Cost implications of various Euro 4 and 5 after treatment solutions for heavy duty diesel vehicles

Book Section

Cost implications of various Euro 4 and 5 aftertreatment solutions for heavy duty diesel vehicles

James P. Warren
The Open University, UK
Paper no. C588/015/2000.

Synopsis

This study is firstly a short review of the types of exhaust systems predicted for Euro 4 (2005) and Euro 5 (2008), particularly focussed on the effects of combined NOx (nitrogen oxides) and PM (particulate matter) aftertreatment systems. Secondly, it explores in detail the implications of using a liquid secondary water-based fuel of urea on board heavy duty diesel vehicles in Europe as a basis for NOx reduction via selective catalytic reduction (SCR). Some of the main points that become apparent when using integrated SCR systems are: the potential costs of increased urea production in Europe (including possible fuel taxation), refuelling issues, secondary fuel cost, logistics of urea supply, and cost of implementation of the urea fuel delivery method. From the original equipment manufacturers view, the hardware cost will be increased substantially when compared to current silencer systems. From the vehicle owner's point of view, the possibility of large running cost increases is not desired, and the system solution cost and its benefits must ultimately be acceptable. This paper will attempt to put the life-time costs of various systems within perspective in order to assess the feasibility of implementing selective catalytic reduction systems (SCR) Europe wide for the near future.

1 INTRODUCTION

Within Europe, legislative emphasis has been increasingly placed on lowering emissions of heavy duty diesel (HDD) vehicles and this currently effects the HDD vehicle sales in Western Europe which is estimated to be nearly 278,000 trucks per annum (2000) (1). Currently European emissions legislation is the main driver for lowered tailpipe emissions - focussed on both NOx and PM abatement, as shown in Figure 1. For the far future (2008) diesel powered trucks will most likely need to achieve emissions of less than 2.0 g/kWhr NOx and 0.03 g/kWhr PM under the so-called EU 5 requirements requiring fittment with advanced aftertreatment devices such as a diesel particulate filter (DPF). The standards translate to engineering targets which may be substantially lower depending on the manufacturers in-house requirements – for example the target for NOx may be as low as ~1.8 g/kWhr NOx to ensure compliance. To date there are various systems being tested under trial conditions with promising results, with approximately some 10,000 advanced aftertreatment systems fitted to date in Europe. The majority of these are continuously regenerating diesel particulate trap devices which combust PM by utilising small quantities of nitrogen dioxide, produced upstream by means of a platinum based catalyst (2). Known and trade-marked as CRT™ systems (Continuously Regenerating Trap), a substantial number of these devices have been running in Sweden since 1994 (and some before this) with individual vehicles having accumulated mileages of $\geq$ 0.5 million kilometres (3). The balance of these systems are called catalysed soot filters (CSF), which have the catalyst coating integrated onto the trap surface, thus potentially removing the need for a separate catalyst module. CSF systems are made by Engelhard (4) and generally known as DPX™. The CSF coating contains precious metal(s) in the coatings, so the units are susceptible to poisoning, etc, just as any highly active Pt-based catalyst device (4-5). Due to the stringent fuel quality readily available (maximum fuel sulfur level has been 10 ppm S since 1991, but typical values are 2-5 ppm S) Sweden is a good candidate for testing catalytic devices which are particualrly sensitive towards sulfur (3). However, even though these filters systems are both extremely efficient for reduction of PM, hydrocarbons (HC) and carbon monoxide (CO) they alone will not meet the required levels of NOx proposed for the future within some additional input – engine modifications and perhaps the use of other catalyst systems. Legislation is the main driver for lowered NOx and PM emissions; these proposed levels are summarised for the EU and the US (federal) in Table 1.

Table 1: Summary of likely emissions targets for heavy duty diesel vehicles.

Euro Stage/Year	EU III, 2000	EU IV, 2005	EU V, 2008
NOx (g/kWhr)	5.0	3.5	2.0
PM (g/kWhr)	0.1	0.02	0.02
Federal regulations	Current, 2000	2004	Proposal, 2007
NOx (g/bhphr)	4.0	2.5	0.2
PM (g/bhphr)	0.1	0.1	0.01

