

APPENDIX 1 CRITICAL VEHICLE TECHNOLOGIES

1.1 Petrol Engine Technologies

1.1.1 Available – ‘Baseline’ - Technologies

A 1991 study examined the likely and potential fuel consumption improvement of the then Australian passenger car fleet, with projections to 2005 (Nelson English, 1991). Twenty-one technologies were identified which could produce fuel consumption improvements. All these technologies were ‘available’, i.e. adopted on at least one model somewhere in the world. Mostly, they had already been adopted on some models available in Australia in 1991. Eight of these technologies related to engine design –

1. Low friction pistons/rings – better piston designs, low tension rings and improved quality control.
2. Roller cam followers – reduce friction.
3. Advanced friction reduction – low mass squeeze cast aluminium pistons, lightweight valves and titanium springs, improved control of bore and piston dimensions.
4. 4-valves/cylinder – Improved thermodynamic efficiency due to compact combustion chamber, central spark plug and higher ratio. Reduced pumping loss due to reduced displacement and larger valve area.
5. Variable valve control – varies intake valve timing and lift to match engine speed and load requirements. Reduces pumping loss.
6. Two-stroke engine - Advanced engine as pioneered by Orbital, with direct injection stratified charge combustion system.
7. Central fuel injection – Replaces carburettor. Improved fuel atomisation, and reduced cold start fuel consumption.
8. Multi-point fuel injection – Allows more precise fuel metering, use of deceleration fuel shutoff and tuned intake manifold with long runners to maximise torque.

These technologies were predicted to be adopted progressively and substantially by the industry.

During the 1990s, these technologies have in fact been adopted on the majority of vehicle models supplied in Australia, with the exception of variable valve control and the Orbital 2-stroke engine. Prevailing technologies on Australian vehicles are largely consistent with the baseline technologies defined in Section 2.1.1 as the mainstream technologies used for Euro 1 and 2, and US Tier 1 compliance.

1.1.2 Developments in the 'Baseline' Technologies

Engine-out emissions vary among engine types, as does the need for additional emission control hardware and systems, such as exhaust gas recirculation (EGR), temperature controlled sensors, different engine management techniques, and additional after treatment systems. Emission control packages generally require integration of several of these elements.

Whatever combination of engine technologies is used, compliance with all first-world emission standards is very heavily dependent on the efficiency of modern catalytic exhaust after-treatment systems.

The USEPA implemented an amended Federal Test Procedure (FTP) from 1998. A study examining the major impacts of the amended FTP, found that substantial increases in emissions are observed (Dunleep et al, 1996). This study produced a number of pointers for the developments in technologies that manufacturers were likely to adopt in response to the new FTP requirements –

1. **Improved control of Air/Fuel ratio.** In 3-way catalyst closed loop control configuration (the mainstream technology), the exhaust gas oxygen (EGO) sensor provides a step output signal to the computer management system, which in turn provides signals to the fuel injection system causing the AIR/FUEL ratio to oscillate about the stoichiometric mixture. The size and frequency of the oscillations depend on the frequency response of the system.
2. **Sequential fuel injection (SFI)** allows fuel delivery to be tailored for each combustion event rather than for each complete engine cycle, giving better control of transients.
3. **Heated EGO (HEGO)** sensors reduce response time, which is function of temperature.
4. **Universal EGO (UEGO)** sensors produce an output as a function of AIR/FUEL ratio over a wider range, allowing a degree of proportional control.
5. Auto manufacturers confirmed that virtually all cars would soon have SFI and HEGO to meet the new FTP requirements, with improved driveability, cold ambient emissions and fuel economy. Manufacturers did not see UEGO as cost effective.
6. **Electronic filtering**, incorporating predictive algorithms within the control circuitry would provide anticipative control of air fuel ratio.
7. **Increased computational speed and memory** availability can enhance the frequency with which fuel requirement calculations can be updated, and therefore can increase the accuracy of control.
8. **Control to stoichiometry at high engine loads** (reducing power enrichment) would substantially reduce engine-out CO and HC emissions, but would slightly reduce power. It would also tend to increase combustion pressures and temperatures, which may lead to new requirements for component materials and heat shielding.

9. **Increased EGR** with extension to higher load conditions would tend to reduce combustion temperature and pressure, reduce engine-out NO_x emission and may improve fuel efficiency. Due to difficulties with mechanical/vacuum systems this may require vacuum reservoirs, or electrical actuation with electronic control.
10. **Calibration changes** at the higher load and speed points falling within the new FTP.
11. **Increased catalyst volume**, by an estimated 50%, in order to maintain conversion efficiency at the higher exhaust gas temperature and flow conditions experienced in the new FTP.
12. **Higher temperature catalyst formulations** may be required to cope with higher temperature operation (to greater than 1700 degrees F) which causes deterioration of performance. Palladium-only catalyst looks especially promising.

Compliance with more stringent test requirements, together with the more stringent emission limits in the Euro 3/4, and in the US Tier 2, TLEV and ULEV requirements, could probably be achieved with the 'baseline' technologies, given the range of further developments and refinements in process. However, this approach on its own would likely lead to some compromises in engine performance and fuel efficiency, at least in the short term.

Manufacturers are therefore pressing developments of a range of technologies that have the potential to enable emission requirements to be met while at the same time enabling substantial improvement in fuel efficiency. Some of these 'emerging' technologies are already available on some vehicle models in Europe, Japan and North America. They are likely to become the 'mainstream' technologies within a few years.

1.1.3 Variable Valve Timing

Over the last several years, variable valve timing (VVT) has been introduced by several overseas manufacturers on selected (generally top-of-the-range) production vehicles. Various VVT systems are in use, all of which are targeted to reduce the impact of design compromises inherent in 'fixed' valve timing, particularly for the inlet valve (Robnett et al, 1993) -

- optimum volumetric efficiency at lower engine speeds (maximum engine torque) requires inlet valve closure shortly after bottom dead centre (BDC).
- optimum volumetric efficiency at high engine speeds (maximum engine power), requires much later inlet valve closure.

Under low load and part load conditions, late closing of the inlet valve increases throttle opening, thus reducing pumping loss and increasing fuel efficiency. Increasing valve 'overlap' (the time during which the exhaust and inlet valve are both open) by adjusting 'cam phasing', allows some exhaust gas to re-enter the combustion chamber. The 'trapped residuals' perform the same function as external EGR. They reduce the inlet charge and therefore the pumping loss, improving fuel efficiency,

while at the same time they reduce combustion temperature and therefore reduce NO_x and HC emission (Toyota 1997).

