3 ENGINES FOR GASEOUS FUELS

3.1 General

As mentioned in the Introduction, one could say that in general, the existing gas engines are not as sophisticated as their gasoline or diesel fuelled counterparts. All light-duty gas engines are based on gasoline engines, and most of them are bi-fuel engines, which do not take full advantage of the gaseous fuel.

As the supply of high-displacement gasoline engines is rather limited today, most of the heavy-duty gas engines are based on converted diesel engines. To use the original diesel engine as the base of the conversion is advantageous from the point of view of compatibility with the engine mountings and transmission of the vehicle. For heavy-duty engines, robust design and long service life are expected. There are, however, also a number of drawbacks like possible problems with higher heat rejection rates, and an engine, which from the point of view of mechanical loads is over-dimensioned.

The performance of the gas engine with respect to power output, fuel consumption and especially exhaust emissions is highly dependent on the combustion system. Most emission-optimised gas engines are spark-ignition engines. Pilot- or dual-fuel applications, in which gaseous fuel is fed into the intake system and ignited by diesel injection, are rare in Europe today, although there is some development work going on in Northern America /20/. Previously it was questionable whether a pilot injection gas engine could give any real emission benefits. Today's advanced electronic systems might change the situation.

To improve the fuel economy of gasoline engines some manufacturers have introduced direct injection gasoline engines. The working principle of these engines is based on timed fuel injection and a system which provides charge stratification and an ignitable mixture close to the spark plug /45/.

In the case of natural gas it is more difficult to arrange charge stratification and also high-pressure fuel feed in cases where the tank pressure is low.

At the moment, there is no real pressure to introduce gas direct injection for light-duty vehicles. Due to fuel chemistry, going over from gasoline to natural gas will automatically reduce CO_2 emissions considerably, and no increase in energy consumption is to be expected /41/.

The situation for heavy-duty vehicles is quite different, as natural gas in a spark-ignition gas engine replaces diesel fuel in a diesel engine. Switching to gas in this case means increasing the energy consumption of the vehicle by some 20-30 % /23,41,46/. Therefore some engine manufacturers and research organisations are working on increasing the efficiency of the spark-ignited gas engine.

Actions which can contribute to higher engine efficiency include /19/:

- increasing the specific output (brake mean effective pressure, BMEP) of the engine
- favouring lean-burn concepts over stoichiometric concepts
- increasing compression ratio in combination with adaptive knock control
- the use of variable valve timing and modified working cycles (Miller, Atkinson)
- ultimately direct injection (especially interesting in the case of LNG)
- EGR (exhaust gas recirculation)

In general, three main features or components determine the emission performance of a gas engine:

- combustion system
- fuel system
- catalyst technology

These items will be discussed in the following. The variations in technology for light-duty vehicles are rather small, as all current concepts are based on stoichiometric combustion and the use of a three-way-catalyst. There are, however, small variations in fuel system technology. In the case of heavy-duty engines there is a broader spectrum of alternative technologies.

3.2 Combustion systems

Engine-out emissions of a spark-ignition engine vary strongly with air-fuel ratio. Figure 3.1 shows the general influence of air-fuel ratio on emissions of a spark-ignition engine. Relative air-fuel ratio lambda (λ) is often used to describe mixture strength. At stoichiometry lambda is one. A λ-value less than one means that the mixture is rich, a λ-value greater than one that the mixture is lean.

All gas engines for automotive applications (cylinder diameter less than 150 mm) have an open-type combustion chamber. Prechamber arrangements are used on larger engines only.

A division of spark-ignition (SI) automotive gas engines into three categories according to the relative air-fuel ratio can be made /23/:

- stoichiometric (SM) engines	(λ=1.00)
- lean-burn (LB) engines	($\lambda \geq$1.50)
- engines optimised for low fuel consumption	(1.1<λ<1.3 typically).

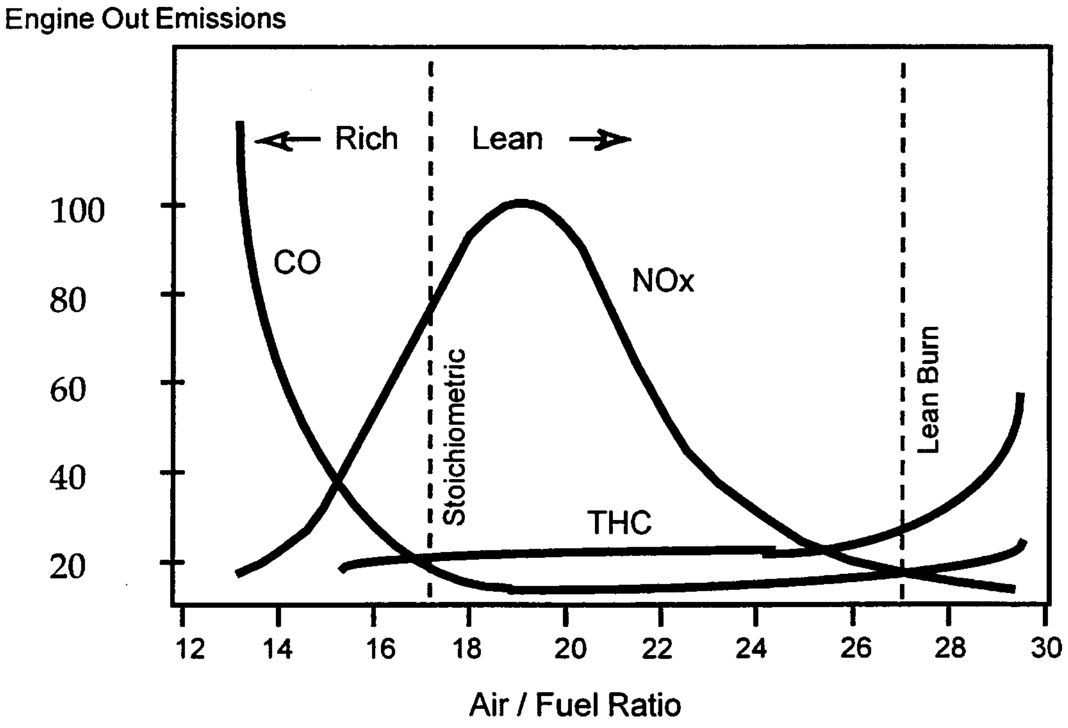

Figure 3.1. Influence of air-fuel ratio on emissions and fuel consumption of a spark-ignition engine (stoichiometric means relative air/fuel ratio l =1) /47/.

Previously, most automotive gas engines were tuned slightly lean for low fuel consumption. This, however, resulted in very high emissions of nitrogen oxides, and therefore such concepts cannot be used any more on new vehicles in countries with stringent exhaust gas legislation.

The stoichiometric engine is equipped with a closed-loop fuel system and a three-way catalyst for very low exhaust emissions. The emission level of such an engine is totally dependent on the performance of the catalyst and the closed-loop fuel system.

The lean-burn engine runs on a λ value which is typically 1.5-1.6 /34/. The formation of nitrogen oxides is controlled in the combustion process itself, by using excess air to cool down the process.

The diesel engine is also a lean-burn engine, and the average air-fuel ratio is in the order of 1.5-2.0. However, due to the heterogeneous combustion (in the flame zone λ is close to one), at a given average λ value, the diesel produces much higher emissions of nitrogen oxides. The nitrogen oxide emission level of a lean-burn gas engine is roughly 1/4…1/3 of that of a corresponding diesel engine /35/.

Figure 3.2 illustrates the relationship between λ, exhaust gas nitrogen oxide concentration and thermal efficiency for a gas engine. Nitrogen oxides and also engine efficiency peaks at around λ=1.2. At λ=1.5, when the emission of nitrogen oxides has dropped to an acceptable level, engine efficiency has also gone down to a level which is close to what is achieved in stoichiometric operation (app. 36 %). When a TWC is applied using stoichiometric mixture, nitrogen oxide emissions practically drop to zero level.

