EXHAUST EMISSIONS – VEHICLE EXHAUST AFTER TREATMENT

Introduction

The need to remove major pollutants from vehicle exhaust gases was first legislated for in America in the late 1960's, partly as a result of the air quality of Los Angeles, where photochemical smog was of increasing concern. The initial targets were carbon monoxide (CO) and unburned hydrocarbons (HCs); interest in oxides of nitrogen (NO_x) came later. The serious regard the Americans had for controlling these pollutants, and the automobile industry also, became apparent to me when I worked for Ford in Europe in 1971 as Resident Engineer in the Dagenham Engine Plant. It was a requirement of the Environmental Protection Agency (EPA) regulations that all vehicles being marketed in the USA had to have a sticker in their windows showing the emission standard that was being met. We had a shipment of Cortinas going to the States, and we hadn't had the labels delivered in time to be stuck on the windscreens whilst the cars were going down the line. No matter, I thought, they can be stuck on at the dockside. Fortunately I telexed Ford's emission office in Detroit to ask if this was permitted. The answer came back, that, if this happened, I'd made the company liable for a $6 million fine. The cars stayed at the plant until the labels had been put on.

The reasons behind these draconian penalties were recognition by the legislators of the wiles of the industry in getting round the legal requirements. For example, I think it was Volkswagen who realised that, with the early regulations based around pollutant concentrations at the tailpipe, a low cost solution was to mount a large air pump on the engine, and dilute the exhaust gases sufficiently to meet the requirements. The morals of the industry haven't changed very much in the last quarter-century, as I shall touch on later. The history of exhaust emission legislation is that each downward step in pollutant levels has been fought by the industry tooth and nail. Unfortunately, at each stage, the claim of impossibility promoted by the industry has been shown to be incorrect, so that the industry's credibilty was eroded early on and has never quite recovered.

The EPA struck back at the industry with new regulations that specified pollutants in terms of grams per mile – obviously the EPA had difficulty (and still does) with metrication. The methods of measurement were also specified, using constant volume sampling, gas collection and standardised methods of analysis. All gases had to be collected during the operation of the vehicle to a standardised driving pattern which reproduced a drive in downtown Los Angeles, using chassis dynamometers incorporating flywheels to enable vehicle inertia to be simulated.

Other countries also started to realise the environmental damage associated with vehicle emissions, and adopted regulations to compel the industry to reduce the pollutant emissions. In general, the measurement and analysis methods were similar to those adopted in America, but different driving patterns were adopted, supposedly representative of urban operation in the various countries concerned. In the early days,