'Internal' EGR is a more efficient way of introducing extra diluent into the combustion chamber than is external EGR. That is, for the same mass or EGR dilution ration, the trapped residuals have a higher temperature and volume, providing a greater reduction in manifold depression and therefore a greater reduction in pumping loss (Houston and Cathcart, 1998).

VVT provides significant performance, fuel efficiency and emission control benefits compared to fixed valve timing. However, their slow penetration into the market reflects (presumably) their high additional complexity and cost. Much greater benefit might be available with more complete control of valve timing and lift than is obtained by most current production systems. In this regard, it is noted that Honda recently launched a new S2000 sports car for Japan, Europe, and USA, having a 2-litre DOHC 'VTEC' engine with electronically controlled variable valve timing and lift, claimed to reduce emission levels below 50% of Japan's year-2000 requirements (Walsh May 1999).

Lean Burn

Burning lean mixtures reduces pumping and heat loss, and increases thermal efficiency and fuel efficiency, compared to the 'baseline' technology (homogenous, stoichiometric charge). Engine-out emissions of HC and NO_x are also reduced.

Too lean a mixture leads to combustion instability with consequent loss of efficiency and driveability. Engine-out HC emissions will also be increased.

Developments in engine technology, especially in the last 10 to 15 years, have enabled the lean limit for homogenous charge combustion stability to be progressively extended, so as to achieve significantly improved part load fuel efficiency together with lower engine-out emissions.

While engine-out HC and CO emission can be further controlled by catalytic aftertreatment, NO_x reduction under lean (oxidising) exhaust conditions sufficient to meet stringent NO_x emission standards, has proved difficult. Consequently, present engine control strategies ignore the lean burn opportunity in favour of stoichiometric burn with aftertreatment by 3-way catalyst, although lean burn technology has been maintained in some markets, for example by Toyota in Japan and Europe (Toyota 1999).

Toyota introduced a lean burn 1.6 litre engine in Japan in 1984, and in Europe in 1988 (Toyota, 1999). This engine incorporated Toyota's Lean Combustion System (T-LCS) which used a lean exhaust gas oxygen sensor to provide feedback to control AIR/FUEL ratio under part load conditions. In 1994, Toyota introduced a 'new generation' 1.8 litre, 4-valve, MPFI, lean burn engine in both Japan and Europe, which incorporated a number of new features, including –

- a helical port/swirl guide/electronic swirl control valve (E-SCV) system, that promotes high swirl and stable combustion under part load, lean charge conditions.

- a combustion pressure sensor, providing early detection of combustion instability and feedback to the engine control unit for fuel mixture control.
- a ‘NO_x storage/reduction’ catalytic converter.

The engine operates at air/fuel ratios up to 25:1 under light load conditions, progressing to stoichiometric at high load, and is claimed to reduce fuel consumption by 20% over the Japanese test cycle.

1.1.4 Stratified Charge Combustion, Petrol (Gasoline) Direct Injection (GDI)

In a compression-ignition (diesel) engine, fuel is injected into the cylinder during the compression stroke. Thorough mixing with air is constrained by in-cylinder airflow, which results in a rich mixture plume surrounded by regions of progressively weaker mixtures. Subsequent combustion begins at any point in the plume where conditions support auto-ignition.

This stratified charge combustion enables overall ultra-lean mixtures to be combusted (air/fuel > 100:1), which allows unthrottled engine operation even at idle. Consequently, pumping loss is low; heat loss to the cylinder walls is low; and thermal efficiency is high, which accounts in large part for the diesel engine’s substantial fuel economy advantage over conventional petrol engines.

Application of the stratified charge combustion process to spark-ignited engines, where the rich-stratified mixture plume must be stabilised in contact with the spark plug at ignition, has challenged engine designers for many years. The best known early approaches were made during the 1970s, these being the Texaco TCCS system (Alperstein et al, 1974) and the Ford PROCOS system (Scussel et al, 1978). Both of these (and other) approaches showed promise, but difficulties with precise control of the stratified mixture formation ultimately led to poor soot and HC emission, and limited operational zones (Houston and Cathcart, 1998).

Development of stratified charge technologies was overtaken by rapid developments in multi port fuel injection (MPFI) engines using homogenous stoichiometric fuel strategies with 3-way catalysts, which were shown to provide competitive performance and fuel economy while complying with US and Japanese emission control standards. This technology was fully commercialised during the 1980s, and remains the mainstream technology in emission controlled markets.

More recent events around the world have focused engine development to achieve substantial reduction in fuel consumption and CO₂ emissions to meet greenhouse gas reduction targets, together with further reduction in noxious exhaust emissions. This has again raised interest in the stratified charge GDI concept as the most promising future strategy for fuel economy improvement in spark-ignited engines (Fraidl, 1996). Recent developments in design, measurement and modelling technologies have given new insights into the processes of mixture formation, stable charge stratification and combustion. Also, developments in machining technologies have enabled manufacture of engine/fuel system components with very high precision. These developments are enabling rapid refinement of GDI combustion systems.

GDI development is focused to achieving –

1. increased compression ratio compared to multi port fuel injection (MPFI) engines;
2. unthrottled operation down to very low load and even to idle (overall air/fuel ratios >100) which eliminates pumping losses and (theoretically) should reduce fuel consumption by about 20% over the USFTP and/4 cycles, compared to throttled operation. Charge stabilisation is achieved through control of injection, in-cylinder air-flow and turbulence, keeping the mixture plume away from the cool cylinder walls and crevice volumes to minimise heat loss, HC and soot emission. This provides further significant fuel consumption reduction. The overall lean mixture operation at part loads reduces combustion temperature and therefore substantially reduces engine-out NO_x emission compared to stoichiometric operation (around 50% without EGR, and up to 90% with high EGR rates);
3. transition to full homogenised lean mixtures (air/fuel ratio $<25:1$) at higher part loads;
4. transition to stoichiometric mixtures at full load to provide the same power and performance as MPFI engines (Toyota 1997)

Air assisted direct mixture injection appears to have some characteristic advantages over high pressure direct fuel injection (according to both Fraidl 1996 and Houston and Cathcart 1998), providing –

- greater charge stratification and overall leaner light load mixtures (100:1 compared to 50:1 for direct fuel injection),
- slightly greater fuel consumption reduction,
- significantly lower HC emission,
- greater tolerance of high EGR rates ($>40\%$ at part loads) with potential for significantly lower NO_x emission (up to 90% at part loads).