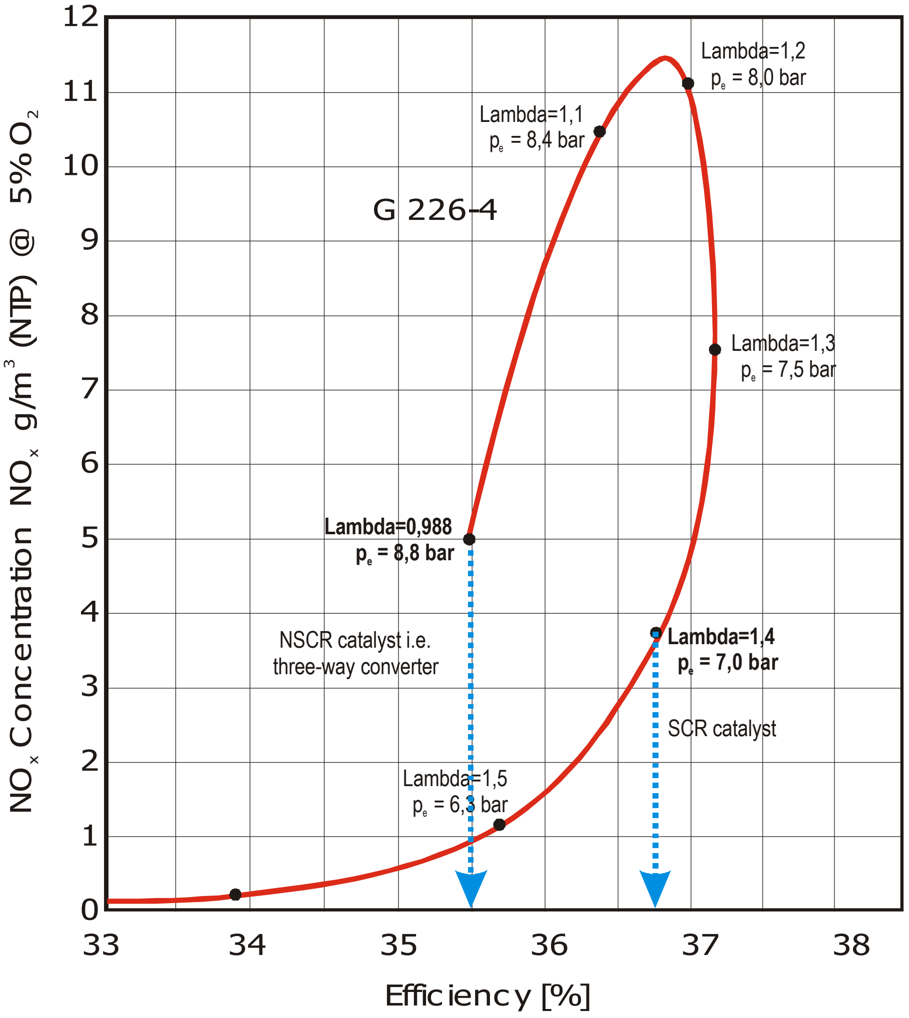

Figure 3.2. Trade-off between NO_x emission and engine efficiency. Arrows show that exhaust gas aftertreatment brings NO_x concentrations down to zero level /35/.

Figure 3.3 shows an example on an engine map showing the relationship between λ value and NO_x emission. It can be seen that the λ value has to be in the order of 1.5…1.55 to achieve a NO_x emission below 2 g/kWh.

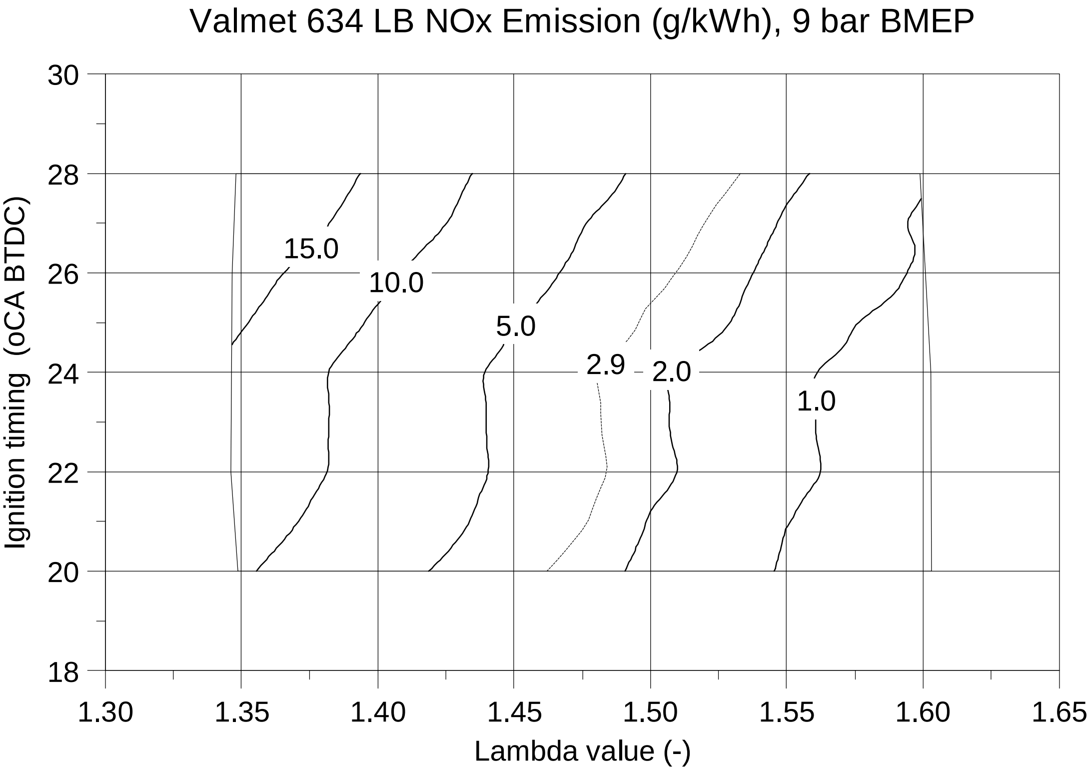

Figure 3.3. The NO_x emission of a lean-burn gas engine as a function of l and ignition timing /48/.

Nearly all current gasoline engines use stoichiometric combustion and a TWC, as this concept gives by far the lowest emissions compared to any other concepts. This also in practice applies for all gas fuelled light-duty vehicles. As for heavy-duty automotive gas engines, both stoichiometric and lean-burn engines are well represented.

As one might expect, both combustion systems have their benefits and drawbacks. These benefits and drawbacks have been discussed in a number of references /17,34,35,49,50,51/. The following is a simplified summary of the main characteristics of the two combustion systems for heavy-duty engines /23/.

The benefits of the stoichiometric concept are:

- the possibility of achieving extremely low exhaust emissions
- stable engine operation
- moderate requirements on the ignition system
- high BMEP for a naturally aspirated engine

The drawbacks are:

- a closed-loop fuel system and a three-way catalyst are needed for emission control
- the emissions are highly dependent on the reliability of the oxygen sensor and the control system
- high thermal loadings compared to diesel or lean-burn operation
- restricted possibilities for turbocharging
- in some cases a fuel consumption penalty compared to lean-burn operation
- not suitable for fuels with low knock resistance.

The benefits of the lean-burn concept are:

- moderate exhaust emissions
- NO_X formation controlled already during combustion
- high power output if turbocharging is used
- thermal loading close to diesel operation.

The drawbacks are:

- turbocharging necessary to obtain sufficient power output
- transient engine response
- high requirements on the ignition system
- high cycle-to-cycle variations
- high methane emission with natural gas (unburned methane is hard to oxidise)
- oxidation catalyst needed for CO and HC control.

In general, lean-burn combustion seems to be the preference of the engine manufacturers, for reasons of lower thermal loading and higher power output. The stoichiometric concept often requires changes in both materials and component design, i.e. modifications, which add to the price of the conversion.

The following list gives some examples of the preference of the engine manufacturers.

Stoichiometric combustion:

- DAF (LPG engine) /52/
- Iveco /53/
- MAN /54/
- Mercedes-Benz /55/ (Mercedes-Benz is going to launch a new lean-burn engine)

Lean-burn combustion:

- Cummins /47/
- Detroit Diesel /56/
- Hercules /57/
- Scania /58/
- Volvo /59/

3.3 Fuel systems

The fuel system of a vehicle has the following main components:

- gas storage (mainly compressed natural gas, alternatively LPG or LNG)
- multiple stage pressure regulation
- air and fuel mixing unit or metering unit.

Normally the fuel is brought in gaseous form up to the mixing or metering unit. With LPG there is the possibility to have the fuel as liquid up to the electrically controlled injectors of a fuel injection system /60/. LNG would give the same opportunity.

There are two basic ways to arrange the gas supply system, i.e. mechanical or electrical fuel control. Depending on the type of the fuel systems, the gas engines can be divided into three categories:

1st generation: mechanical fuel metering, no feedback
2nd generation: mechanical fuel metering + closed-loop electronic λ control
alternatively: fuel injection, no feedback
3rd generation: fuel injection, closed-loop control

A fourth category could be added to this list, i.e. 4th generation system with OBD capabilities (see 3.6).

A parallel to gasoline engines would be:

1st generation: carburetted
2nd generation: fuel injection
3rd generation: closed-loop multi-point fuel injection

The conventional way, both for light- and heavy-duty engines, is to have a venturi or a similar mechanical device for fuel metering. In a fully mechanical fuel system, the actual λ value will always vary with running conditions and environmental conditions, i.e. engine speed and load, tank pressure, temperature, etc. /29/.

The stringent emission regulations in North America and Europe cannot be met with simple 1st generation mechanical systems. Figure 3.4 shows a simple 1st generation CNG system with a "bolt-on" gas mixer.

