle
EEV	Enhanced Environmental Friendly Vehicles
EGAS	Exhaust Gas After treatment device/system
EGR	Exhaust Gas Recirculation
EOBD	European On Board Diagnostics
EPA	Environment Protection Agency
ESC	European Steady Cycle
ETC	European Transient Cycle
EUI	Electronic Unit Injector
EUP	Electronic Unit Pump

F

FBC	Fuel Born Catalysts
FTP	Federal Test Procedure

G

g/bhp-hr	gram per brake horse power hour
GVWR	Gross Vehicle Weight Rating

H

HC	Hydro Carbon
HD	Heavy Duty
HDV	Heavy Duty Vehicle

I

I/M	Inspection/Maintenance
ISO	International Organisation for Standardisation
IUC	In Use Compliance/Conformity

L

LAT	Laboratory of Applied Thermodynamics (University Thessaloniki)
LCV	Light Commercial Vehicle
LD	Light Duty
LDV	Light Duty Vehicle

M

MEMS	Mobile Emissions Measurement System
MI	Malfunction Indication
MIL	Malfunction Indication Light
MIRA	Motor Industry Research Association
MY	Model/Make Year

N

NEDC	New European Driving Cycle
NH_3	Ammonia
NMHC	Non-Methan Hydrocarbons
NO_x	Nitrogen Oxide

O

OBD	On Board Diagnostics
OBM	On Board Monitoring/Measurement
OEM	Original Equipment Manufacturer

OREMS	On Road Emission Measurement System
P	
PM	Particulate Matter
PTO	Power Take Off (unit)
R	
RC	Readiness Code
ROVER	Real time On road Vehicle Emission Reporter
RPM	Revolutions Per Minute
S	
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SCRT	Combination SCR & CRT
T	
THC	Total Hydro Carbon
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
V	
Vito	Flemish Institute for Technological Research
VOEM	Vito's On the road Emission and energy Measurement system
VTG	Variable Turbocharger Geometry
W	
WHDC	World Heavy Duty engine test Cycle

15 ANNEXES

15.1 ANNEX I

OBD Terminology

Emission control system

The electronic engine management controller and any emission-related component in the exhaust that supplies an input to or receives an output from this controller

Readiness Code (RC)

Furthermore the system features a "readiness code" (RC) operation that serves as an indicator to identify or not whether a specific monitor has completed its task. Each system has its own readiness code.

Malfunction

Malfunction means the failure of an emission control component or system that would result in emissions exceeding the legal limits, or if the OBD system is unable to fulfil the basic monitoring requirements, or if the malfunction complies with the definition of "major functional failure".

Permanent emission fault mode

A when the engine management controller permanently switches to a setting that does not require an input from a failed component or system where such a failed component or system would result in an increase in emissions from the engine to a level above the limits.

Diagnostic Fault (Trouble) Code (DFC)

The OBD system must record fault codes indication the status of the emission control system. A fault code must be stored for any detected and verified malfunction causing MI activation and must identify the malfunctioning system (subsystem) or component as uniquely as possible. The diagnostic trouble code refers to an alphanumeric code that is associated with a specific test.

Freeze Frame Data

If an emission related malfunction occurs, the related DFC and vehicle operating parameters will be stored in the ECS memory. This is typically referred as “freeze frame data”. Only emission related data should be stored in freeze frame. Freeze frame data such as:

- Diagnostic Fault/Trouble Code
- Engine rpm
- Engine load
- Vehicle speed
- Coolant temperature
- Intake manifold pressures

The following additional information must be made available via the serial port on the standardised data link connector

- Injection timing
- Intake air temperature
- Air flow rate
- Pedal position
- Fuel pressure

The freeze frame data will allow the technician to spot any failures that can occur under specific conditions, which can be valuable when repairing or servicing the vehicle. Therefore all possibilities for storing data should be utilised.

A number of frames must be applied, operating as “first-in -first out buffer memory. The number of hours ran by the engine since the first appearance of a malfunction of any component or system should be attached to each frame of data.

Repair Information

Information required for diagnosis, servicing, periodic monitoring or repair of the engine and which the manufacturers provide for their authorised dealers /repair shops such as handbooks, technical manuals, diagnosis information etc.

Access

The Availability of all emission related OBD data including all fault codes required for inspection, diagnosis, servicing or repair of emission related parts of the vehicle, via the serial interface for the standard diagnostic connection.

Standardised

OBD data, including all fault codes used, should be produced only in accordance with industry standards, which, by virtue of the fact that their format and the permitted options are clearly defined, provide for a maximum level of harmonisation in the motor vehicle industry.