In spite of the much lower NO_x levels achieved in GDI engines, further exhaust catalytic aftertreatment will be required to meet Euro 3/4 requirements. Both Mitsubishi and Toyota have introduced NO_x storage/release or de- NO_x catalysts on their GDI engines. Cathcart suggests the Orbital Engine Process might be calibrated with very high EGR to achieve very low NO_x at part load, and with stoichiometric calibration at high load so as to meet Euro 3 (if not Euro 4) NO_x levels using 3-way catalyst.

1.1.5 Advanced Catalyst Configurations/Formulations

Progressively tighter emission standards in the US, Japan and more recently in Europe, have forced continuing developments/refinements in engine technologies that have enabled dramatic improvements in engine-out and tailpipe emissions to be achieved. Nevertheless, compliance with the very stringent Euro 3/4 and US Tier 2, LEV and ULEV emission standards, measured over more stringent test procedures, is dependent upon continuing development in catalytic aftertreatment. These developments are generally targeted to achieve –

- faster warm-up and lower light-off temperatures in order to reduce the 70% to 90% of total test pollutants emitted before the catalyst achieves full efficiency.
- higher thermal stability and high temperature durability, to allow placement of catalysts closer to the exhaust manifold for faster light-off.
- higher conversion efficiencies, particularly with the higher feed gas flows implied by the new test procedures.
- resistance to poisoning, especially by residual fuel sulfur.

Catalyst manufacturers are under continuing pressure to reduce converter size to fit within the space constraints of modern vehicle designs, and to keep costs (and therefore technical complexity) under control. In this regard, while there are a number of ‘active’ aftertreatment solutions under development (e.g. burners, exhaust ignition systems, electrically heated catalysts), these represent heavy technical as well as financial commitments (Brueur et al 1997). Therefore, optimisation of ‘passive’ systems takes precedence owing to their development and cost potential. Relocation of the converter closer to the engine; reduction of the thermal mass upstream of the catalyst; and optimisation of the catalyst washcoat and converter support substrate with respect to cold start, constitute the essential measures.

Alternative approaches, including pre-converters, electrically heated catalysts and in-line adsorbers have demonstrated their feasibility for meeting cold start emissions regulations, but they add complexity and cost. Therefore, automakers are seeking simple, passive and cost effective systems that require minimal modifications in space and/or ancillary equipment like batteries and air pumps (Gulati et al 1997).

Advanced catalyst formulations – Three-Way Catalyst

Catalyst formulation includes –

- The type and amount of washcoat applied to the support substrate. In most cases this is based on alumina. In some cases the washcoat contains zirconia or titania. Each of these materials produces very high washcoat porosity, giving a very high total surface area with which to contact the exhaust stream.
- The type, combination and loading of precious metal catalyst applied to the washcoat. Platinum (Pt), Palladium (Pd) and Rhodium (Rh) are the Platinum Group Metal (PGM) catalysts currently in use.
- The oxygen storage compounds (generally ceria) applied to the washcoat.
- Other compounds applied to the washcoat to promote particular catalytic reactions (promoters) or to stabilise the washcoat/catalyst structure (stabilisers).
- The proprietary processes (impregnation, layering, baking, etc) by which the above components are applied.

Developments in formulation are rapidly improving the performance of the 3-way catalyst, which is likely to remain the short/medium term mainstream aftertreatment technology.

- Advanced Pd-base formulations have superior HC activity, are quicker to light-off, and are thermally more stable than Pt/Rh-based formulations. They are therefore more suitable for use in the higher temperature environments, closer-coupled to the exhaust manifold.

Pd-based catalysts are very sensitive to sulfur poisoning, especially with respect to their CO and NO_x activity. Addition of Lanthium may improve Pd activity with low sulfur fuel, and some of this enhanced activity may be retained at higher sulfur levels. Advanced Pd-promoters have improved Pd activity with both high and low sulfur fuels.

- Rh-containing catalysts have superior NO_x and CO activity, and are less sensitive to sulfur poisoning. Deactivation with sulfur is partly reversible.

Thermal deactivation is more detrimental for Pt/Rh, than for Pd. Pt/Rh or trimetal catalysts are therefore more suitable in the cooler underbody environment.

- Catalyst location can substantially reduce light-off time. eg 160 sec for underbody vs 70 for close-coupled or semi-close coupled catalyst (Petit et al, 1996).
- Dual (close-coupled or ‘fast light-off’ + main ‘underbody’) catalyst configurations may provide the optimum solution relative to space constraints.

Improved, more thermally stable ceria and PGM dispersions within the washcoat have derived from new production technologies, and through introduction of ceria stabilisers (Dunleep et al 1996).

Improved formulation Pt/Rh catalysts aged at 1050 degrees C perform as well during FTP testing as equivalent ‘standard’ formulation catalysts aged at 900 degrees C (Bartley et al, 1993). This has allowed manufacturers to reduce catalyst light-off time by placing converters in close-coupled or semi-close coupled to the exhaust manifold.

The most promising recent technology is the Pd-only catalyst formulation introduced in the USA during 1995, which offers reduced light-off time, improved thermal stability, and improved stoichiometric conversion of CO, HC and NO_x. Also important, Pd is 1/3 the current cost of Pt/Pd on a ‘per converter’ basis (Dunleep et al 1996).

A critical consideration in catalyst design is the potential for fuel sulfur level to impact on the ability to reach TLEV, LEV and ULEV emission levels (Thos et al 1997).

The US Auto/Oil Air Quality Improvement Research Program (AQIRP) Phase I, carried out during 1989 – 91, showed sulfur in petrol to be a short-term deactivator of catalytic converters. In US Tier 0-technology vehicles (model years 1983 to 1989)

AQIRP showed reducing sulfur from 450 ppm to 50 ppm reduced tailpipe emissions by 19% for CO, 18% for HC and 8% for NO_x (Benson et al 1991, AQIRP 1997). A similar effect was noted for Tier 1-technology vehicles in the AQIRP Phase 2 program (AQIRP 1997) where reducing fuel sulfur from 320 ppm to 35 ppm reduced tailpipe emissions by 16% for CO, 20% for HC and 9% for NO_x. In both AQIRP phases, sulfur content had no effect on CO₂ emission or fuel economy.