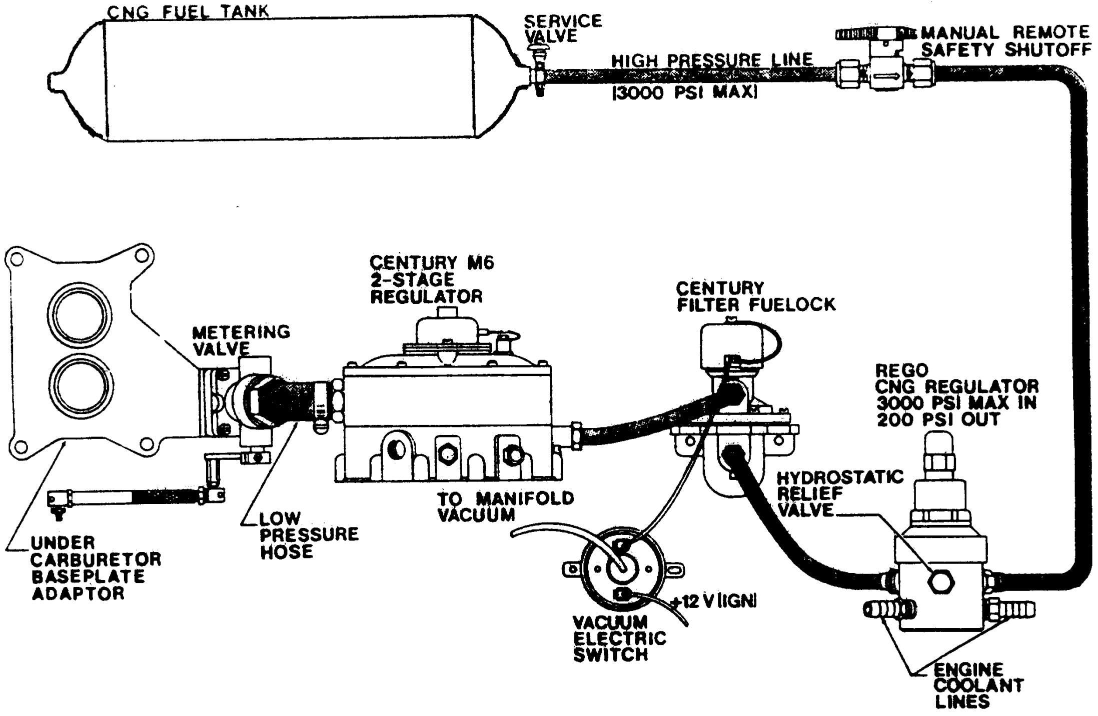

Figure 3.4. A 1st generation CNG system /61/.

If a TWC is used, a feedback system giving precise control of the λ value must be used. Exhaust gas oxygen sensors are used to provide a feedback signal of the air-fuel ratio. These sensors, originally developed for stoichiometric gasoline engines, work at their best very close to a stoichiometric mixture.

The oxygen sensor of the fuel control system provides a voltage signal which indicates when the air/fuel mixture is rich of stoichiometry, and when it is lean, but it does not provide information on the magnitude of rich or lean operation. When the voltage indicates rich operation, the fuel control system ramps the air/fuel ratio in the lean direction. The speed with which this ramp occurs, the amount of overshoot which occurs in the lean direction, and the switching frequency from rich to lean conditions, all have a major effect on achieving lowest emission performance.

The strategy of managing air/fuel ratio control has therefore evolved with sophisticated techniques of strategy and software, and resulted in natural gas vehicles (including the best bi-fuel solutions) to achieve SULEV emission standards (see 4.2.2). In this respect, the most recent bi-fuel natural gas vehicles have become quite sophisticated.

Also in a lean-burn engine it is beneficial to have a closed-loop fuel system for λ control. The oxygen sensors for lean-burn operation have previously not been altogether reliable /62/. Today, however, most lean-burn engines are equipped with closed-loop fuel system.

Closed-loop control can be achieved either by adding an electronically controlled device (e.g. stepper motor operated gas valve or modulation of gas supply pressure) to a basically mechanical fuel system (2nd generation) or by having a completely electronic fuel metering system (3rd generation).

2nd generation fuel systems, either fuel injection systems without feedback or mechanical systems with added-on λ control, have limitations in terms of accuracy, speed and /or emission stability, thus the designation. Figure 3.5 shows a 2nd generation fuel system for a heavy-duty gas engine.

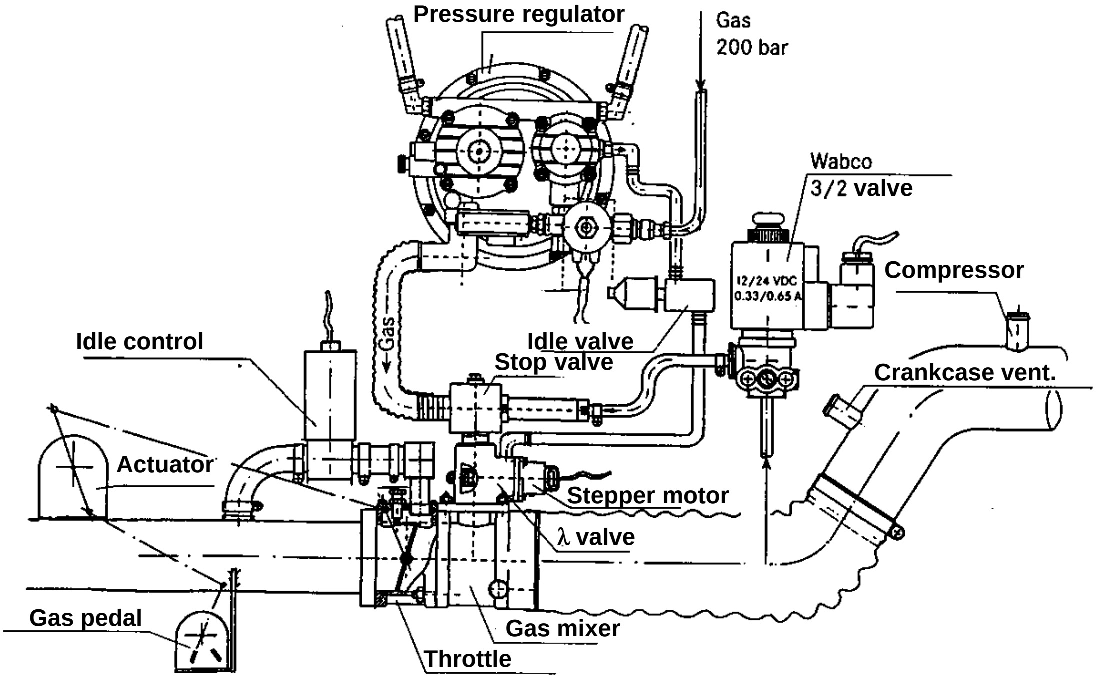

Figure 3.5. A 2nd generation fuel system (stepper-motor) for a heavy-duty engine /55/.

To achieve good dynamic emission performance, a 3rd generation fuel system is needed. Light-duty vehicles are tested for emissions over a dynamic cycle, and the current emission limits cannot be met without precise fuel control.

In North America, the heavy-duty engines have been tested over a dynamic cycle for a number of years. The situation in Europe will also change, as heavy-duty gas engines will be subjected to dynamic emission testing beginning in 2000 (see 4.3). This will definitely have an impact on European heavy-duty gas engine technology.

Included in the category of electronically controlled fuel systems are both single- and multi-point gas injection systems, multi-point injection systems with sequential injection being “top-of-the-line”. The 3rd generation systems, which feature fully electronic control, have significantly better performance and accuracy than conventional mechanical systems.

One of the pioneers in this field is the GFI system, originally developed at the former Ortech, Canada /63/. GFI was originally a single point gas injection system. The metering unit was a block with seven electrically controlled sonic valves, five of which were of an on-off type and two of which were pulse width modulated. GFI Control Systems, Inc. now has both continuous and sequential multi-point injection system versions available (Figure 3.6).