Test

The “test” is used to reference a sequence of input and/or output analysis, designed to detect failures of that specific input, output or related emission control system

Monitor

An OBD monitor is a test or series of tests that are used to determine operational status of engine or an emission control device or other system.

Two different types of monitor exist:

- Continuous monitors: These monitors run continuously for the whole length of the driving time
- Non-continuous monitors: These only conduct tests for short period of time, long enough to be able to gather the required determination, either pass or fail. They are normally used under stable conditions, when the engine is running at a constant load for a short period.

Driving Cycle

Vehicle operation consisting of an engine start and a driving period where a malfunction would be detected if present followed by an engine shut-off.

Warm-up Cycle

A warm up cycle means sufficient vehicle operation such that the coolant has risen by at least 22° K from engine start and reaches a minimum temperature of 343°K (70°C). This information can be used to determine when the ECS is allowed to clear DTC information.

Trip

Trip is a term used to identify a vehicle drive cycle in which a series of tests have been undertaken.

Enable Criteria

This term is useful in describing OBD functions and diagnostic operations. It is defined as "the vehicle operating conditions required for a diagnostic test or the monitor to run”.

Conformity of Production (COP)

The end of production line test, in which diagnostic routines are performed. Results of these test need to be periodically forwarded to the certification agency.

Defeat Device

Any manipulation (hardware or software), which switches off or disables emission control devices is called “defeat device” i.e. switching off catalyst pre-heater. Defeat devices are prohibited.

OBD Limits / Thresholds

These limits are set by OBD/emission legislation. Also engineering limits established which are lower than the legal requirements. When a threshold is exceeded the MI must be activated

The determination of the engineering thresholds requires bench and vehicle testing until sufficient experience is established.

Deficiency

Two separate components or systems that are monitored each containing temporary or permanent operating characteristics that impair the otherwise efficient OBD monitoring of those components or systems or do not meet all the other detailed requirements for OBD. It could be possible to achieve type approval even when one or more deficiencies exist.

15.2 Annex II

Table 8

Sensors and Supplier	
Soot Sensor (PM)	
No information about automotive application available.	
Exhaust Temperature Sensor	
Supplier	Epiq (www.epiq.com)
Range	< 1000 °C
Availability	series production for gasoline engines since 2001
Supplier	Beru (www.beru.com)
Range	< 1000 °C
Availability	samples available (e.g. HTS1000), no information about series production
Supplier	Denso (www.globaldenso.com)
Range	< 1000 °C
Availability	series production for diesel engine passenger cars using particulate Filters
Exhaust Differential Pressure Sensor	
Supplier	Kavlico(www.kavlico.com)
Range	0 .. 1000 mBar (customer specific range); +/- 3%; +40° .. 125°C
Application	loading of particulate filter
Availability	samples available, series production intended for year 2003
Supplier	Bosch (www.bosch.com)
Range	0 .. 1000 mBar,
Application	loading of particulate filter
Availability	samples available, no information about series production
Supplier	Motorola (www.motorola.com)
Range	0 .. 1200 mBar,
Application	loading of particulate filter
Availability	samples available, no information about series production

Sensors and Supplier	
Exhaust hot Mass flow Sensor	
Supplier	Kavlico(www.kavlico.com)
Range	0 .. 350 mBar,
Application	indirect measuring of EGR-mass flow through EGR-Valve
Availability	samples available, series production intended for year 2003
Supplier	Epiq (www.epiq.com)
Range	0 .. 600 kg/h, -40 .. 350°C
Application	Electrical heater (similar to PT100 temperature sensor) heats up to a constant temperature difference to the EGR-mass flow. The electrical power used for heating up is proportional to the mass flow. Same principle as for air mass sensors, except
Availability	samples available, series production intended for year 2003
NO_x sensor	
Supplier	Siemens VDO (NGK sensor element) (www.siemens.de)
Range	NOx 0 .. 500 PPM
Availability	samples available, series production for gasoline engines intended for end 2002
Supplier	NGK_NTK (www.ntkngk.co.jp)
Availability	series production for gasoline engines since 2001
Supplier	Delphi (www.delphiauto.com)
Availability	sensor in development, (received a cost sharing research award from the United States Department of Energy for approximately $1.85 million to develop a low cost, commercially viable automotive nitrogen oxide sensor for clean and more fuel efficient vehicles)
NH_3 Sensor	
Development on base of NOx sensors. But no specific information available.	
CO Sensor	
No information available.	

Sensors and Supplier	
Lambda Sensor	
Supplier	Bosch (www.bosch.com)
Availability	samples for diesel engines available (LSU 4.x), no information about series production
Supplier	Siemens VDO (www.siemens.de)
Range	lambda 0.75 to air
Availability	samples available, no information about series production