Confirmation of sulfur's deleterious effects on catalysts in European vehicles was provided by the European Program on Emissions Fuels and Engine Technologies (EPEFE) (Petit et al 1996). This work showed –

- Reducing sulfur from 382 to 18 ppm decreased CO, HC and NO_x by about 10% over the ECE+EUDC cycle, and by 43% CO, 52% HC and 20% NO_x over the EUDC alone. On the low speed ECE cycle, CO was reduced by about 6%, while there was no significant difference in HC or NO_x. There was no change in emissions during the first ECE cycle, when the catalyst is not fully warmed.
- Effects varied widely from car to car, reflecting different catalyst technologies.
- There was no change in engine-out emissions, so all changes related to catalyst effects.
- There was no effect on CO₂ or fuel consumption.
- Pd-based catalysts were more sensitive to sulfur than Pt/Rh catalysts.
- Close-coupled catalysts appeared to be more sensitive to sulfur than underbody catalysts.
- These results were broadly in line with AQIRP bearing in mind procedural differences.

Other tests for sulfur sensitivity in LEV and ULEV vehicles have been conducted in the USA, and analysed together with the AQIRP results for sensitivity in the range 40 ppm to 320 ppm, by the Environmental Protection Agency (USEPA 1999). This analysis indicates

- LEV and ULEV technologies are on average much more sensitive to sulfur than Tier 0 or Tier 1 technology, up to 10 times more sensitive for NO_x.
- There was an overall trend observed that sulfur's impact increases as the overall stringency of control increases.
- Those vehicles with least sulfur sensitivity towards NO_x had slightly greater sensitivity towards NMHC.

USEPA observed that the new FTP requirements, not reflected in these vehicle test data, would impose new requirements for engine management and catalyst operation, that may further affect manufacturers' ability to design for lower sulfur sensitivity.

The EPEFE and AQIRP programs implied that catalyst poisoning through operation on high sulfur fuel was reversed once operation on low sulfur fuel was re-established. However, for catalyst efficiency to be restored, the vehicle must be operated through a range of AIR/FUEL ratios and exhaust temperatures that may not be typical of normal road use, and may be less common with vehicles designed for the new FTP (USEPA 1999).

Overall, the literature suggests very strongly that catalysts can be formulated to be sufficiently active and durable to meet the Euro 3/4 and California LEV and ULEV requirements, provided that low sulfur levels are maintained in market fuels.

In this regard, the US, European and Japanese motor industries have called for petrol sulfur levels to be limited to 30 ppm in markets with advanced emission control requirements (AAMA, EMA, ACEA, JAMA, 1998).

Advanced catalyst formulations – Lean-NO_x Catalyst

Vehicle manufacturers have explored lean-burn and ultra-lean burn engine strategies for many years in pursuit of their fuel efficiency benefits. However, while such engines have comparatively low engine-out NO_x emissions, catalytic reduction of NO_x in lean exhaust conditions sufficient to meet NO_x emission control standards has proved difficult. This has limited introduction of lean burn strategies in series production vehicles.

In the late 1980s, catalysts based on metal-doped zeolites were discovered that promoted NO_x reduction in lean exhaust gases (Fekete et al 1997). There followed considerable research activity among vehicle and catalyst manufacturers aimed at developing this and other lean-NO_x catalyst technologies. Generally, these passive selective catalytic reduction (SCR) technologies seek to promote reaction of NO_x with HCs in the exhaust stream to form N₂, H₂O and CO₂. According to Fekete, published scientific information suggests this technology was not at that time able to meet Euro 3/4 emission standards, and that thermal durability was questioned.

Active SCR technologies have also been under development for many years, particularly for stationary plant, and more recently for diesel and gas engines. In these technologies, a NO_x-reducing agent such as ammonia or urea is injected into the exhaust stream ahead of the catalyst.

The Siemens SINOX system, developed for diesel engines, is under investigation for use in petrol vehicles where higher exhaust gas temperature requirements have to be met. However, currently available direct reduction processes are typically either susceptible to sulfur poisoning or have not yet demonstrated the NO_x conversion rate necessary to meet Euro 4 emission levels (Stocker and Houston 1999).

In 1994, Toyota announced joint development with Cataler Industrial Co Ltd, of a NO_x storage and release catalyst (Walsh September 1994). NO_x storage/release converters include a compound such as a barium oxide within the washcoat, together with a conventional PGM catalyst such as platinum (Kobayashi et al 1997). During lean operation, NO is oxidised on the catalyst to NO₂, which then reacts with the barium oxide and is 'stored' as barium nitrate. Under rich exhaust conditions NO₂ is

released and reduced to N_2 . At stoichiometric mixtures, the catalyst has 3-way operation.

NO_x release and reduction within the converter requires short excursions to rich exhaust conditions (a few seconds each couple of minutes). This requires precise fuel injection and sophisticated engine management capable of managing vigorous transients while switching between lean and rich conditions. This approach provides higher overall NO_x conversion and better, but (then) still insufficient durability, compared to current SCR systems (Fekete et al 1997). However the NO_x storage capability is very sensitive to poisoning by sulfur, which reacts with the storage compound, eventually forming high temperature stable sulphate.

It might be fair to assume that many manufacturers would prefer to adopt a passive SCR approach for lean- NO_x control, if it proved to have equivalent performance to the more complex storage/release approach. Given the industry's need to move to lean and ultra-lean burn strategies to achieve vehicle fuel consumption reduction targets, especially in Europe, it might also be assumed that manufacturers will vigorously pursue all available catalytic lean- NO_x control technologies.

With low sulfur petrol (30 - 50 ppm) now available in Japan and California, and becoming available in Europe and the US, manufacturers have more freedom to pursue more-active catalyst formulations to meet very stringent emission control requirements.

However, industry concerns for long term catalyst durability even at these low levels of sulfur, appear to persist. This is reflected in the US, European and Japanese motor industry's recent addition of a new category of fuels into its *World-Wide Fuel Charter* (in AECC 1999). This new category has maximum sulfur in the range 5 to 10 ppm, and has been designed for 'lean NO_x ' and ' NO_x adsorber' catalyst systems and to control diesel particulates.