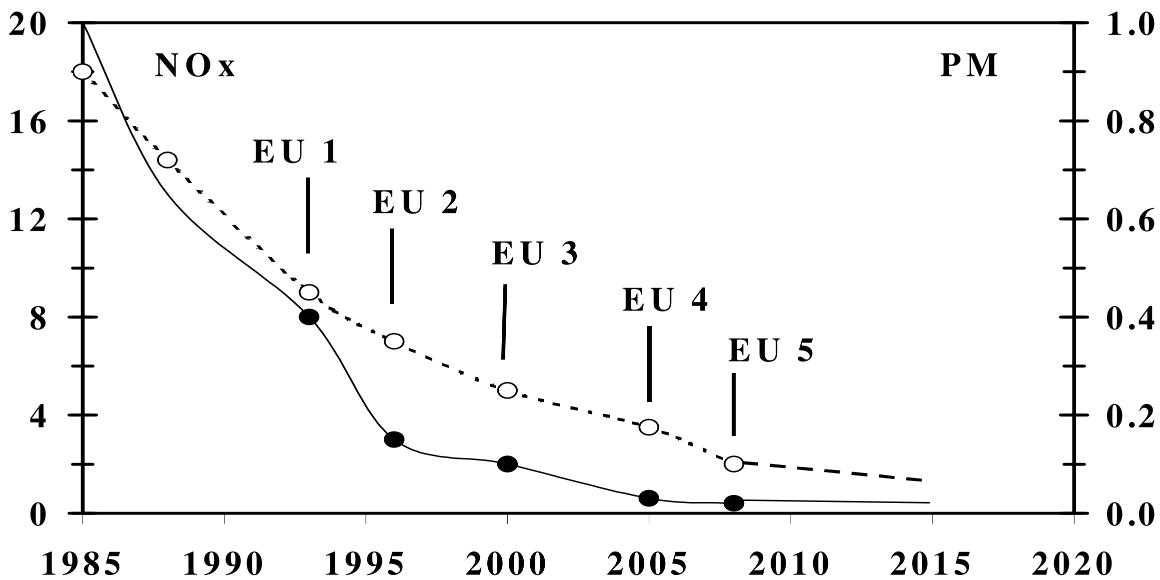

Figure 1: European heavy duty diesel legislative trends (in g/kW hr).

If one converts the federal NOx limit values to g/kWhr, it can be observed that the EU and US limits are nearly the same for 2000-2005, with the US being significantly more severe for the year 2007. Achieving 0.27 g NOx/kWhr will be a very demanding target, even if significant engine modifications along with the most advanced SCR systems are in place. To reasonably forecast current EU based NOx and PM emissions limits for a hypothetical EU 6 emission one can extend current and previous limits to estimate future levels. An approximate NOx level of ~ 1 $\pm$ 0.5 g/kWhr, which translates to a 50% reduction in the limits from 2008 is predicted in Figure 1 (see dashed line with open symbols). When considering PM target values, the EU legislation has been very pro-active in setting the lower than expected 0.02 g/kWhr target level (see Fig. 1, filled symbols and solid line). Beyond this timeframe, targets of 0.01 PM or even lower (either grams per kilowatt or horsepower hour) will require new methods of measurement to increase accuracy and reproducibility of the prescribed test procedure (6). At this stage it is difficult to precisely predict the NOx and PM emissions limits for the very far future, but clearly a lowering of emissions levels is most likely set to continue. This must be carefully thought out as there are certain technology constraints and other external factors to be considered such a ‘best available technology for acceptable cost’.

Diesel fuel quality is also set to change considerably. Current proposals indicate that the EU will enforce a maximum level of 50 ppm sulfur (S) from 2005, with perhaps a trend to lowering the sulfur in both diesel fuel and even lubricating oil substantially beyond this timeframe. In the US, the Environmental Protection Agency (EPA), has proposed new standards for diesel fuel sulfur, namely, a maximum of 15 ppm S beginning in June 2006 (6). These changes in fuel specifications are required to some extent to ensure long life times of the catalyst systems, as well as substantially reduce a large portion of sulfate derived PM emissions from all diesel vehicles. The fuel sulfur level has been found to have a severe effect on the PM emissions due to high activity of the Pt-based catalyst, which when above 25 ppm S (in the fuel) causes the future PM emissions limits to be exceeded (8) when fitted with a trapping device. Similarly, another study found that 40-60% of all the available fuel sulfur is effectively converted to sulfate, therefore increasing the overall PM mass per power time(4-5). This effect, along with the fact that many precious metal based aftertreatment systems (e.g. catalysts, catalysed traps, NOx storage devices, etc.) are sensitive to S-poisoning have brought about the effective reduction of sulfur within the diesel fuel feedstream.