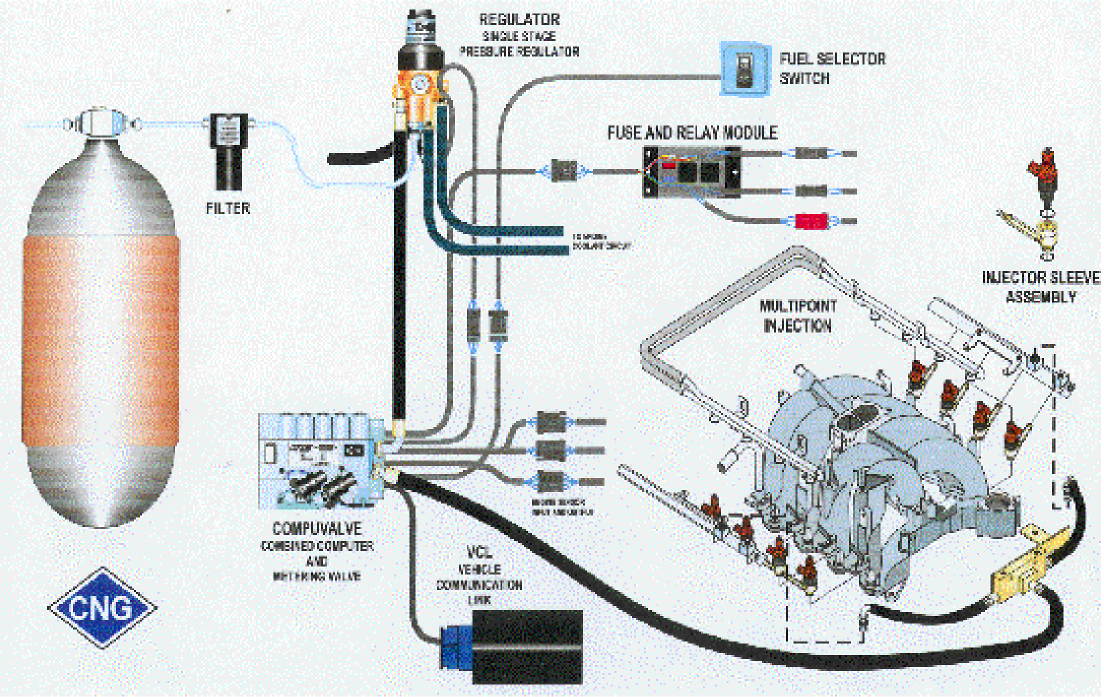

Figure 3.6. A multi-point fuel injection system from GFI Control Systems, Inc. */63/.*

Several other component manufacturers, among them Gentec /64/, Koltec /65/ and Transcom /66/ (recently renamed Advanced Engine Components), also have multi-point fuel injection systems available. Iveco uses injector components originating from Fiat passenger cars /67/. A multi-point fuel injection gives better cylinder-to-cylinder fuel control, makes it possible to use sequential fuel delivery and reduces the risk of backfire /64/. One vision of the future is that gas engines will have sequential multi-point fuel injection, and that they will have closed-loop control for both stoichiometric and lean-burn operation.

There are also multi-point fuel injection systems available for LPG. Figure 3.7 shows the schematic design of a multi-point fuel injection system for liquid LPG (DAF/Gentec) /68/. Figure 3.8 shows the design of a fuel injector for natural gas /69/.

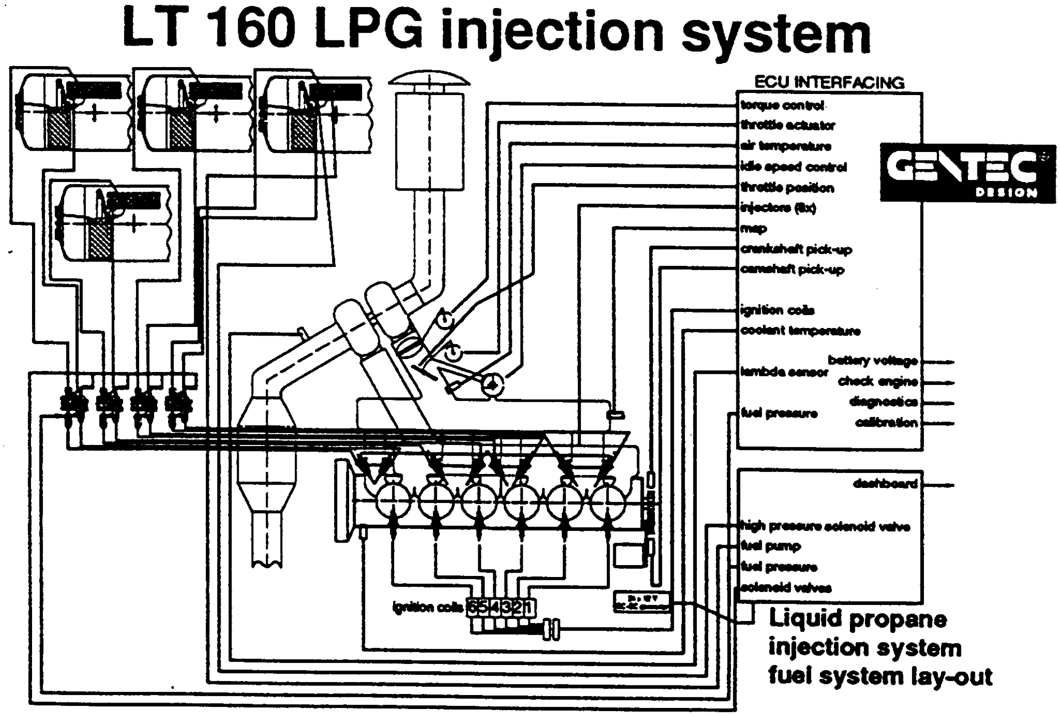

Figure 3.7. The schematic design of a multi-point fuel injection system for liquid LPG /68/.

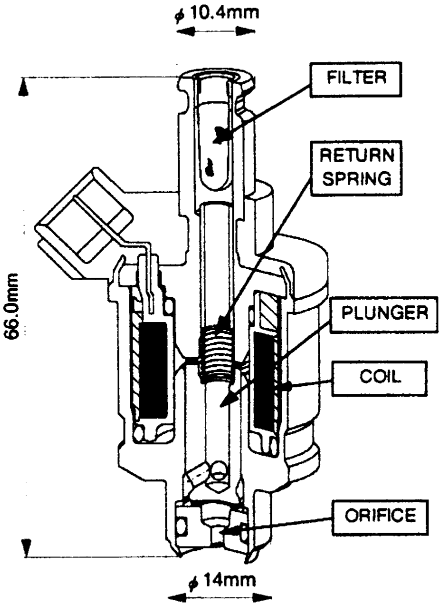

Figure 3.8. The design of a fuel injector for natural gas /69/.

Figure 3.9 shows the overall engine management control of the lean-burn Cummins C8.3G natural gas engine, a system which also incorporates a “drive-by-wire” throttle actuator.

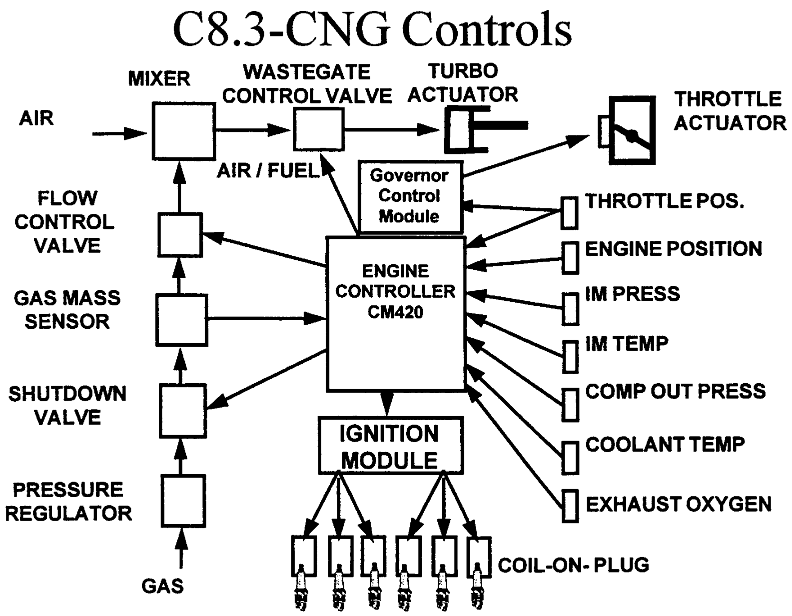

Figure 3.9. Engine management control for the Cummins C8.3G natural gas engine /47/.

3.4 Ignition systems

Gasoline engines operating on stoichiometric mixtures set moderate requirements on the ignition system and ignition energy. This is demonstrated by the fact that spark-plug replacement intervals for modern vehicles can be up to 100,000 km. US emission legislation for light-duty vehicles requires spark-plug durability of at least 30 000 miles /70/.

Gasoline and LPG have roughly the same minimum ignition energy requirement. Therefore, conventional ignition systems can also handle propane, at least with stoichiometric mixtures. High ignition energy is needed with natural gas, especially with lean mixtures /34,49/. The ignition energy required in lean-burn operation can amount to 150 mJ, compared to 0.25 mJ for normal stoichiometric gasoline operation.

A common problem in lean-burn operation is rapid erosion of the spark-plug electrodes. The spark plug replacement time can be as short as 300 hours /34/. Misfiring leads to rough engine operation, high hydrocarbon emission and possible also to catalyst overheating.

Figure 3.10 shows the evolution of ignition systems for Cummins gas engines.