Advanced Catalyst Support Substrates

Cordierite ceramic honeycomb substrates have been the predominant catalyst support since the mid-1970s. They –

- have a large geometric surface area on which to place the washcoat and catalyst.
- present a low back pressure to exhaust flow.
- are light and strong.
- have high thermal and mechanical durability.

In the 1970s, these substrates had a cell wall thickness of 12 thousandths of an inch (mil) and a cell density of 300 cells per square inch (cpsi). In the 1980s substrates were introduced having 6 mil / 400 cpsi construction. These had a lower bulk density (therefore lower heat capacity and faster warm-up), a much higher surface area (and therefore greater conversion efficiency/volume) and presented lower backpressure. These substrates have remained until very recently, the industry standard.

Following considerable advances in manufacturing technologies, advanced cordierite ceramic substrates have recently become available that have ultra-thin wall thickness (4 mil, 3 mil and even 2 mil) and higher cell densities 600 cpsi and 900 cpsi. These substrates enable considerable light-off improvement, and conversion efficiency improvement for the same overall volume, compared to the standard 6 mil / 400 cpsi designs (Umehara et al 1997).

A number of manufacturers have offered metallic substrates, which have increasing acceptance by vehicle manufacturers. Depending on their design, they may offer some advantages over ceramic substrates (Luoma et al 1997) particularly for fast light-off, and for situations where space is a constraint. On the other hand, their performance may be comparable (Day P 1997).

A comparatively recent, novel metallic substrate design appears to demonstrate significant benefits in a light-off configuration (Roychoudhury et al 1997). This Microlith™ 'fast light-off Preconverter' consists of multiple, low thermal mass, short metal monolith substrates with enhanced mass transfer, inter element mixing and boundary layer break up. The substrate has a cell density of 2500 cpsi, wall thickness of 0.076 mm (3 mil) and a cell length of less than 0.2 mm. It is capable of withstanding continuous high operating temperatures to 1050 degrees C with excursions to 1200 degrees C, using a proprietary catalyst coating technique with no washcoat. Tests on a US specification 1.9 litre Ford Escort, with the preconverter in front of a close-coupled main converter gave light-off in 15 seconds, and ULEV emission levels both with and without secondary air. In configuration with an underbody main converter, potential gave close to ULEV emission levels.

Electrically Heated Catalyst (EHC)

Recent improvements in catalyst formulations, particularly Pd-only technologies, have achieved high levels of thermal durability. These advanced formulations have enabled fast light-off catalysts to be installed close-coupled to the exhaust manifold. When installed ahead of a semi-close coupled, or underbody main catalyst, these systems have been demonstrated to meet ULEV standards.

On vehicles with large displacement or on high performance engines, such systems may result in significant increase in back pressure and consequent loss of engine power. EHC is well suited to these vehicles (Shimasaki et al 1997).

Several Manufacturers have introduced vehicles with electrically heated catalysts to enable California ULEV compliance.

Most EHC systems use high power (2 to 3 kW) full-face heating for optimum light-off and cold emissions reduction. However, this puts a high electrical load on the battery or alternator.

On some vehicles, zoned heating of the catalyst face at reduced electrical power levels might produce an adequate solution, even though HC emission benefits are significantly reduced (Kubsh and Brunson 1996).

In 1995, the BMW ALPINA B12, having a 12-cylinder 5.7 litre engine, became the first vehicle to be introduced into the European and Japanese markets with EHC

(Hanel et al 1997). This system has two battery-coupled 2-kW Emicat™ metallic EHCs installed in the underbody area ahead of a single metallic main catalyst. The EHCs are heated in turn, 12 seconds for the first then 11 seconds for the second. The system achieved 85% lower emission than required by the Euro 2 limits, and easily meets Euro 3.

Honda has fitted a number of 2.2-litre engine Accords with alternator powered 2-kW EHCs (Shimasaki et al 1997). The systems comprise a Pd-only EHC on an extruded metal substrate, mounted in cascade with a tri-metal light-off catalyst on a ceramic substrate, and a tri-metal main catalyst on a ceramic substrate. The system has achieved ULEV standards over 100,000 miles of fleet testing without failure. The EHC and light off assembly has accumulated 1.1m miles over 19 vehicles without failure. This has achieved the 'final milestone' in addressing EHC as a realistic technology for 1999 production for ULEV and Euro 3 standards.

Other Cold Start Strategies

Other strategies have been under development aimed at reducing emissions during the catalyst warm-up period. These systems add significant complexity, and may have been overtaken by recent developments in fast warm-up catalysts. They include –

1. Hydrocarbon adsorber systems (Williams et al 1996, Hertl et al 1996, Patil et al 1996, Ballinger et al 1997), are designed to adsorb cold engine-out HC emissions for subsequent desorption once the main catalyst has reached light-off. These systems adsorb heavier hydrocarbons quite effectively, but smaller species such as methane, ethane and ethene are not adsorbed. Nevertheless, HC adsorbers have been shown to be effective at LEV and ULEV levels.
2. Air assisted fuel vaporiser systems are designed to replace the conventional multi-point fuel injectors. Jackson (1996) describes a system incorporating a glow plug on to which fuel is injected, vaporised and mixed with air before injection into the combustion chamber. Using this system, a stoichiometric fuel strategy is possible during cold start and idle, eliminating puddling at the inlet port and consequent entry of liquid fuel or rich AIR/FUEL mixture into the chamber. The system also promotes a faster warm-up and reduces engine-out HC emissions by around 45%.
3. The rapid exhaust port oxidation (REPO) process developed by Southwest Research Institute uses an ultra-rich fuel mixture for engine start (fuel/air equivalence ratio of about 1.6) while metering near stoichiometric fractions of air directly into the exhaust ports (Crane et al 1997). This approach leads to combustion of exhaust gases in the exhaust pipe, fast catalyst warm-up and light-off, yielding HC and CO reductions of 68% and 50% respectively during the first 70 seconds of the FTP.