2 AFTERTREATMENT SOLUTIONS - REVIEWED

Currently, it seems likely that Euro 4 emissions limits will be met by the use of engine modifications such as cooled exhaust gas recirculation (EGR) possibly coupled with some type of particulate filtration system (9). This approach will rely on the DPF being particularly effective for PM removal, as well as the EGR system being able to reduce the NOx significantly with minimal impact on fuel consumption. An alternate route using NOx ‘trapping’ or storage components within the catalyst seems less likely, for a variety of reasons. Firstly these catalyst coatings are even less sulfur-tolerant than DPF devices, and secondly the NOx release/conversion mechanism presents further difficulties in the combined engine/catalyst management of the regeneration step. Furthermore, unacceptably large catalyst volumes would be required to store the relatively high amounts of nitrogen oxides that would be released from a HDD engine. A typical EU 4 engine and aftertreatment hardware layout will probably include the following items integrated in such a way to maximise fuel efficiency and good transient response – DPF, cooled EGR via the high pressure/short route, optimised combustion (inter- and aftercooled), with a single stage wastegated, turbocompound configuration (10). There is also the possibility that common rail fuel injection may replace electronic unit injectors, but this is unknown (10), partly due to the question of durability of the rail hardware under heavy duty engine application. Other layout variations may involve variable geometry turbine or a more integrated form of EGR (10). Even if PM limits can be met without the use of a trapping device, it seems that the trend is to incorporate a DPF in order to further reduce the ultra-fine particle emissions. There is a body of evidence gathering which indicates that removal of PM_{10} and particles below this diameter size can be removed effectively with the use of a DPF (2, 9, 11).

The other major solution for NOx/PM control would be based on SCR methodology. Catalysts based on stationary SCR systems have be used for various HDD trucks and engines over the last 4-5 years on an experimental (12-13) and trial basis (14-15). The main principle of SCR utilises the activity of ammonia to remove NOx where the ammonia is derived from urea. Urea is a water based solution which can, in theory, be stored relatively safely and easily on board most heavy duty diesel vehicles. Urea content is typically 32.5 % (14) and tank size would be expected to be about one-tenth of the diesel fuel tank capacity (15). Associated major hardware that would be expected with the SCR catalyst units would include: a high grade plastic, or steel, urea tank, urea fuel lines, urea pump with metering capability, urea injector, and the injector control unit (14-15). Control of the urea injected could either be based on a relatively simple ‘look-up’ table which would base the NOx emissions on the engine running condition, and inject urea accordingly. A more advanced control system would utilise the engine operation map parameters (nitrogen oxides emissions, fuel flow and intake air flow) coupled with the catalyst conversion efficiencies (exhaust gas flow rate, catalyst temperature and species converted) to drive the injector effectively to reduce the maximum amount of NOx (14). Other urea related hardware expected on-board the vehicle would be: tank level sensor, tank indicator (on dashboard) and possibly tank heater/insulated delivery lines for cold weather situations (14). In place of a tank heater to prevent urea freezing occurring, additives, in small quantities, could be added on a seasonal basis to depress the freezing point (15). Other sources of the active component, ammonia, could be ammonium carbamate solid, ammonia liquid or ammonia gas. Each source of ammonia has various limitations and advantages; only urea (as an aqueous liquid) is considered in this work.

One of the key issues for the future yet to be implemented is the need for on board diagnostics (OBD) required by EU legislation for future HDD vehicles. As with OBD for passenger cars, the OBD system must be able to ‘monitor’ the effectiveness of the aftertreatment device and report the results to the main electronic control unit (ECU). The European Commission will in due course issue further proposals about the new rules for OBD systems for HDD vehicles, but at this point in time it is difficult to know exactly what type of system would be employed. Trial systems have included prototype NOx sensors, which correlate well with NOx analysis (15). Thus, if dependable, inexpensive NOx sensors are readily available, their use within the OBD monitoring system could be envisioned. Clearly, some of the total aftertreatment system cost must include some provisional expense for the OBD function, which ultimately may be ‘visible’ to the driver as some form of malfunction indicator light (MIL) on the dashboard. The MIL would also be then linked to the ECU in order to store certain failure codes and their frequency. In theory it may be possible to access the stored memory codes remotely using telematics in order to reduce the vehicle down time, but again this advanced technology would incur some expense. Lastly, the OBD system, working together with the ECU, must be able to ensure that exhaust treatment device is not defeated, or reduced in its control of emissions. In other words, if the system continues to fail to control emissions, or if the secondary fuel is depleted, the system would most likely be required by legislation to shut down the engine as long as the safety of the vehicle and driver were not compromised. In a similar way, the DPF must also be OBD compliant. The system must be guaranteed to regenerate frequently enough to ensure high PM conversion (whilst meeting legislated emissions limits over the various testing cycles), acceptable back-pressure and minimal fuel consumption increases. If the DPF would suffer a failure due to thermal shock, vibration or some other mechanical means then the diagnostic system would need to detect this and register it in some way and take appropriate action as required.