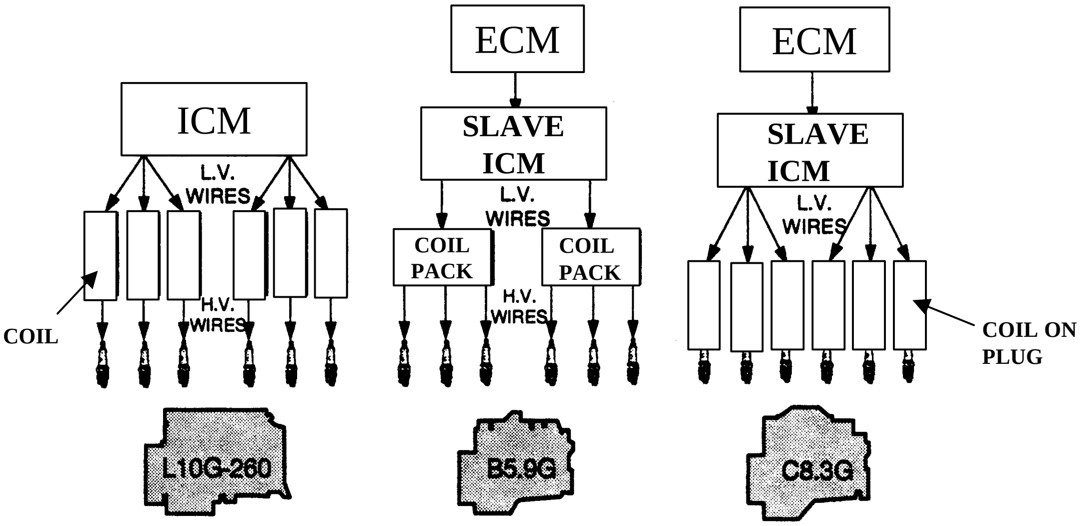

Figure 3.10. Evolution of ignition systems for Cummins gas engines /47/.

The first L10G-engines, like many other lean-burn natural gas engines, had a capacitor-discharge ignition system from Altronic /71/. This distributorless system with no moving parts normally has one step-up coil for each cylinder. The coils are normally mounted close to the spark plugs, and thus the length of high-tension cables is minimised. A pick-up on the camshaft drive gives the triggering pulse. Today coil-on-plug-systems, which eliminate the high-tension wires, are used. Figure 3.11 shows a detail of such a system (Volvo). Spark-plugs with precious metal electrodes are used in the Volvo lean-burn gas engine /49/.

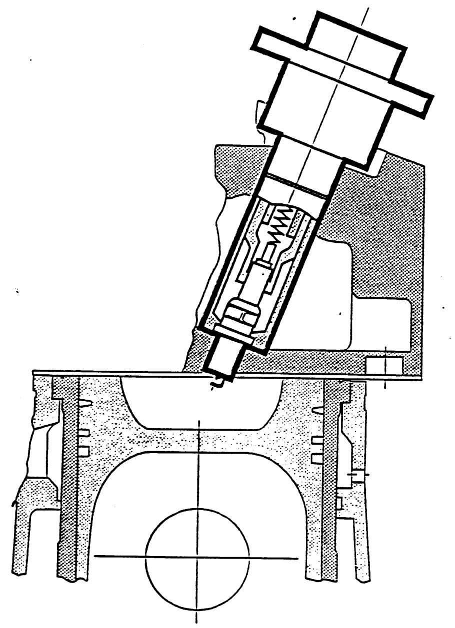

Figure 3.11. Volvo's coil-on-plug ignition system /49/.

3.5 Exhaust gas aftertreatment

Both the stoichiometric engine and the lean-burn gas engine need a catalyst to achieve low exhaust emissions. The stoichiometric engine uses a three-way catalyst, which is capable of simultaneously reducing NO_x and oxidising CO and HC. On a gas engine the TWC can reduce these components by some 90 to 95 % /72/.

On a lean-burn engine, an oxidation catalyst is often used to reduce CO and HC emissions. The lean-burn engine operates on excess air, and therefore the conditions in the exhaust are such that reduction of NO_x cannot take place to any greater extent in conventional catalysts /72,73/. Efforts are being made to develop catalysts that would be able to reduce NO_X also in oxidising conditions, either by selective catalytic reduction (SCR) or lean-NO_x trap (LNT) technology /10,11,74/.

In SCR systems, injection of urea or hydrocarbons into the catalyst is used to reduce nitrogen oxides. The German company Siemens has an urea-based SCR-system available for diesel engines (Figure 3.12). LNT-type traps store nitrogen oxides under lean operation. NO_x is reduced by enriching the fuel mixture periodically. Lean-NO_x trap-type abatement devices are commercially found today only in direct-injection gasoline fuelled vehicles.

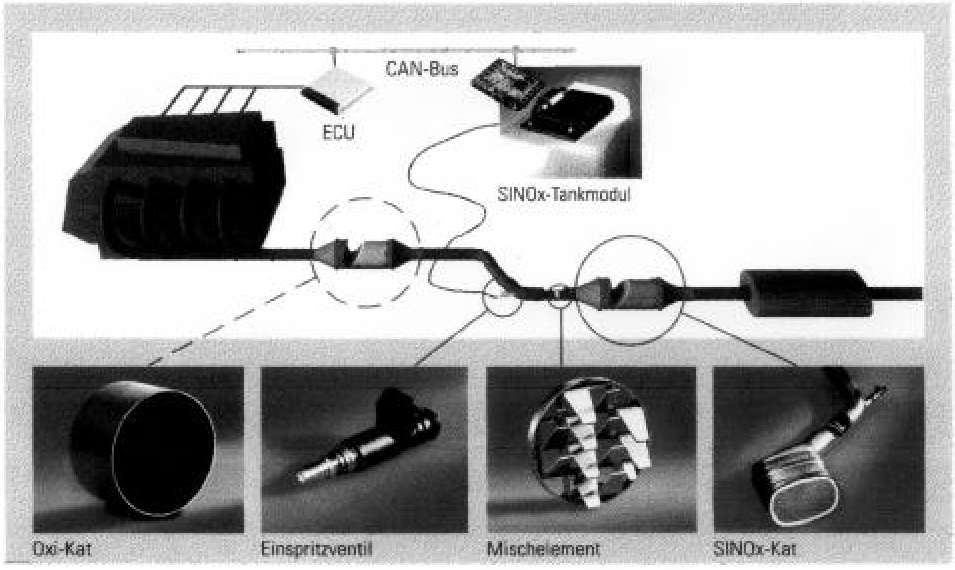

Figure 3.12. The Siemens SINOx SCR catalyst system /75/.

A TWC (Figure 3.13) works is such a way that it utilises CO and HC to reduce NO_x (i.e. remove oxygen), and then, on the other hand, it utilises discharged oxygen to oxidise both CO and HC /76/. In order to maintain both oxidation and reduction reactions in balance, the air-fuel mixture has to be controlled exactly to stoichiometry, as discussed in 3.3.

Air-fuel ratio control, fuel chemistry and exhaust temperature all have a major impact on the performance of the catalyst /1,34,77/. The optimum working temperature for a catalyst is 300 - 800 ^{o}C /72 /.

The stoichiometric LPG engine is not a problem regarding catalyst formulation and performance. The exhaust from a stoichiometric engine is hot enough to keep the catalyst at the optimum working temperature. Propane is rather easily oxidised, and catalyst formulations that are used for gasoline engines also work well with propane. Catalyst size and precious metal loading, however, have a major influence on both catalyst performance and durability /23,46,78/.

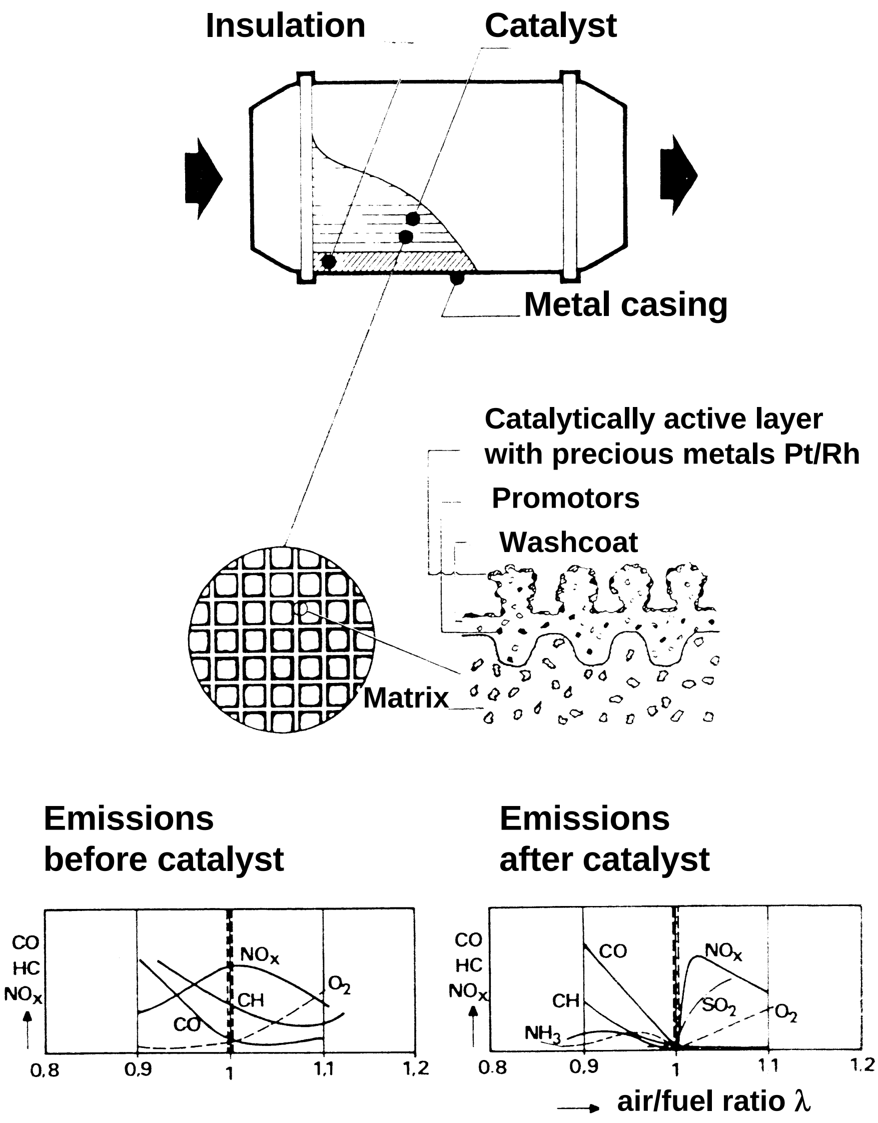

Figure 3.13. The structure of a TWC catalyst and the influence of l on emissions /76/.