1.1.6 On Board Diagnostics (OBD) Systems

US requirements for OBD systems demand (among other things) a means of monitoring catalyst efficiency and providing a warning when tailpipe hydrocarbon emissions would exceed 1.5 times the applicable standard. Prevailing OBD systems achieve this by monitoring exhaust oxygen upstream and downstream of the catalyst, thereby providing some measure of oxygen storage capacity and inferring HC

conversion efficiency. Sulfur interferes with the oxygen storage and monitoring mechanism, in some cases causing false warning of failure and in other cases causing a failure to be undetected.

The US Environment Protection Agency evaluated the potential of sulfur to interfere with the proper operation of catalyst monitors in 1997 (USEPA 1998). The EPA concluded there was insufficient data available to indicate a broad-based problem with OBD catalyst monitors. However, EPA found there may be a need in a few cases for manufacturers to adjust their California-certified OBD systems to reduce 'false failures' on higher sulfur fuel outside California. EPA acknowledged it was unaware of any adjustments that could be made to reduce the number of 'false passes', that would reduce the effectiveness of the OBD monitor particularly in an inspection/maintenance program. EPA observed that for LEV and ULEV vehicles, higher sulfur levels have the potential to increase emissions in the range that OBD systems are designed to detect.

1.2 Diesel Technologies

1.2.1 Computerised fuel and engine management

The use of computerised engine control for both heavy and light-duty engines has been rapidly growing since the late 1980s. This technology has proved to be a powerful tool for achieving reductions of all regulated diesel emissions and for delivering significant improvements in fuel economy.

Compared with older, mechanical arrangements, electronic systems provide much more precise control over fuel, air and exhaust gas recirculation (EGR). Moreover, this control is executed over the engine lifetime, compensating for engine wear and deterioration. Additionally, as required in an increasing number of applications, engine emission controls can be supported by on-board diagnostic (OBD) systems, which activate a malfunction indicator in the vehicle when an emission fault is detected.

Typical electronic control systems for diesel engines include a range of sensors, a microprocessor (the electronic control unit, or ECU), and a set of actuators. The sensors measure physical variables and pass the information in the form of electrical signals to the controller. Examples include crank speed, boost pressure, intake manifold temperature and pressure. The actuators perform mechanical actions as directed by signals from the microprocessor. Examples of actuators are EGR valves or variable geometry turbochargers. The system generally covers:

- Fuel quantity control
- Fuel timing control
- Boost pressure control
- EGR control

Fuel Quantity Control

The optimal fuel requirements for the entire operating range of a given engine are determined by analysis, testing and computer modelling as part of the engine's design and development. These parameters are then stored by the ECU as a three-dimensional map of fuel supply versus engine speed and throttle position.

The engine controller will first calculate the fuel rate from the map. This demanded fuel rate is then compared with other computed fuel rates needed to satisfy other engine conditions, for example the air flow limited fuel rate. The lowest useable fuel rate value is selected and passed to the fuelling system.

Fuel Timing

Injection timing is one of the most important factors influencing combustion and the resulting emissions. All important engine performance parameters, including specific fuel consumption, emissions of NO_x, PM and HC are strongly influenced by injection timing.

Mechanical fuel systems have fairly limited injection timing capabilities. In contrast, electronic control allows to-command injection timing in response to engine load, engine speed, or ambient conditions. Exhaust emissions can be optimised over a wide range of engine speeds and loads, through implementing injection timings that optimise emissions and fuel consumption over local regions of the operating spectrum.

The electronic injection control also allows for much better accuracy of the injection timing. Some engines ([Bauder 1990](#)), use an injector needle lift sensor to provide feedback, with a claimed injection timing accuracy of ± 1 degree of crankshaft rotation.

Boost Pressure

Practically all today's automotive diesel engines are turbocharged. Modern turbochargers, including the *wastegated turbocharger* and *variable geometry turbocharger* technologies, allow control of the intake manifold (boost) pressure and, thus, the air flow rate to the engine cylinders. A wastegate bypasses some of the exhaust gas around the turbocharger turbine at high speeds to prevent excessive boost pressure and airflow.

Many mechanical wastegate systems develop inaccuracies through their inability to adapt to wear and friction over their operating life, with consequential adverse effects on engine performance.

Electronic wastegate control is now treated as an integrated engine control strategy, with true closed-loop control of the boost pressure, compensated for manufacturing variability and changes during engine lifetime, as well as environmental conditions including altitude.

EGR Control

Exhaust gas recirculation (EGR) is now increasingly used as a means to control NO_x emission. Gas to be recirculated is drawn from the exhaust manifold upstream of the turbocharger and transferred to the intake manifold through an EGR valve. The amount of EGR is electronically controlled in response to various parameters, including the throttle position and ambient conditions. Most current implementations use open-loop EGR.

Different degrees of EGR control are possible. In the simplest open-loop system, the EGR valve is closed by the ECU during start-up and when the engine coolant is below prescribed temperature. A more sophisticated implementation of the open-loop EGR control involves modulating the EGR valve according to a valve position schedule stored as a look-up table in the ECU.

1.2.2 Direct and Common Rail High Pressure Fuel Injection

Direct injection (DI) involves firing a cloud of finely atomised fuel directly into the combustion chamber at an optimum point in the engine cycle. Older, indirect injection systems for diesel engines simply entrain fuel into the inlet air stream in a pre-ignition chamber so there is little control over the ignition timing.

In heavy duty engines, DI has been used for many years, with increasing levels of technical sophistication and ever-increasing operating pressures. A key feature of high-pressure systems is that they can provide good fuel atomisation, which is needed for low particulate and hydrocarbons emissions.

Since the early 1990's commercial competition and regulatory action have also pushed manufacturers of light duty diesel vehicles towards using a high pressure direct injection combustion process.

The most recent commercialisation of high pressure DI is Common Rail technology. Instead of an injector pump sending a timed "pulse" of fuel to each cylinder's injector in turn, the fuel is continuously pressurised and held at this high pressure in a tubular reservoir (the common rail), to which all the computer controlled injectors are connected. A computer-controlled signal actuates each injector at exactly the correct time in the cycle.

Post-Injection

The common rail also has the capability of introducing fuel post-injection, which is used with some catalytic emission control technologies. These technologies include the following NO_x catalysts (which are discussed in later sections):

- passive diesel particulate filter systems
- lean NO_x catalysts utilising selective reduction with hydrocarbons
- NO_x traps which require a rich exhaust condition for regeneration.