3 COST ASSESSMENT OF VARIOUS SYSTEMS

This section is an overview of likely scenarios or possible routes to emissions control after ~2008 (and beyond) from a technology feasibility standpoint as well as an assessment based on a calculated (cost) methodology. The assessment attempts to place explicit values on the aftertreament devices, fuels and vehicle usage for both the SCR system and the EGR + DPF system. NOx trapping devices have not been considered but currently do not look promising under HDD conditions due to lack of efficiency (20). Similarly, active de-NOx (NOx conversion via HC injection) and plasma will not be considered within this paper. By placing a value on the device, as well as other factors, calculations can show which system is most economically favourable for use under certain conditions based on a discounted cost method. It seems likely however that eventually all future diesel vehicles will contain some type of particulate filtering device due to increasingly low standards and the pressure to reduce not only PM mass but also PM aerodynamic particle sizes.

Briefly, for EU 4 there is a possibility that by tuning the HDD engine towards low PM emissions, high fuel economy and high NOx emissions, that the cost of the fuel saved (when compared to a baseline case of EU 3/EU 2) can result in a cost savings. Thus various scenarios are dependent on the following variables which are listed in Table 2.

Table 2: Cost assessment items and variables.

Item or Variable:	Estimated item cost (€):
SCR system	3100
EGR plus trap system	2500
High grade urea	0.22 per litre
Diesel fuel	0.68 per litre
Fuel consumption	34 litres/100 km
Urea consumption	3% of fuel consumption
Annual mileage	50,000-300,000 km/yr

Previous results using a cost assessment methodology have shown that depending on the cost of the device and the yearly mileage driven that the device can pay for itself within a period of 1 year (16). This was found to be true if the vehicle accumulated ~150,000 km/year assuming various factors including that the vehicle was in the ‘heavy’ class (e.g. 34 L/100 km fuel consumption) with a good saving on fuel due to SCR use (e.g. ~7%). At that time diesel fuel prices were rather lower than currently, and this has a significant impact on a break-even analysis. Medium duty vehicles (MDV) were found to not be economical for SCR adaptation, mainly due to 2 important factors, when compared to the ‘heavy’ class of truck. These were the relatively good fuel consumption of MDVs coupled with the low yearly mileage typically observed for delivery vehicles (16, 17). In this study, the fuel price has been updated based on a simple average fuel price for the EU-15 countries for the second half of 1999 (18) with all taxes included (e.g. actual retail pump price). A weighted average based on fuel use in each country would be more applicable, but conversely fuel sales to vehicles based outside of that country are difficult to estimate. The lowest prices per litre in 1999 were observed to be 0.53 €, with the highest value being 1.11 € (18). By looking at the long-term trends, future fuel prices can be estimated to be ~17 to 21 % higher in 2008 than 1999. This linear trend gives an estimated fuel cost of 0.90 €/litre in 2008. Thus for a HD truck running about 100,000 km/yr the device will be paid for in just over 2 yrs (see solid line in Figure 2). Using 2008 fuel prices, the device would be paid for within a very rapid 1.5 yrs when accumulating 100,000 km/yr. Clearly, fuel price sensitivity must be taken into account. The base interest rate was set at 6%. No increase in fuel consumption due to increases in back-pressure was assumed for the SCR cases.

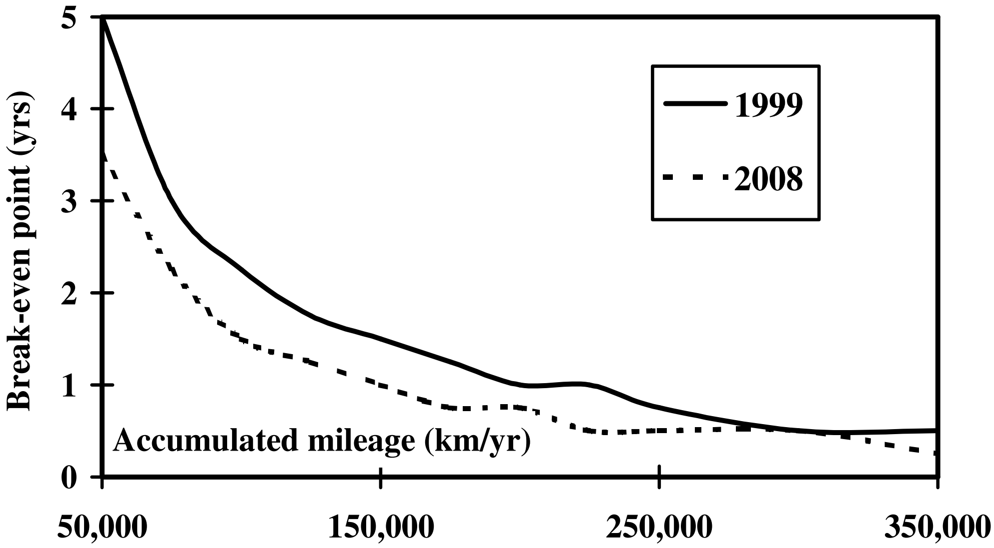

Figure 2: A break-even point analysis as a function of yearly vehicle mileage and increasing fuel price. See text for full details.