Methane is more difficult in both lean-burn and stoichiometric operation from a catalyst point of view. The methane molecule is stable and hard to oxidise. This is a problem particularly in lean-burn engines with low exhaust temperatures. When exhaust temperature is low, the methane conversion ratio is low.

When running on stoichiometry, the high exhaust temperature enhances the catalyst performance. Conventional Pt/Rh catalysts have been used for stoichiometric natural gas engines /72,79,80/. In general they work rather well. The problems that may occur are very much related to correct air-fuel ratio control.

Figure 3.13 also shows the influence of λ on the performance of a TWC. On rich mixtures CO and HC emissions are high, on lean mixtures NO_x is high, and there is a very clear trade-off between CO and NO_x /1,76/. The air-fuel ratio band within which CO, HC and NO_x are simultaneously low, i.e. the conversion efficiency is high, is called the window.

Translated into emission performance of a heavy-duty gas engine the TWC catalyst performance and the CO/ NO_x trade-off means that the aggregate CO + NO_x sum of a well-tuned engine should be below 3 g/kWh (European ECE R49 test) /23/.

The combustion of methane produces less CO than combustion of gasoline. As CO is needed for the reduction of NO_X, the mixture has to be somewhat richer than on gasoline for proper catalyst operation. The correct λ value for natural gas is around 0.99 /80,81/.

The λ window for proper catalyst performance is quite narrow. Ageing of the catalyst both narrows the window and increases the minimum attainable simultaneous level of CO and NO_x. One additional problem is that the conventional λ sensor is not very selective at the air-fuel ratio values needed for proper operation on methane /80/.

Figure 3.14 shows the methane conversion of a natural gas fuelled passenger car in an US FTP (Federal Test Procedure) type emission test. Over the whole test, methane conversion was 85-90 % with catalysts optimised for methane. The catalysts contain two bricks. The first brick has an ordinary Pt/Rh coating, the second is palladium-coated. Catalyst 3 has a higher palladium loading than catalyst 4. The methane conversion of an ordinary gasoline catalyst in a corresponding test was roughly 70 % /79/.

For lean-burn engines, typical values for methane reduction in an oxidation catalyst are as low as 30 - 50 % /34/. The sulphur based odorant (tetrahydrotiofen THT) used in natural gas at concentration levels of only 10-15 mg/m^3 of natural gas can have a very detrimental effect of the conversion efficiency of oxidation catalysts.

Figure 3.15 shows the conversion rate of methane versus running time for several catalyst configurations. One of the catalysts loses its conversion efficiency almost immediately, whereas the best catalysts have a conversion efficiency of some 60 % even after 1.000 hours of ageing. In the case of the best catalysts, poisoning by THT has been taken into account in catalyst chemistry.

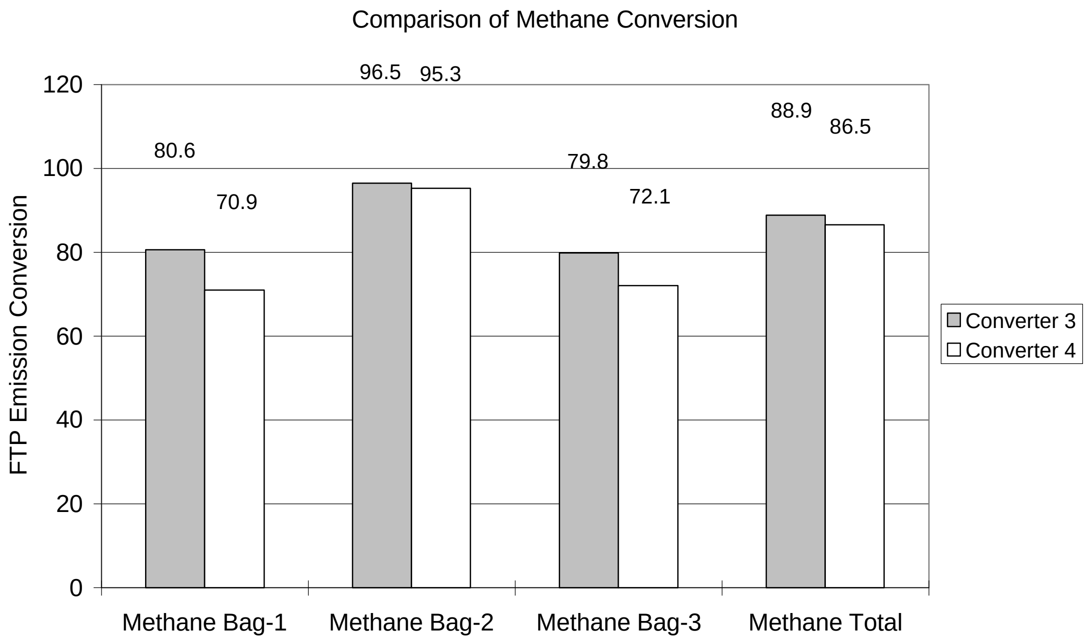

Figure 3.14. Methane conversion of optimised natural gas catalysts /79 /.

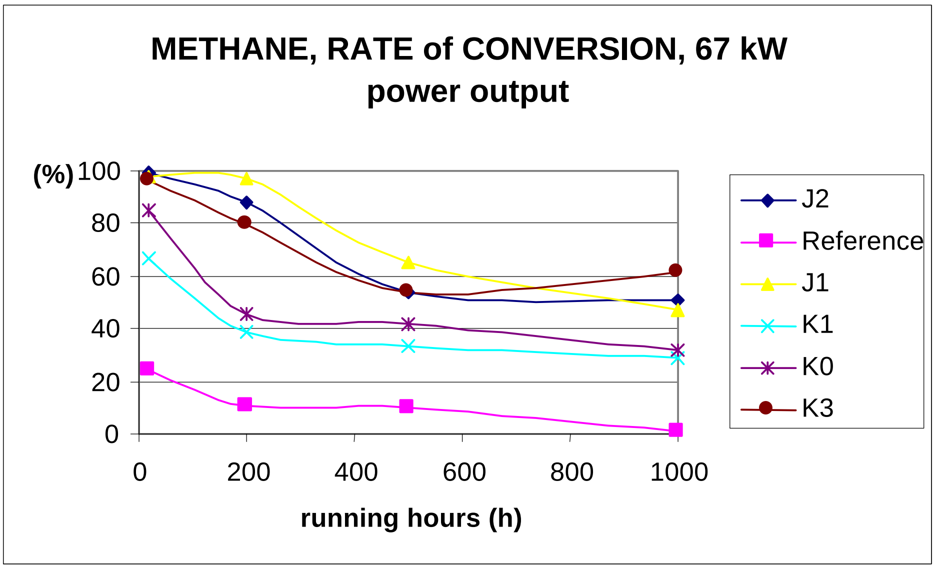

Figure 3.15. Methane conversion as a function of time for different catalysts (l = 1.5, BMEP 7.3 bar) /82/.

Figure 3.16 shows the conversion efficiency for methane as a function of engine load (exhaust temperature) for the same catalysts as in Figure 3.15. Also in this respect there are big differences in catalyst performance.

Work to develop methane selective catalysts still continues. One of the aims is to reduce the light-off temperature for methane conversion from 500 to around 300 ^{o}C. The expected methane reduction is some 85 % /83/. Platinum has been used in oxidising catalyst for natural gas engines. There is, however, evidence that palladium could be more effective in methane conversion /79/. CO is easier to oxidise than methane, and CO reductions of more than 90 % can be achieved with an oxidising catalyst /34/.