Passive particulate filter systems rely on the exhaust gas temperature and, usually, a catalyst or fuel additive for regeneration. Post-injection of fuel may be used to periodically increase the exhaust temperature to enhance the filter regeneration. A filter system utilizing such engine management strategy has recently been developed by Peugeot.

1.2.3 2-way Catalyst (Diesel Oxidation Catalyst)

Diesel oxidation catalyst (DOC) technology promotes a range of oxidation reactions utilising the excess oxygen present in diesel exhaust at all engine operating conditions.

The oxidation reactions may also be combined with selective catalytic reduction (SCR) and lean NO_x catalyst (LNC). SCR systems are used in to reduce NO_x emissions through selective reaction with a reducing agent, such as ammonia or urea, which is injected upstream of the catalyst bed. The lean NO_x catalyst, intended to reduce nitrogen oxides in an oxidising atmosphere from mobile engines, is now becoming a commercial reality.

Diesel oxidation catalyst can be used to reduce the following emissions:

- gas phase hydrocarbons (HC),
- the organic fraction of diesel particulates (SOF),
- carbon monoxide (CO).

The emission reductions in the DOC occur through the chemical oxidation of pollutants. Hydrocarbons are oxidised to form carbon dioxide and water vapour. Carbon monoxide is oxidised to carbon dioxide. Since carbon dioxide and water vapour are non-toxic, the above reactions bring an obvious emission benefit.

Some of the oxidation reactions that may occur in the diesel catalyst can produce undesirable products and act counter-productively to the catalyst purpose. Oxidation of sulfur dioxide to sulfur trioxide with the subsequent formation of sulfuric acid (H₂SO₄), is certainly the most important of these processes. When the exhaust gases are discharged from the tailpipe and mixed with air, their temperature decreases and the gaseous H₂SO₄ combines with water molecules. These highly aggressive sulphate particulates increase the total particulate matter emissions from the engine. Special catalyst formulations are used to suppress this process, making the diesel oxidation catalyst a viable particulate reduction approach.

The diesel oxidation catalyst is an effective device to control carbon monoxide and hydrocarbons emissions from diesel engines, including the PAH and hydrocarbon derivatives such as aldehydes.

Low sulfur fuels minimise sulphate production and increase the benefit of the diesel oxidation catalyst, but in practice, if sulfur is present in the fuel, there is always a temperature above which an increase of particulate emissions will start to increase. If sulfur-free fuel is used, the highly active platinum/alumina based catalyst systems are still the best choice for both the particulate and the gas phase emission control.

Deactivation of Diesel Catalyst

The main cause for the deactivation of diesel catalysts is poisoning by sulfur, as well as by lubrication oil additives. Phosphorus is the most common oil-derived catalyst poison.

Sulfur poisoning is frequently reversible by high temperatures, under which the sulfur compounds decompose and are released from the catalyst washcoat. However, due to the low diesel exhaust temperatures, in many diesel engine applications the conditions needed for catalyst regeneration may never be reached.

1.2.4 Lean NO_x (De-NO_x) Catalyst

Methods for catalytic reduction of nitrogen oxides under lean exhaust conditions include selective catalytic reduction with urea or ammonia, selective catalytic reduction with hydrocarbons, and NO_x trap/catalyst systems.

Reduction with ammonia, originally used only in stationary applications, is now becoming available for road vehicles (Peugeot). Several catalyst systems have been proposed for the reduction of NO_x with hydrocarbons, including a copper substituted zeolite ZSM5 catalyst, which is active at high temperatures, and a platinum/alumina catalyst, exhibiting low temperature activity. Both these catalysts have narrow operating temperature windows and still require improvement.

NO_x traps are the newest technology which is being developed for partial lean burn petrol engines but is also considered for diesel engines. The traps adsorb nitrogen oxides during lean engine operation and require short enrichment 'spikes' for the desorption and reduction of NO_x using post-injection techniques.

Catalytic Reduction of NO_x

Oxides of nitrogen can be very efficiently reduced from exhaust gases of rich-burning engines, such as those used in today's petrol-powered cars. The three-way catalyst, which has been developed for that purpose, promotes a non-selective reduction of NO_x by other exhaust gas components such as carbon monoxide and hydrocarbons.

High NO_x reductions can be only achieved if the engine operates close to the stoichiometric air to fuel ratio. Since the presence of oxygen in the exhaust gas rapidly deteriorates the NO_x performance of the three-way catalyst, that technology is ineffective in controlling nitrogen oxides emission from diesel engines.

A catalyst capable of reducing NO_x in exhaust gases from lean-burning engines, i.e., in the presence of oxygen, is called a lean NO_x catalyst (LNC). This technology is being very actively pursued not only for diesel NO_x reductions, but also for petrol engines, where lean burn offers very significant fuel consumption (and hence greenhouse) benefits.

The following catalytic approaches have been investigated for the NO_x control in lean exhaust gases:

- NO decomposition catalyst
- Selective catalytic reduction with nitrogen containing compounds (ammonia, urea)
- Selective catalytic reduction with hydrocarbons
- NO_x trap-catalyst systems.

Although initially promising, **Catalytic Decomposition** of NO has proven to be difficult to realise. The decomposition of NO on Cu/ZSM5 is subject to inhibition by water, is very sensitive to poisoning by SO₂, is effective only at low space velocities, and the catalyst activity and selectivity are not satisfactory (Iwamoto 1991).

Selective Catalytic Reduction (SCR) of NO_x can be achieved if a reducing agent is injected into the gas upstream of the catalyst bed. SCR processes utilising nitrogen-containing reductants such as ammonia or urea are commercially available for stationary diesel engines and for industrial sources. Although considered in the past not to be an attractive option for diesel trucks and cars, the use of ammonia, or preferably urea, is now becoming a commercial reality in some light and heavy duty diesel applications.

A number of catalysts have been found to promote Selective Catalytic Reduction of NO_x by hydrocarbons, alcohols, or other combustion gases (Shelef 1995). Reduction by HC is less susceptible to sulfur poisoning than the NO decomposition and higher conversion efficiencies have been demonstrated.

In the case of diesel application, diesel fuel was the obvious source of hydrocarbons necessary for the reaction, and the computerised common rail post-injection techniques outlined previously, now make this approach both feasible and economically attractive.