Estimating the cost of the aftertreatment device can be a difficult task, but the US EPA predicts the cost to be approximately $1000-1600 per vehicle for an advanced system (7). Although it is unclear whether this system would contain both NOx and PM reducing measures, the very low US emission targets currently proposed seem to indicate both a particle trap and some type of SCR will be required. In this study the device and all associated equipment was set to be 3100 €, with two other costs investigated – one much lower (1500€) and one ~33% higher (4100 €). It was thought that even a combined system would have some cost savings in production as some exhaust concepts are highly modular and various integrated systems have shown emissions benefits (19-20).

Figure 3 demonstrates the device cost sensitivity for the 3 levels of pricing- half the base cost, the base cost and 1000 Euros above the base cost. For a typical HD truck, accumulating 100,000 km/yr, the break-even point was found to be just under 1 yr, 1 ½ yrs and 2 ¼ yrs for the 3 cases, respectively. Even the most expensive device will pay for itself in fuel savings in ~5 yrs for the lowest yearly mileages. If the device is as inexpensive as EPA predicts, then rather short investment times are observed, even for smaller (rigid body) MD trucks which have much better fuel consumption when compared to the larger articulated trucks (17). MDVs will be discussed in more depth later in this paper.

Final urea cost at the pump for the consumer is also currently unclear, and previous work (16) have employed a price of about a quarter Euro per litre, or roughly 10X the current bulk market rate of urea for sale as a commodity (for use in fertiliser, chemical industry, etc.). This seems to be a reasonable starting point, although SCR use may require a higher purity level if deemed critical by the exhaust system components (e.g. sensors, catalyst coatings). Furthermore, governments may use the introduction of a 'secondary fuel' tax primarily based on pollution control as a means to implementing a new tax based on potential for environmental and health effect damages. In other words the cost of urea could be much higher than previously assumed.

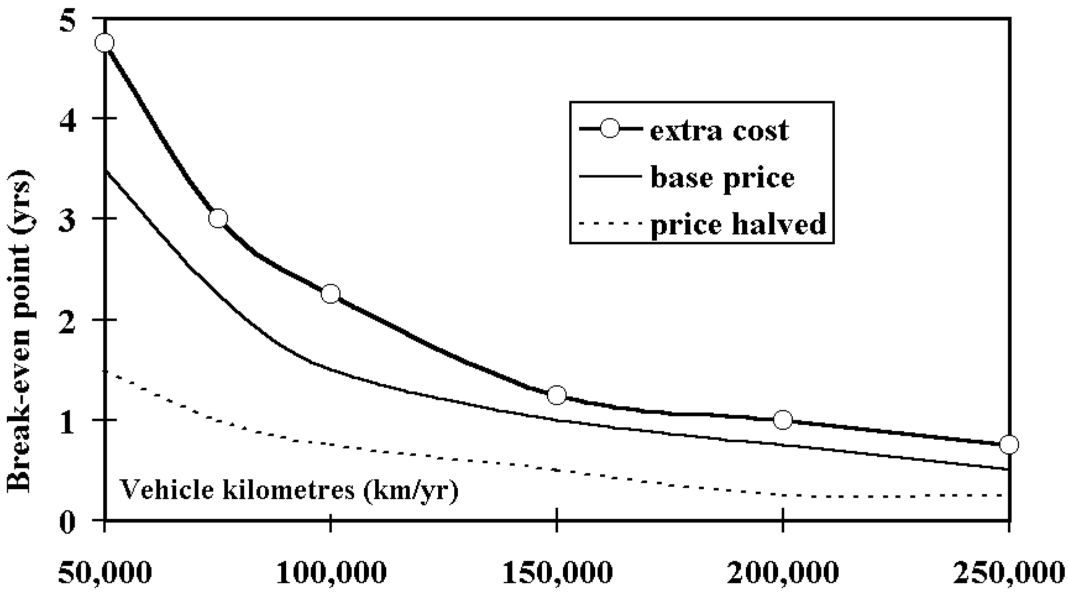

Figure 3: Aftertreatment device cost varied as a function of vehicle kilometres.