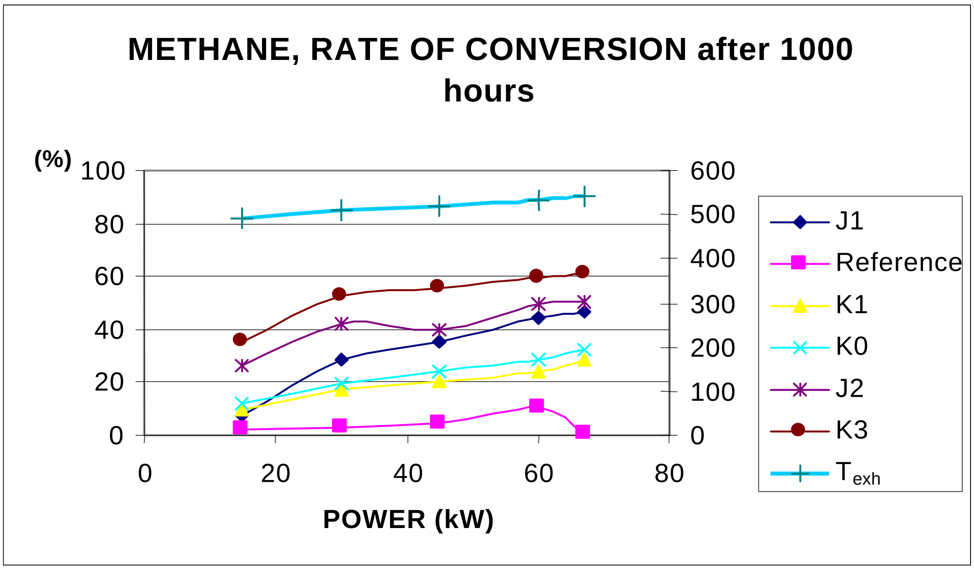

Figure 3.16 Methane conversion as a function of engine load (l= 1.5, running time 1,000 hours). T_{exh} stands for exhaust temperature /82/.

3.6 OBD systems

3.6.1 General

The abbreviation OBD stands for on-board diagnostics. An OBD system is a diagnostic system, which can detect malfunctions of the engine and the exhaust clean-up system. Figure 3.17 shows the schematics of an OBD equipped gasoline engine and its subsystems /84/.

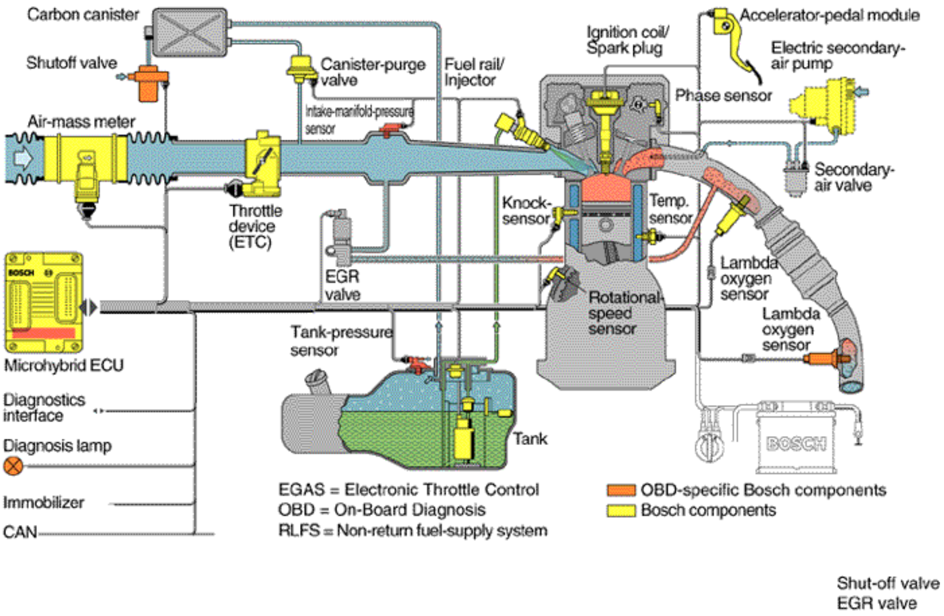

Figure 3.17. Components of an engine equipped with OBD (Bosch Motronic ME7) /84/.

The OBD ties together the different subsystems of the engine /85/:

- fuel system
- lambda control system
- ignition system (misfire)
- catalyst
- particulate trap (diesel vehicles)
- EGR system (functionality)
- engine management

OBD systems for gasoline vehicles were originally introduced in California in 1991 (OBD I) /86/. The requirements have since been tightened, both on the State and Federal level. In Europe, OBD will be required for new gasoline vehicles beginning 2000 and for new diesel passenger cars in 2005 /5/. In the future, OBD might also be required in heavy-duty vehicles.

An OBD system is designed to detect adverse behaviour of the engine management system which would cause emissions to increase beyond the design threshold over the useful life of the vehicle. The US EPA has defined the useful life of the vehicle to be 100,000 miles for passenger cars, and 120,000 miles for light and medium duty trucks /87/.

Thresholds are currently set so that a malfunction indicator light, located in the vehicle dashboard, will be illuminated if the emissions exceed 1.5 times the applicable emission standard. In essence, the system is an enhancement of the annual vehicle emissions inspections carried out in many countries. The intent is to provide reliable monitoring of the emission control system performance on a continuous basis, so that faults can be detected as they occur, and the vehicle will continue to provide satisfactory emissions performance over its useful life.

3.6.2 History of OBD

In 1991, California introduced OBD I regulations for gasoline vehicles /86,87/. The year 1996 was a watershed year for alternative fuel vehicles. All alternative fuel vehicles were required to be equipped with OBD I systems, both California and EPA required OBD II systems for all fuels (but would consider annual waivers for alternative fuels), and emissions durability requirements were phased in for alternative fuel vehicles. This meant that alternative fuel systems had to be equipped with basic diagnostic systems which would detect, for example, complete sensor failures. Malfunction of a sensor, such as out of range, would not require to be monitored.

The advent of OBD II systems on gasoline meant that when such a vehicle was operated on an alternative fuel, the OBD II monitors would perceive incorrectly that a fault had apparently occurred, and a false malfunction indicator light would be set. Some method had to be devised to prevent this from happening, and is discussed later.

Emissions durability requirements were largely an issue for California in 1996, since aftermarket conversions could continue in the 49 states under Memorandum 1A (see 3.6.5 below) until the year 2000.

In 1998, Canada required OBD II systems to be fully functional on gasoline, and in 2000, Europe requires EOBD compliance for gasoline vehicles. This phase-in of OBD II type systems is likely to continue in other countries, and it appears likely that Japan, Mexico, and other countries may require OBD II systems for gasoline vehicles by 2002/3.

By 2004, all OBD monitors will have to be active on all fuels, and no further waivers will be permitted for alternative fuels. In 2005, EOBD compliance will be required on alternative fuels. This could be a major impediment to the growth of alternative fuel vehicles.

3.6.3 OBD II monitoring requirements

OBD II systems require sophisticated monitors which detect adverse behaviour in the primary engine management system. An OBD monitor must quickly turn on the malfunction indicator light (MIL) when the engine has a fault, and must not turn on the MIL when the engine is operating properly.

Monitoring requires a decision at the end of each evaluation period to determine if the engine condition is good or bad. The decisions can either be correct or incorrect, and noise (electrical) in the system will inevitably lead to decision errors. These errors lead to either a false alarm, when the engine is actually operating properly, or to a failure to detect when a real malfunction occurs /88/.

Because of noise in the system, false alarms are inevitable, and there is a need to estimate the delay required to detect a real fault. This becomes clear when the probability of detecting a fault is examined relative to the number of independent decisions or trips, as shown in Figure 3.18.

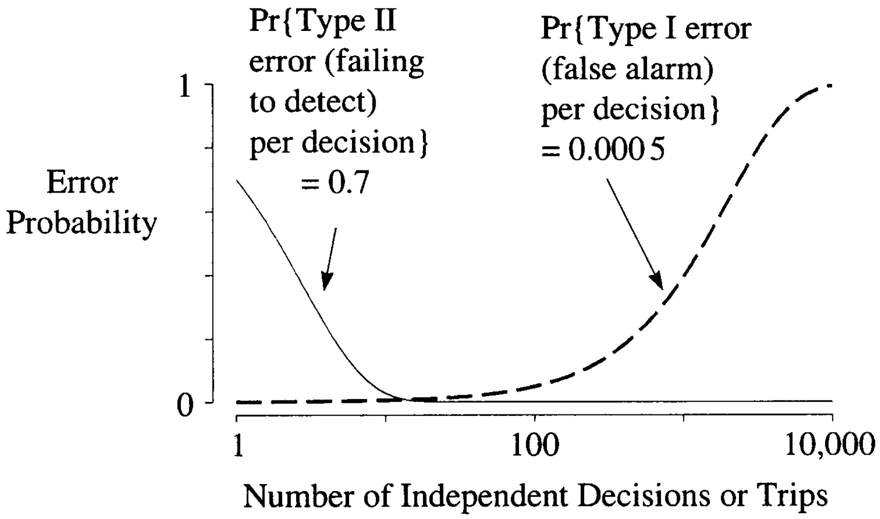

Figure 3.18. The probability of detection failures and false alarms /88/.