EVOLUTION OF JAPANESE EMISSION REGULATIONS FOR PETROL VEHICLES

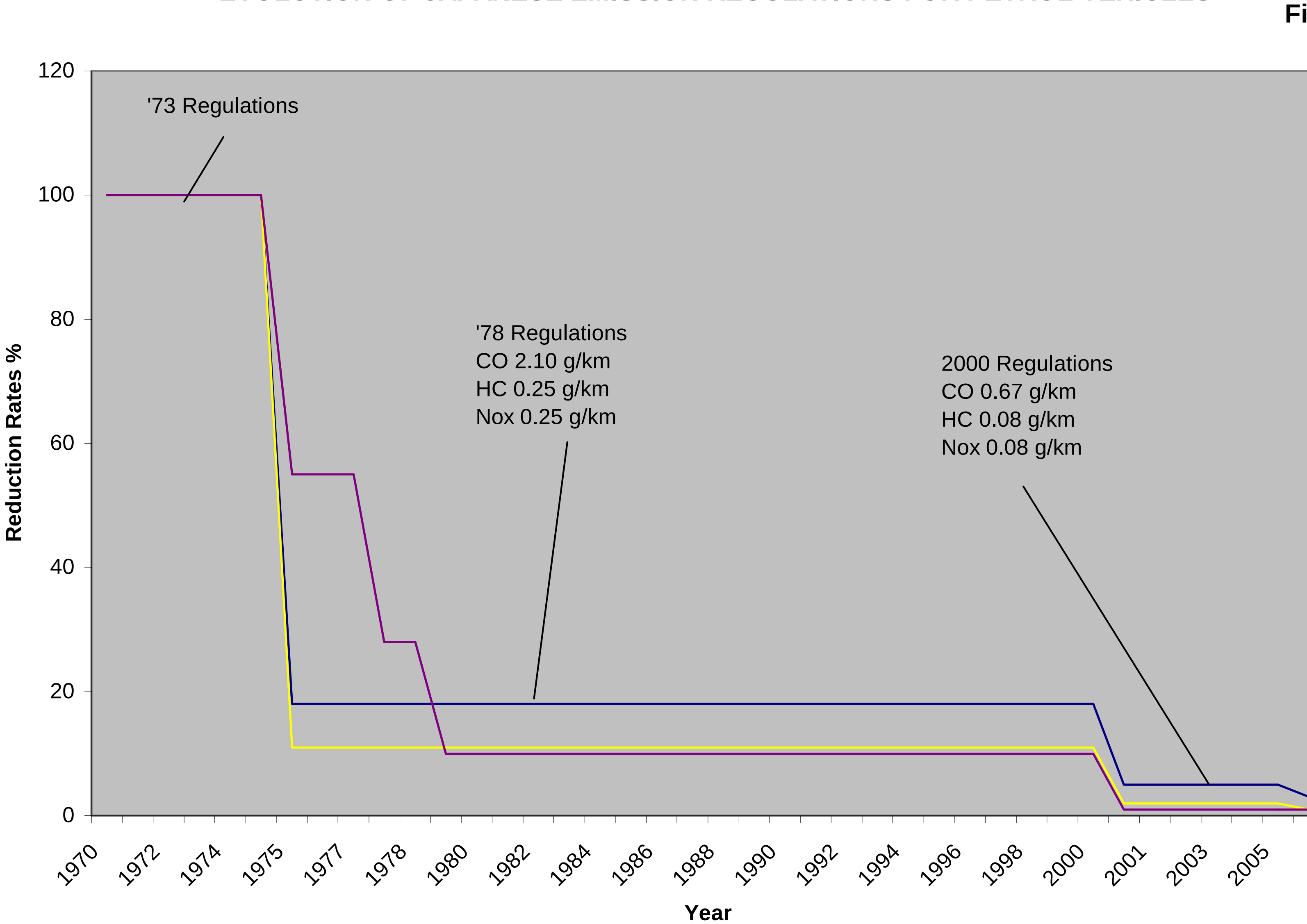

Fig.1

attention was almost entirely on urban operation, and it was quite a while before open road operation was considered by the legislators.

How far emission requirements have changed since those early days can best be demonstrated by Fig.1, which shows how the required levels have changed in Japan over time since their first regulations came in in 1974. And, of course, California has been pushing for ultra-low levels and zero emission levels for proportions of the Californian fleet for some time.

To reduce emissions, obviously a threefold attack is desirable, tailoring fuels, engines and exhaust treatment appropriately to minimise pollutant concentrations, but in this paper I have been asked to concentrate on the final stage of the process. This is not altogether practicable: for example, to use catalysts, catalyst poisons such as lead have to be removed from petrol. Nonetheless, I shall try and focus on my target as much as I feel it deserves.

Early Approaches to Emission Control in Petrol Vehicles

Exhaust emission control technology can be divided, very broadly into two approaches: without exhaust catalysts, relying on better control of mixture preparation and combustion, and with catalysts fitted in the exhaust system to change exhaust gas chemistry. In the late 1960s and early 1970s knowledge of what actually happened in combustion chambers was sparse, and in petrol engines generations of automotive engineers had solved many a valve and piston durability problem by richening up the mixture a bit when more power output was needed. The result was CO levels of over 10% for some parts of the performance envelope, plus high concentrations of HCs. And, of course, a good many vehicles still had manual chokes, so that emissions during cold start and warm-up were variable and horrendous. The control of automatic chokes 20 years ago was not what it might have been for emission control purposes, but better than the vagaries of manual control.

The immediate effect of emission control legislation was to put an end, for quite a few years, to increases in specific power outputs. This was simply because weak mixtures were the only way in which CO and HC levels could be reduced in the state of then-current knowledge, and weak mixtures and high specific outputs did not go together. In Europe the emissions reductions obtainable by improved mixture preparation and better combustion control were considered sufficient for much longer than in the USA and Japan, where what were called two-way catalysts started to appear during the 1970's. Two-way, because they oxidised both CO and HCs to water and CO_2.

By the early 1980s, carburettors were disappearing, simply because they were failing to match the requirements of fuel metering required as catalysts were introduced and exhaust emission limits reduced. Without catalysts, carburetted vehicles were being produced whose CO levels, in urban operation and fully warmed-up, were well under 1%, and with HC levels around 200 ppm. Unfortunately, it took a long time for industry and legislators to come to terms with the excess of emissions produced during cold start and warm-up, and to accept that most urban journeys are short and start with a cold engine.

