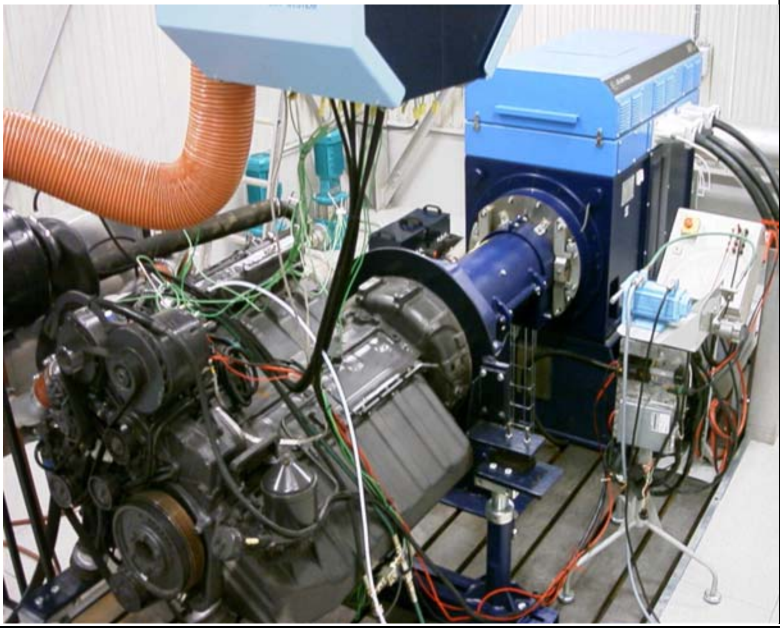
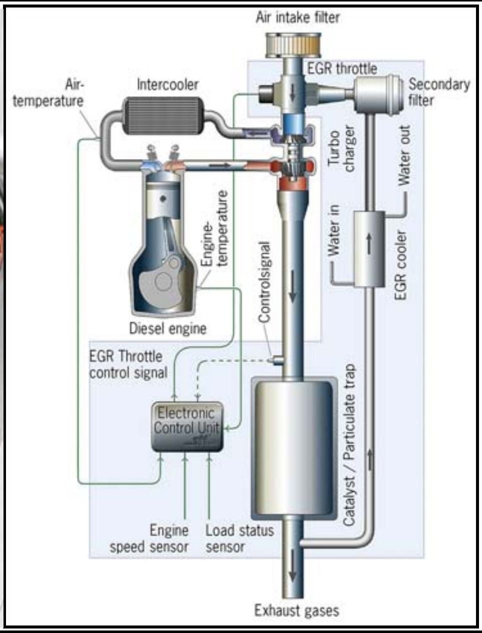
A CLEAN ETHANOL FUELLED COMPRESSION IGNITION BUS ENGINE





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SUMMARY

The purpose of this investigation was to study whether an ethanol fuelled heavy duty engine which was already in production for use in city buses could successfully be equipped with an exhaust control system, and whether it could be verified that the future EU emission standards would be met if this emission control system is used. The engine was taken to a company named STT Emtec, which works in the field of automotive engines and advanced emission control systems.

At STT Emtec the engine was installed on an engine test bed and equipped with a system for exhaust gas recirculation (EGR) named DNO_x™ and with different systems for exhaust gas after treatment. An extensive program especially for emission testing, designed by STT Emtec was carried out, evaluated and summarized in a short report. The report has been subject to further evaluation sponsored by the BioAlcohol Foundation (Baff) in Sweden. This report is the result of the further evaluation. The purpose of the evaluation of the data and the preparation of the report has been to clearly present what has been achieved by the program at STT Emtec and what could be achieved with further development of especially the system for after treatment of the exhaust.

When considering the positive influence on the emissions of EGR and the after treatment devices used, and the negative effect on the fuel consumption, it is obvious that the most favourable alternative for this engine is an EGR ratio related to "40% NO_x reduction" combined with an exhaust after treatment system. Furthermore, during the evaluation it became clear that the goal of meeting the future EU emission standards defined as "B2 (2008)" and "C (EEV)" in Table 1 during this investigation could best be reached with the combined exhaust after treatment system including a catalyst plus filter. Therefore the further evaluation was focused on this combination. That does not mean that no other alternative could be of interest.

A refined system including the engine and emission control system could certainly result in even lower emission limits being achieved with fewer components in the system.