In the selective catalytic reduction, the hydrocarbons selectively react with NO_x , rather than with O_2 , to form nitrogen, CO_2 , and water. The catalyst-reductant system has to be optimised to promote the desired selective reaction and suppress the undesired reactions with oxygen. Catalyst selectivity depends on several factors including the catalyst formulation, the hydrocarbon species used for the reaction, and the HC/ NO_x ratio.

NO_x Trap - Catalyst Systems

The concept of NO_x traps is to incorporate NO_x trapping compounds into the catalyst washcoat, with a controlled release under favourable catalysing conditions.

In **Temperature Regenerated NO_x Traps**, these compounds adsorb NO_x during periods of low exhaust gas temperature then, at higher temperatures, the stored NO_x is released and reduced in the catalyst. Several materials, including various types of zeolites, have been evaluated as candidates for temperature regenerated NO_x traps.

Another, different NO_x trap/catalyst technology is based on acid-base washcoat chemistry. It involves trapping NO_x during lean driving conditions and releasing it under short periods of deliberately induced rich operation. The released NO_x must be catalytically converted to nitrogen just as in current three-way catalysts.

This 'rich spike regeneration' trap concept was originally developed primarily for petrol engines, but work is underway to utilise this technology for diesel NO_x reduction also.

The following are some of the issues which are currently being resolved:

- High temperature limitations related to the decomposition temperature of barium nitrate in the catalyst washcoat. (Probably not critical for diesel applications).

- Deactivation of the trap by sulfur. Sulfur compounds form barium sulphate which is more stable than barium nitrate. Desulfation of the trap could be performed by applying high concentrations of reductants or by exposure to high temperatures (above 500°C). However, some barium sites appear to be permanently and irreversibly poisoned by sulfur (Dou 1998).
- The impact of phosphorus and zinc, known poisons of the 3-way catalyst, on the NO_x trap is still not fully understood.
- Vehicle driveability problems can occur during the brief but necessary periodic mixture enrichment.
- Mixture enrichment needs to be carefully applied. In-cylinder enrichment creates high particulate emissions, and exhaust system enrichment requires not only that a reductant be injected but, first of all, that the oxygen levels in the exhaust gas be lowered. Post-injection using common rail injection systems are likely to provide the answer to this problem.

1.2.5 Continuously Regenerating Particulate Trap

Diesel particulate traps physically capture diesel particulates preventing their release to the atmosphere. Diesel traps work primarily through a combination of deep-bed filtration mechanisms, such as diffusional and inertial particle deposition. The most common filter materials are ceramic wall-flow monoliths and filters made of continuous ceramic fibres.

A number of methods have been developed to regenerate diesel filters. Passive filter systems utilize a catalyst to lower the soot combustion temperature. Active filter systems incorporate electric heaters or fuel burners to burn the collected particulates.

Diesel traps are most effective in collecting the solid carbonaceous fraction of diesel particulate matter. The effectiveness of diesel traps in controlling the organic fraction of particulate matter (SOF) depends on the type of trap and on its operating conditions. Depending on the circumstances, it may be lower than the SOF abatement effectiveness of the diesel oxidation catalyst.

All diesel traps of practical importance are diesel particulate filters (DPF). The terms "diesel trap" and "diesel filter" are frequently used as synonyms. Some of diesel filter materials show quite impressive filtration efficiencies, frequently in excess of 90%, as well as acceptable mechanical and thermal durability.

In fact, diesel traps are the only emission control measures which reduce diesel particulate emissions with high efficiencies.

The most important issue with diesel traps is filter regeneration. Soot generated by diesel engines is characterized by low bulk density and, therefore, high volume. Due to the high volumes of generated particulates, it is necessary that the filter be regenerated, either periodically or continuously, during the regular engine operation. The on-vehicle filter regeneration is most commonly realized by oxidizing (burning) of soot in the filter.

Filter (Trap) Regeneration

In an ideal situation, particulates that enter the filter are oxidised in a continuous or almost continuous manner. The filter maintains an approximately constant, moderate soot load, which produces an acceptable pressure loss. Continuous regeneration does not produce high temperature peaks due to the exothermic combustion of soot. Thus, there is little thermal stress on the filter material.

Rapid regeneration occurs when a high load of soot becomes 'ignited'. Such regeneration, also called 'uncontrolled' or 'run-away' regeneration, is the opposite of the ideal, continuous regeneration mode. The 'ignited' soot load burns rapidly releasing high quantities of heat, raising filter temperature, and eventually, causing damage (melting, cracking) to the filter material.

In passive systems the soot combustion temperature is lowered to a level allowing for auto-regeneration during regular vehicle operation. This can be achieved by introducing an oxidation catalyst to the system. The catalyst can be placed directly onto the trap surface or added to the diesel fuel as fuel additive. Active ingredients of available fuel additives include iron, cerium, copper, platinum, or mixtures of metals.

A different principle has been utilized in the CRT Trap, where the catalyst, placed upstream of the filter, is used to generate nitrogen dioxide which then oxidizes the collected soot.

The second approach is to actively trigger regeneration by raising the temperature in the trap, using electric heaters or fuel burners. Active trap systems are much more complex than passive filters. They require sophisticated hardware, including an electronic control unit to trigger and control the regeneration process.

Plasma Exhaust Treatment

Non-thermal plasma technologies have the potential to reduce several diesel and automotive exhaust emissions including NO_x , particulate matter, and hydrocarbons.

The focus in plasma research is on nitrogen oxides reduction. Since oxidation reactions dominate during plasma discharges in lean exhaust, the plasma alone is probably ineffective in reducing NO_x . Instead, combined plasma-catalyst systems have been proposed and are investigated.

Early reports indicate that plasma may enhance the catalyst selectivity and removal efficiency. Today's plasma exhaust treatment technologies are in their early stage of development. It is still impossible to predict whether or not they will become a viable emission control option.

1.2.6 On Board Diagnostics

On-board diagnostics (OBD) is a system designed to monitor the performance of vehicle's emission controls, such as catalytic converters, diesel traps, evaporative emissions, engine misfire, etc., and to detect emission faults. OBD systems are or will be required by emission regulations in several countries.

Generally, there will be differences between requirements for diesel and petrol fuelled vehicles. The following components or systems are typically monitored:

- Emission after-treatment devices (catalysts, traps)
- Engine misfire
- Fuel system
- EGR system
- Air conditioning system (CFC refrigerants)
- Evaporative system, secondary air system, oxygen sensor (petrol engines).