Catalyst Technology

Catalyst technology has only recently started to cope with this area of operation, and even using platinum, which "lights up" at lower temperatures than other noble metal catalysts, early types of catalyst still allowed significant unmitigated emissions to escape before becoming effective. Fig 2 shows the rate of warm-up of a typical catalyst during a test using the American Federal Test Procedure (FTP), and it can be seen that the catalyst temperature does not reach $300^{o}C$ until around 100 seconds has elapsed.

The result, as the recent Vehicle Fleet Emissions Control Strategy (VFECS) work by the Ministry of Transport (MoT) has shown, is that exhaust gas pollution in urban corridors cannot necessarily be reduced by the "magic bullet" of fitting even recent generation emission controls. To be effective, catalysts have preferably to be pre-warmed, and also fitted as close as possible to cylinder heads. They also require minimal thermal inertia.

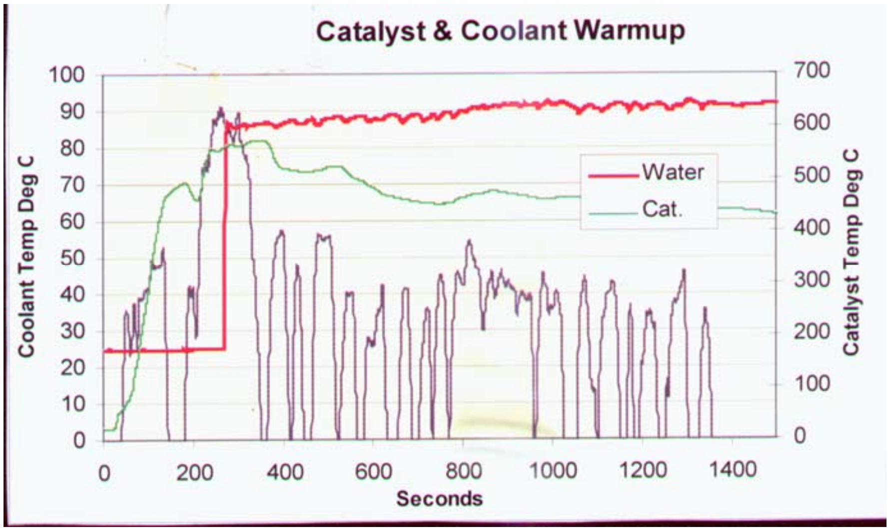

Fig. 2. Catalyst & Coolant Temperature Changes over FTP Cycle

Oxides of Nitrogen (NOx)

The most significant change in engine and catalyst technology came with the recognition of the adverse effect of oxides of nitrogen (NOx) on the environment. NOx is a contributor, with unburned hydrocarbons and sunshine, to photochemical smog, a significant ingredient of acid rain, a greenhouse gas, and a destroyer of the ozone layer. Given carefully controlled combustion at close to stoichiometric fuel/air ratios, suitable catalysts can reduce the NOx content of the exhaust gases to nitrogen, and subsequently, with additional air, oxidise the HCs and CO. such catalysts are known as three-way catalysts from their triple action, and associated with them are sensors in the exhaust gas stream linked to electronic fuel injection to maintain the required closely defined ratio of fuel and air. There are adverse effects associated with the fuel/air ratio being close to stoichiometric – combustion temperatures are high, which tends to increase the generation of NOx, and as a consequence, yet another technology has been introduced, exhaust gas recirculation (EGR). EGR simply dilutes the charge in the cylinder with an inert gas, thereby lowering the combustion temperature reducing NOx generation. Fuel economy also suffers.

Early catalysts were generally of two types: monolithic ceramic honeycombs in a metal case; or metal containers of ceramic beads, In both cases the ceramic was coated with a thin layer of a “wash” in which the catalytic metal was dispersed, and which, after being fired on to the ceramic, presented a suitably extended area of catalytic surface to the exhaust gases as they passed through the containers. More recently, metallic substrate catalysts have found favour because of low thermal inertia, and alternatives to precious metal catalyst materials have been researched over many years – cerium oxide is showing promise in recent research.