Urea price was varied in this work from half the expected cost (0.11 €/litre) to double the cost of diesel fuel in 2008 (1.8 €/litre) in order to observe the trends associated with a secondary fuel cost as shown in Figure 4. The figure plot depicts a break-even analysis for a HDV running either 50, 100 or 150 k km/yr as a function of urea cost. At the lowest urea prices break-even points (BEPs) are observed for the high annual mileages from 1-1 ½ yrs, with low mileages (50 k km) needing more than 3 yrs to break-even. The time to reach the BEP rises steadily with urea price, becoming exponentially costly when prices approach 1-1.5 €/litre, especially for low annual mileage vehicles. If urea price would become twice as costly as diesel fuel, then the time to break even would be a minimum of 8 yrs, for the very highest mileage trucks, with BEPs of 14 yrs for lower mileage vehicles.

Other costs, such as installation of new urea tanks at fuel stations, are not considered here due to space limitations. It is assumed with a new large truck population in 2008, that even in the maximum urea demand case, only about 0.2% of the total global urea would be needed for trucks based in Europe (15). This has been estimated as ~ 300,000 tonnes/yr. Urea pumps and fuel nozzles are predicted to be separate supply lines from the diesel to avoid accidental mixing and cross-contamination. Dual-fuel nozzle supply systems are not expected as only the newest vehicles would require urea initially; also emulsions of urea-diesel fuels could create problems if combusted accidentally within the engine, or if cross-contaminated within the storage tanks.

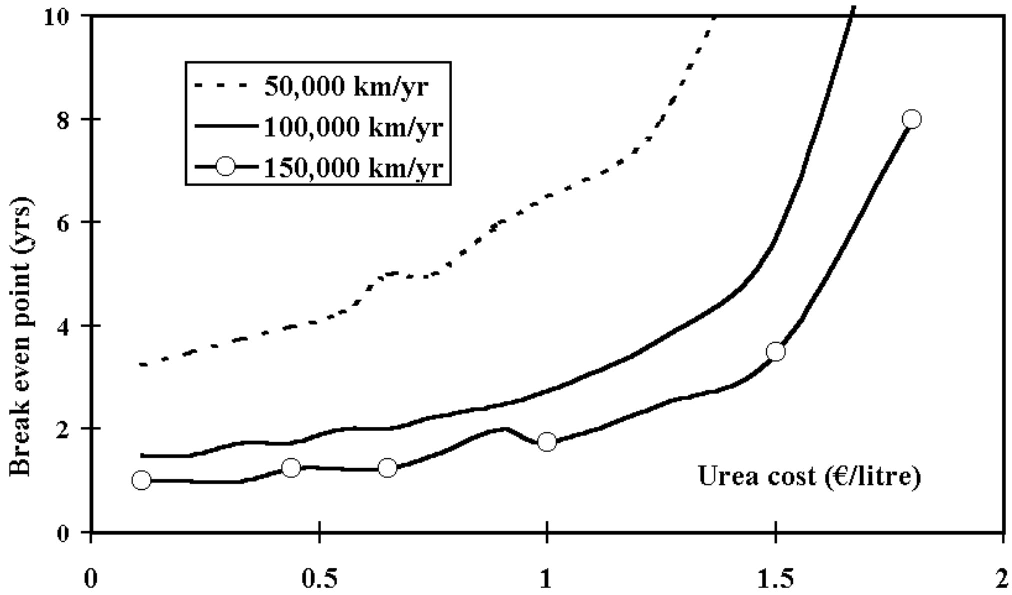

Figure 4: Break-even analysis for urea cost at various yearly mileages.

There is a significant fuel consumption difference in HDD and MD vehicles, with an average UK consumption of 36.7 and 34 l/100 km for the two classes respectively (17). In the MDVs classes, most vehicles fall into the smaller classes (e.g. < 7.5 and 7.5-14 ton, GVW) which comprise some 60% of all trucks in the UK (17). For this reason MDV fuel consumption was defined as 22 l/100 km for the year 2008, with current average consumption being ~ 25. MDVs tend to have much lower annual mileage than HDDVs, typically 39,000 km/yr versus 96,000 km/yr (17). Previous work showed that MDVs fitted with SCR would probably be too costly due to the low mileages accrued, relatively good fuel economy and the cost of the device (16). Although the analysis in this work yields similar results, it may be a matter of opinion as to whether or not SCR is cost effective for MDV.

Figure 5 shows a comparison of MDV vehicle fitted with SCR (dotted line) as well as a HDV with SCR, with typical fuel consumptions, and fuel costs of 2008 for various annual mileages. Clearly, the HDV device reaches the BEP before the MDV, but the 2 scenarios are rather similar as the device cost (base case level) has been held constant. If the device cost is lowered significantly to the half-cost level, the pay back time is just over 2 yrs for 50 k km/yr (see Fig. 5, solid line with open circles). Furthermore, if applying today's average annual mileage values (e.g. 39 and 96 k km/yr) BEPs are indicated as 3 ¼ yrs and 1 ¾ yrs for MD and HD diesel trucks, respectively when using the half-price cost for the device for MDVs (base cost for HDD). Clearly the exact lifetime of the truck is of great importance to the investor if the equipment costs are to be recouped rapidly. EPA estimates truck lifetime at 30 years, but it is unclear whether most trucks stay in the possession of the original owner/purchaser or if the vehicles are sold on after few years. Finally, note that whilst diesel buses are excellent candidates for SCR fittment, this topic has not been addressed here as European bus sales are expected to account for only 8-10% of all HDD vehicle sales.