A trip is defined as a set of driving conditions covering acceleration, cruise, and idle. So, a trip could be just a few km, or it could be 100 km. If the probability of failing to detect a real fault is 0.7, then over the first few trips, the probability of failing to detect a fault is quite high, but decreases with the number of trips recorded. Because of this, the MIL is usually not illuminated until at least 10 trips have been recorded, at which point the probability is good that the error is real one. So, if the system detects a fault over the first trip, it will not set a warning light.

However, if it continues to detect the same fault after 10 trips, then it will set the MIL. The probability of detecting a false alarm, however, increases with the number of trips. Therefore, to avoid excessive false alarms, the probability of such errors occurring must be set very low (0.0005).

In most applications, there are a range of possible conditions of the engine, not just "Good" or "Bad". One way of illustrating this is depicted in Figure 3.19.

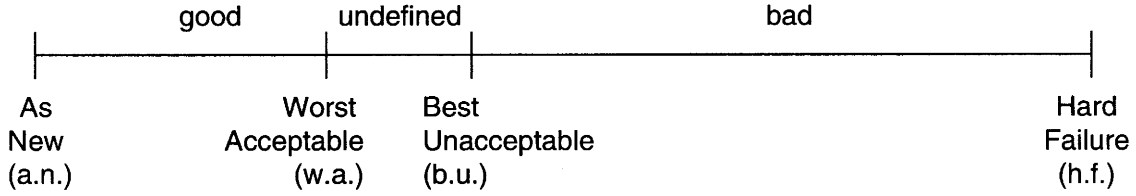

Figure 3.19. Possible conditions of the engine /88/.

In the range of bad conditions of the engine, there will be a point where the condition is considered the best unacceptable. Similarly, there will be a worst acceptable condition within the range of good conditions of the engine. Between the two lies an undefined region. This region is important, because if the undefined region is too large, the monitor may be unusable. The processing efficiency of the monitor algorithm, or the signal to noise ratio, needs to be high, so that the monitor can respond with a low probability of falsely declaring a malfunction during the "good" life of the system. The design of monitors can therefore be highly sophisticated using statistical tools to achieve robust models.

Ideally, the emission standard should be the worst acceptable point. However, in recognition of the uncertainties involved in monitoring, the US EPA and the California Air Resources Board (CARB) have defined thresholds for warning the driver that a malfunction of the emission control system has occurred. For example, CARB has set a threshold for emissions which exceed 1.5 times the FTP emission standard for many of the monitors. 1.5 times the emissions standard could be considered the best unacceptable condition, and is the point beyond which a fault code will be set in the computer, and the MIL will be illuminated.

The threshold limits for setting fault codes vary with the monitor, and the standard to which the vehicle will be certified. For example for low emission vehicles, the catalyst monitor threshold is 1.75 times the FTP standard.

3.6.4 Reaction of OBD II monitors to alternative fuels

Typically, there can be up to 10 monitors operating in OBD II systems. These are:

- Catalyst Monitor
- Fuel System Monitor
- Misfire Monitor
- Evaporative System Monitor
- Oxygen Sensor Monitor
- EGR Monitor
- Secondary Air System Monitor
- Comprehensive Component Monitor
- Thermostat Monitor
- PCV Monitor

The monitors are of course designed for gasoline operation. If an OBD II equipped vehicle is operated on an alternative fuel such as propane or natural gas, for which the monitor models are not designed, then it is likely that the monitor will sense that a fault has occurred, even although the vehicle may be operating correctly on the alternative fuel. It will therefore set a false fault code, and illuminate the MIL, when the vehicle is functioning normally. It may not set the fault code immediately, as it checks to make sure that the error repeats itself, and that the probability is low that the fault is a spurious one, but eventually it will recognise that the error remains (while the vehicle continues to operate on the alternative fuel), and fault codes will be set in the computer.

Reasons why exposure to alternative fuels can cause the monitors to set false codes are shown in the examples below.

Catalyst Monitor

Requirement:
- Monitor the catalyst continuously for satisfactory performance once per driving cycle

Malfunction Criteria:
- For low emission vehicles – 1.5 times NMOG standard

Alternative Fuel Issues:

- Catalyst ageing will be different, and require documentation
- Fuel variability will likely cause additional variability in oxygen sensor switching ratios
- Unique strategies and calibrations will be required to vary switching ratio thresholds as a function of fuel type

Fuel System Monitor

Requirement:

- Monitor the fuel delivery system continuously for its ability to comply with the emission standards

Malfunction Criteria:

- 1.5 times the standard for rich and lean fuel system malfunctions

Alternative Fuel Issues:

- Unique strategy/calibration will be required to allow the fuel monitor to interact with modified fuel trim learning algorithms
- High vapour generation rates and the normal interaction of the closed loop purge strategy leaves little time to learn long term fuel trim values to allow the fuel monitor to operate efficiently.
- Stoichiometric differences resulting from fuel composition variations will add to the fuel system variability making it difficult to set thresholds for good monitoring process efficiency

Misfire Monitor

Requirement:

- Monitor engine for misfire and identify the misfiring cylinder.

Malfunction Criteria:

- Misfire resulting in catalyst damage
- Misfire causing vehicle to exceed the standard
- Misfire causing the vehicle to fails the I & M test

Alternative Fuel Issues:

- Catalyst damage table must be remapped for each fuel due to differences in exhaust temperature
- Misfire startup delay times will vary with various fuels
- Engine torque varies with fuel type. A unique strategy/calibration will be required for each fuel type

3.6.5 OBD II compatible alternative fuel systems

General

Current OBD II regulations in the US require alternative fuel vehicles to be compliant with OBD II regulations. The MIL cannot be disabled, since this would be considered tampering with the original emission control system, and would not comply with EPA Mobile Source Enforcement Memorandum 1A.

Memo 1A provides that alterations to the vehicle will not constitute tampering if the dealer has a “reasonable basis” to believe that such acts will not adversely affect emissions performance when operated on the fuel for which the vehicle was originally designed. Relaying out the MIL when the vehicle is operating on the alternative fuel and enabling it when operating on gasoline is also not an option. Fault codes set during operation on the alternative fuel are stored in the computer and will falsely activate the MIL when the vehicle returns to gasoline operation.

However, until 2004, manufacturers of alternative fuel systems may request approval of a monitoring strategy where specific monitoring requirements are disabled for which monitoring may not be reliable with respect to the use of alternative fuels. This means that selected monitors, which would otherwise set a false MIL and codes, can be disabled when operating on the alternative fuel. Similar regulations are emerging in Europe with EOBD systems, and it appears likely that manufacturers can apply for a derogation of EOBD monitoring systems for which monitoring may not be reliable on alternative fuels.

It is possible, therefore, to design OBD II compatible alternative fuel systems which will be functional to the greatest extent possible on gasoline, but will disable those monitors which will set false codes on the alternative fuel. Different strategies can be developed depending on whether the alternative fuel conversion is carried out through a partnership between the OEM and alternative fuel system provider, or is carried out as an aftermarket conversion. Two examples of these strategies are provided below.

OEM partnerships

In this case, the OEM and alternative fuel system provider agree to establish a communications link between the gasoline and alternative fuel computers. The OEM flashes a special code into the gasoline computer for alternative fuel designated vehicles, which will receive and transmit message sets from the alternative fuel computer. When the vehicle starts to operate on the alternative fuel, a command is sent to the OEM computer to disable selected OBD II monitors. The vehicle now operates on the alternative fuel without setting false codes. When the vehicle reverts to gasoline operation, the OEM computer is again commanded to enable gasoline monitors to function normally.

Aftermarket conversions

This is more difficult to accomplish, and is very specific to each OEM system. One method is to clear codes as they are set in the OEM computer during operation on the alternative fuel system. Communicating appropriate commands on the data bus can achieve this result without the need for a special strategy in the OEM computer to allow bilateral communications. This type of OBD II compatible aftermarket system has been approved by the California Air Resources Board. Since codes are cleared during alternative fuel operation, the vehicle can revert to gasoline operation without the MIL being falsely activated, and normal OBD II monitoring continues with gasoline operation. During alternative fuel operation, appropriate diagnostics are provided by the alternative fuel computer.

3.6.6 Future of OBD systems

As the emissions standards become increasingly more stringent, catalyst efficiencies must be very high, and the catalyst could fail the OBD threshold even although it is still over 90% efficient. This makes monitoring algorithms even more complex, and will create increasing difficulties for alternative fuel applications.

Additional monitoring requirements are also being proposed by the regulatory bodies. For example, CARB is proposing a NO_x threshold in addition to the current NMHC requirement. Functional monitoring requirements are also being discussed such as “Did the vehicle achieve what the strategy commanded?”

It would appear, therefore, that the OBD systems will become sufficiently complex that only a close working relationship with the OEM will allow suppliers of alternative fuel conversion systems to achieve full OBD II capability.

It is still uncertain (in December 1999) how the EU directives will treat gas fuelled vehicles. Delaying the requirements for gas fuelled vehicles to 2003 or 2005 has been discussed. There is also the possibility of applying for derogation against the OBD requirements through the Committee for Adaptation and Technical Progress (CATP) /89/.