Legislators have steadily reduced the legal limits of emissions over time. Table 1 shows how the USA levels reduced over a 20 year period since the first tentative measurements were made in 1960, followed by legislation in California in 1966. Across the Tasman, Australia is adopting the European legislation, the Euro 2 and Euro 3 standards, though not the European timescale – the European legislation will be adopted at later dates than in Europe. Each level requires improved (and more expensive) technology to reach the targets, especially Euro 3, which targets cold start and warm-up emissions. Table 2 shows the various measures required to reach Euro 2 and Euro 3, and the associated costs in Australian dollars – Euro 3 technology costs nearly twice as much as that required for Euro 2.. For Euro 2, The CO limit is 2.2 g/km, and NOx and HCs combined are limited to 0.5 g/km. Euro 3 separates NOx and HCs, requiring 0.2 g/km HC, and 0.15 g/km NOx, and allowing 2.3 g/km CO. The HC level is the significant number, as without effective control almost immediately after starting, this level cannot be attained.

Table 1

USA Passenger cars with gasoline engines 1960-1985

	Emission limits (CA = California)			Test Method	Remarks
Year	NOx g/km	HC g/km	CO g/km		
1960	2.55	6.58	52.1	(75FTP)	Sampling only
1966		3.91	31.7	(75FTP)	California
1968		2.91	31.7	(75FTP)	Federal 49 States
1970	(CA2.48)	2.55	21.1		
1972	(CA 1.86)	1.86	17.4	72FTP(CVS)	
1975	(CA 1.92)	0.93 (CA 0.58)	9.3 (CA 5.6)	7SFTP(CVS)	
1977	1.24(CA 0.93)	0.93(CA 0.25)	9.3	,,	
1980	1.24(CA 0.77)	0.25(CA 0.24)	4.3	,,	
1981	0.62(CA 0.43)	0.25	2.1	,,	up to and inc!. 1985

Table 2 also demonstrates the types of technology becoming necessary to meet the latest emission standards. As the complexity of emission control systems increases, together with the potential to malfunction, so the regulators are starting to require on board diagnostic systems to alert the vehicle operator that servicing or repair is necessary.

Shades of Big Brother also suggest it is practicable for a sick vehicle to notify enforcement agencies that it should not be on the road, and to keep a record of just how far it has traveled in a sick state, in case the need for repair is ignored.

The attraction to vehicle manufacturers of clean alternatives to the petrol engine is obvious, and at one time the diesel engine was looked on as a possible alternative. Today, the exhaust of a diesel engine is looked on with more disfavour than even that of a petrol engine, and there is intensive ongoing research into technologies that can clean up diesel exhaust gases.

Table 2

Data extracted from a 1995 study for large (upper medium) car conversion costs to various levels of emission reduction from a Euro 1 base, converted to A$

Emissions Reduction Technology*	***Costs of Technology (A$)***	
	Approx Euro 2	***Approx Euro 3***
Improved electronic engine control	4	6
Exhaust gas recirculation (EGR)	39	38
Im roved and low lioht-off wash coats	9	19
Greater catalyst loading	9	19
Dual oxygen sensors	54	54
Improved fuel preparation and injection	37	61
Auxiliary air injection	73	73
Air assisted injectors	15	15
Double wall exhaust pipes	9	9
Close coupled catalyst	110	
Heated catalyst		292
Research and development	131	309
Business support (included in above)	23	43
Total	490	896

- Note: **multiples of some technologies are needed**

Diesel Emission Problems

The excess air combustion conditions of diesel engines result in very low emission levels of HCs and CO, and until the adverse effects of NOx were realised, diesel exhaust was considered to be relatively harmless. Once NOx emissions from diesel engines were recognised as a problem, the halo surrounding diesel engines rapidly dimmed. It became even dimmer once it was realised that controlling NOx in diesel exhaust gases was going to be difficult, as the three-way catalysts used on petrol-engines vehicles would not reduce oxides of nitrogen in an oxygen-rich atmosphere.

For a while, it appeared that the only technologies applicable to diesel engines that would reduce NOx emissions were EGR, by reducing combustion temperatures, and better control of combustion, using much greater injection pressures, electronic injection control and increased air swirl in the combustion chamber. Indirect injection engines, with higher compression ratios and prechamber combustion, were worse than direct injection engines, but, until direct injection engine speeds could be increased by new technology, light diesel vehicles were limited to indirect injection. Worse was to follow for diesel engine protagonists, as evidence started to mount that the carbon particulates more or less inherent in diesel exhaust gases were a significant health hazard.