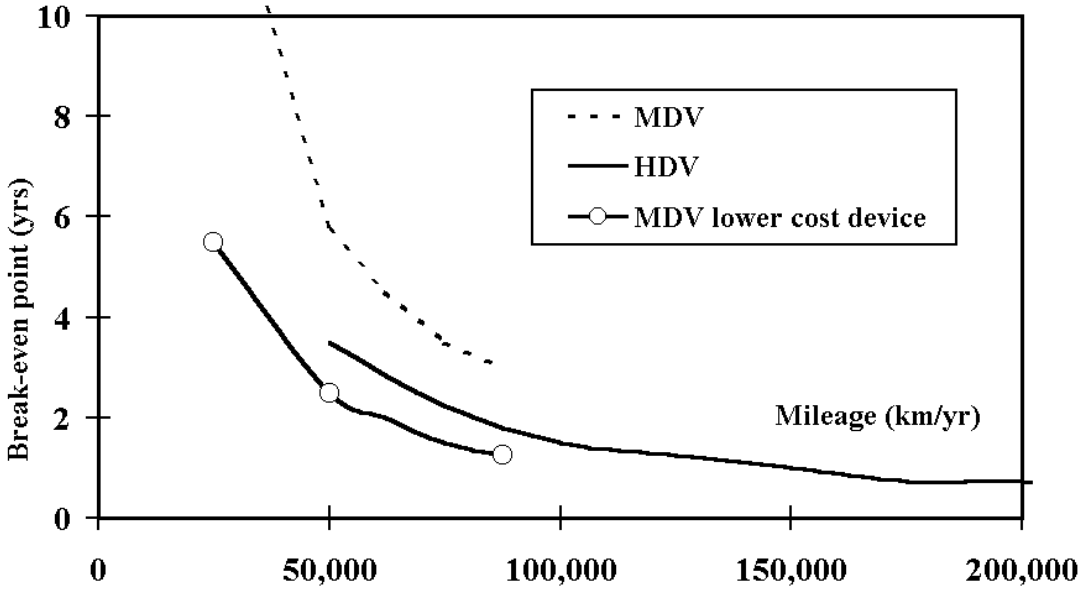

Figure 5: Break-point analysis comparing the case of heavy and medium duty diesel vehicles with possible SCR system fitted.

4 CONCLUSIONS

Although it is not yet clear which type of aftertreatment system will be used in 2008 and beyond, one can make rather good and reliable estimates of what various scenarios might be based on fuel consumption, relative emissions, basic device investment costs, and state-of-art technology applied to exhaust treatment. Here a selective catalytic reduction of nitrogen oxides by the use of urea and catalysts, along with particulate filters fitted as standard, was used to estimate the Euro 5 emissions scenario for heavy duty trucks in Europe.

The calculation method, based on a simple discounted cash flow basis, shows how quickly a relatively expensive item of aftertreatment can pay for itself. High annual vehicle kilometres, a low device cost and relatively high (diesel) fuel prices result in rapid break-even points. Typically these were 1-2 years long for complete return on the money invested.

High urea prices result in poor returns for the SCR systems, especially for smaller vehicle classes with low annual mileage. Conversely smaller vehicles could benefit from SCR if the device price is half the estimated base cost, e.g. ~ € 1500, yielding a break-even period of just over 3 years. Larger vehicles with poorer fuel economy and higher annual mileage will still benefit financially with SCR fitted as long as urea fuel price is not higher than ~ € 1 per litre. The methodology developed in this work should be applicable to other similar scenarios, such as the United States' heavy duty trucking industry, or even to light duty diesel vehicles such as passenger cars and/or light commercial vehicles.

REFERENCES

(1) D Leggett (1999) World heavy commercial vehicle forecasts, the outlook for heavy truck sales, production and vehicles in use to 2005, 1999 edition, The Economist Intelligence Unit, London SW1Y 4LR, UK.

(2) JP Warren, R Allansson, PN Hawker, AJJ Wilkins, "Effects of after-treatment on particulate matter when using the continuously regenerating trap", Inst. Mech. Eng., Diesel Engines-Particulate Control, pages 45-55, paper no. S491/006/98 (ISBN 1 86058 164 1, Professional Engineering Publishing Ltd, London, UK).