How significant was not realised for some time. Eventually, epidemiological research in urban areas in the UK and the USA gave indication of the scale of the problem. Table 3 shows the estimated marginal external health cost per litre of diesel fuel used in various types of diesel vehicles in the UK in 1993, when such vehicles had almost no emission control systems affecting particulate emissions.

Table 3

MARGINAL EXTERNAL HEALTH COST BY VEHICLE TYPE PER LITRE

all prices refer to 1993

Vehicle Type	Total Damage £ million.	Fuel sales/million litres	Marginal external Cost/litre pence
Diesel Car	840	2520	33
Leaded Petrol Car	6375	15000	43
Buses and Coaches	1659	1260	132
Heavy Goods Vehicles and Light Goods Vehicles	9255	10220	91

Source: Calthrop, 1995.

In terms of the average marginal external health cost of each litre of each type of fuel used in the UK, the data is given in Table 4. At the time that data was prepared, in 1993, the marginal cost of each litre of diesel fuel was significantly greater than the actual purchase price of the fuel, and it is hardly surprising that the legislators sat up and took notice. The data in these tables was calculated by a group of economists based at University College in London, and, as might be expected, the UK Department of the Environment, Transport and the Regions set up its own study. The Department’s figures were lower than those of the research group, but not significantly so.

Fig.3 shows how the latest Euro 2 and Euro 3 emission requirements are making it increasingly difficult for engine manufacturers to produce diesel power plants that meet

Table 4

MARGINAL EXTERNAL HEALTH COSTS PER LITRE OF FUEL

All prices refer to 1993

Fuel Type	Total External Cost/ £ millions	Fuel sales/ million litres	Marginal External Cost per litre (p).
Diesel	11,765	14,000	84
Petrol	6,375	15,000	43
Unleaded	1,569	17,000	9
City Diesel			33

Source: Calthrop, *1995.*

Note: The figure with respect to City Diesel is merely an estimate based on advertised reductions in certain pollutants when compared to ordinary diesel.

such standards. Concern initially was about sub-10 micron particles, but, over the last 8 years, that concern has been directed to even smaller particulates, and the latest work by the US EPA has confirmed the adverse health effects of particulates, but has suggested that it is particles smaller than 2.5 microns that are the most significant.

The difficulty of dealing with NOx and particulate emissions from diesel engines has led to suggestions that the diesel engine should be eliminated as a prime mover. However, intensive research has shown that, with low sulphur fuels containing less than 50 ppm of sulphur, sophisticated catalysts and particulate traps will be able to cope at Euro 3 levels. Catalysts able to reduce NOx emissions in an oxygen-rich atmospere have been developed (with spin-offs for the new direct-injection petrol engines), which, combined with EGR and particulate traps, will meet the requirements. For example, Volvo are fitting a system which is reported to reduce CO and HC emissions by 99%, particulates by more than 90% and NOx by 50-60% without negative effects.

However, the claim for absence of negative effects may be incorrect. In America in 1998 new more stringent emission standards came in, akin to the latest European standards, and the effect, compared with previous standards, was an increase in fuel consumption. The industry was equal to the challenge – Caterpillar, Cummins, Detroit Diesel, Mack, Navistar, Renault and Volvo were subsequently discovered to have fitted what were termed “cheat devices” to engines which switched off the emission control systems during highway driving as a means of restoring fuel consumption. Unfortunately for the industry, the cheat devices came to light, and, in line with previous breaches of regulations, fairly stiff penalties resulted , including a fine of $83.4 million, and earlier imposition of yet later regulations which will cost the industry upwards of $1 billion.

The ramifications of this affair are now affecting the Australian regulators. American manufacturers do not make engines complying with European standards, and have claimed that Australia should accept engines complied to the 1998 American regulations instead of Euro 2. However, the removal of cheat devices has been carried out under an agreement with the EPA, not a regulation, and, as the Australians want to bring in the overseas standards by reference in their legislation, there are problems in incorporating into Australian law what has become a “gentlemen’s agreement” between the US industry and the EPA.