(3) R Allansson, BJ Cooper, JE Thoss, A Uusimaki, AP Walker, and JP Warren, "European Experience of High Mileage Durability of Continuously Regenerating Diesel Particulate Filter Technology", SAE technical paper 2000-01-0480, reprinted in Diesel Exhaust Aftertreatment 2000, pages 159-164.

(4) U.S. Dept. of Energy, "DECSE (diesel emission control sulfur effects program) Phase 1 interim data report No. 4: Diesel particulate filters", (January 2000), available from the Office of Transportation Technology: http://www.ott.doe.gov/decse, [accessed 26/01/00].

(5) CY Liang, KJ Baumgard, JE Orban, JME Storey, JC Tan, JE Thoss, W Clark, "Effects of diesel fuel sulfur level on performance of a continuously regenerating diesel particulate filter and a catalysed particulate filter" (2000) SAE technical paper 2000-01-1876.

(6) M Ankowitsch, K Engeljehringer, W Schindler, P Zelenka, " Requirements imposed by the EURO 4 standard for emission measuring techniques for commercial vehicles" (translated from German), 20-21 May 1999, 3rd Dresden engine colloquium (ways to meet the EURO 4 exhaust emission limit values in truck diesel engines, Dresden, pp 84-93. Hochschule fur Technikund Wirtschaft Dresden, Bericthe und Informationen 1/99.

(7) EPA Regulatory announcement Proposed Heavy-duty engine and vehicle standards and highway diesel fuel sulfur control requirements, fact sheet EPA420-F-00-022, dated 17 May, 2000, by Office of Transportation and Air Quality. [Accessed from: http://www.epa.gov/otaq/diesel.htm on 9 June, 2000].

(8) R Allansson, CA Maloney, AP Walker, and JP Warren, "Sulphate production over the CRT™: what fuel sulfur level is required to enable the EU 4 and EU 5 standards to be met ?", SAE technical paper 2000-01-1875, reprinted from: Effects of fuels and lubricants for aftertreatment devices (SP-1546), 19-22 June, 2000.

(9) P Zelenka, H Aufinger, W Reczek, W Cartellieri, "Cooled EGR- a key technology for future efficient HD diesels", (1998) SAE technical paper 98190.

(10) RE Morgan, SP Edwards, AJ Nicol, ID Johnston, JR Needham, "A premium heavy duty engine concept for 2005 and beyond", (1999) SAE technical paper 1999-01-0831.

(11) P Zelenka, M Egert, W Cartellieri, "Ways to meet future emissions standards with diesel engine powered sport utility vehicles (SUV)", (2000) SAE technical paper 2000-01-0181.

(12) C Havenith, RP Verbeek, DM Heaton, P van Sloten, "Development of a urea deNOx catalyst concept for European ultra-low emission heavy-duty diesel engines", (1995) SAE technical paper 952652.

(13) C Havenith, RP Verbeek, "Transient performance of a urea deNOx catalyst for low emissions heavy-duty diesel engines", (1997) SAE technical paper 970185.

(14) N Fritz, W Mathes, J Zuerbig, R Mueller, "On-road demonstration of NOx emission control for diesel trucks with SINOx", (1999) SAE technical paper 1999-01-0111.

(15) W Miller, JT Klein, R Mueller , W Doelling, J Zuerbig, "The development of urea-SCR technology for US heavy duty trucks", (2000) SAE technical paper 2000-01-0190.

(16) C Havenith , W Cartellieri, P Zelenka, "Development strategies to meet Euro 4 and 5 emissions standards for heavy duty diesel engines", (1999) from Engine and Environment

99, Zero or near zero emissions ?, pollutant emissions versus CO_2 – conf. proc., Graz, 2-3 Sept. 1999, p. 159-178.

(17) "Transport of goods by road in Great Britain, 1999 – annual report of the continuing survey of road goods transport", May 2000, Department of the Environment, Transport and the Regions, London SW1E 5DU.

(18) Cronos database, file SIR3S, accessed from Eurostat within Theme 8 (environment and energy, heading SIRENE-energy statistics [via http://reads.dur.ac.uk/newcronos, on 15th August, 2000), source - the European office of statistics. Note- within this work the following exchange rates were used throughout: 0.66 £/€ 1 and US $ 1.62/ £1.

(19) GR Chandler, BJ Cooper, JP Harris, JE Thoss, A Uusimaki, AP Walker, JP Warren, "An integrated SCR and CRT system to meet future NOx and PM legislation", (2000) SAE technical paper 2000-01-0188.

(20) M Khair, J Lemaire, S Fischer, "Achieving heavy duty diesel NOx/PM levels below the EPA 2002 Standards-an integrated solution", (2000) SAE technical paper 2000-01-0187.