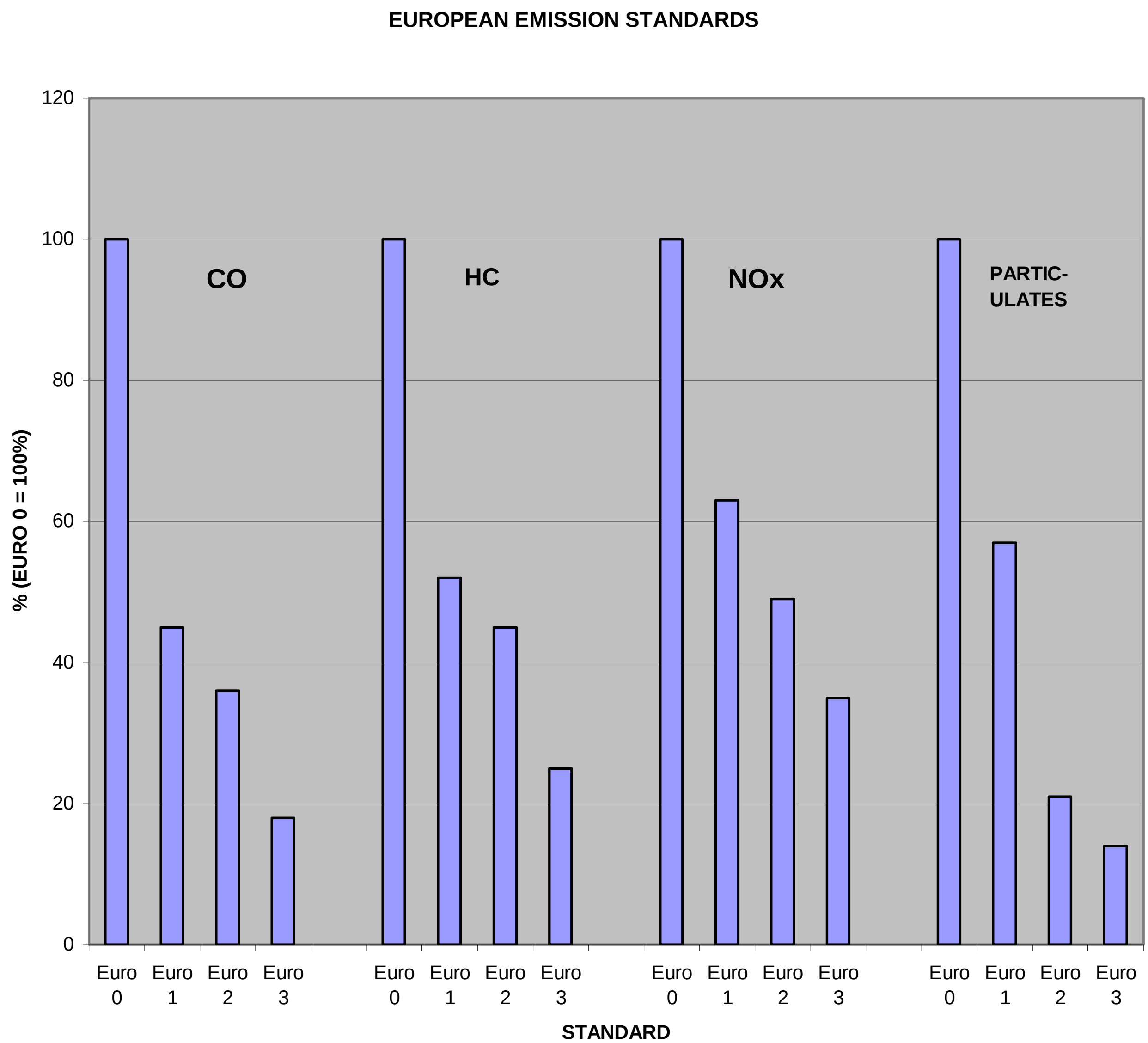

Fig. 3 – Euro Diesel Emission Standards

Because of the potential effects on fuel economy, there have been suggestions that the Australian legislators will not proceed with the Euro 3 regulations, but move directly at a later date to the next stage of the European standards. Whatever happens, the cost of compliance will be that diesel vehicles will become more expensive as exhaust aftertreatment becomes more sophisticated, and the extra costs will feed through into the New Zealand market. Whether the costs are justifiable remains to be seen, as no-one has yet looked in detail at the environmental and health costs imposed by particulate emissions in this country. The overseas data is based on epidemiological studies in large conurbations, and application of the data here may be ill-advised. The Ministry of Transport VFECS studies have demonstrated that vehicle operation rather than the application or absence of exhaust emission control systems is more significant in the urban corridors where New Zealand has an exhaust emissions problem. It may well be that we shall be paying, without option, a good deal more for our vehicles than can be justified by the effects that they have on air quality in most of New Zealand.