Especially when retrofitting an engine or a vehicle there is a need to keep the cost at a minimum. In this case it may be possible to use an exhaust after treatment system with only one component instead of two. Based on the evaluation of the data generated during this investigation it seems likely that a particulate filter with an efficient catalytic function could meet the emission standards defined in Directive 1999/96 EC. On the other hand there are some uncertainties as to whether all of these emission limits can be met using only a catalyst. It is likely that the particles formed during the combustion process in the engine when using EGR will form carbonaceous particles. In that case it may be difficult to treat the particulate emissions using only a catalyst. An efficient filter may be needed.

To sum up the result of the work including the adaptation of the EGR system and the testing it has proved to be very successful in that:

*The EGR functioned very well, even at higher EGR ratios

*The particulate emissions could be kept to a really low level, despite the fact that the systems tested for after treatment of exhaust were not adapted to the engine and were not tested as to best design, from the point of view of their ability to treat the emissions of high priority.

*Despite the fact that the program for the investigation was primarily limited to studying the influence on the emissions of EGR, the future emission standards can be met with a limited setting of the EGR ratio and with the actual engine adapted after treatment system.

*The fuel consumption penalty was moderate with the selected setting of the EGR ratio "40% NO_x reduction" and could certainly be reduced by an optimal matching between the base engine and the EGR.

*The results and experiences achieved show that even lower emission levels, especially for NO_x, could be reached with an ethanol fuelled engine.

Looking beyond the emission standards defined in Directive 1999/96 EC, work is going on within a subgroup of the Motor Vehicle Emission Group (MVEG) with the purpose of developing new emission standards within the European Commission. Proposals for new Euro V and Euro VI emission standards have been published by UBA in Germany. The proposals cover both light duty-vehicles and heavy-duty engines. The outcome of the work within MVEG will certainly be of interest to all who are involved in the development of automotive engines and emission control systems.

The question now is what the outcome of the work will be in terms of new standards and what may be needed to meet the standards. The time schedule for these standards is that they will be in force from 2008/2009 for Euro V and from 2010 for Euro VI.

CONTENTS

1 INTRODUCTION

Historically ethanol and methanol have been used as automotive fuels for long time, both as neat fuels and as blend components in chiefly gasoline. Nikolaus Otto, the father of the Otto engine, regarded ethanol as an attractive fuel for combustion engines and in 1908 Henry Ford started the construction and production of an ethanol fuelled engine and claimed that an alcohol could be an automotive fuel for the future. A new mile-post was reached for Europe on the 8th of May 2003, in this case for the use of bio fuels, when Directive 2003/30EC on the promotion of the use of biofuels or other renewable fuels for transport was released by EU Parliament and Council (EU Directive 2003/30EC, 2003).

Together with USA and Brazil, Sweden has long term experience of the use of alcohol fuels. As mentioned above an intensive investigation of the blending of methanol in gasoline started around 1975 and that was the start of the Swedish trial of reducing the dependency on crude oil as an energy carrier for the transport sector. In addition to the methanol blending project a project called “M 100” was carried out during the years 1984 – 87 (Swedish National Board for Technical Development, 1987). During the latter part of the methanol trial, starting in the early 1980s, the investigations of the use of alcohol fuels have almost entirely focused on ethanol. One important part of this program was the development of ethanol fuelled heavy duty compression ignition engines at Scania Trucks and Buses. This program resulted in investments in ethanol fuelled buses in some cities in Sweden and especially in Stockholm, where initially 32 busses were run on ethanol. This fleet of ethanol fuelled buses in Stockholm has now expanded to 250 buses. In addition ethanol fuelled buses are run in 12 other cities for example Umeå, Borås, Helsingborg, Gävle, Norrköping, Skövde, Örnsköldsvik, Falun and Sundsvall. However, the number of ethanol fuelled buses in the country has not increased during recent years and is still around 400.

In 1991 the Swedish Government allocated 120 million Swedish crowns to the Swedish Transport and Communications Research Board (KFB) as funds for research, development and demonstration in the field of biofuels to be used in the transportation sector. In order to fulfil this obligation a program was presented and approved and this program for engine alcohols and biogas has been carried out between the summer of 1991, and the end of 1997.

The program has generated a broad spectrum of useful results showing that in general terms there are a number of technical problems connected to the use of biofuels and also that there is a need to continue the development of both the fuel and the engines in order to take all the advantages which can be achieved of the use of biofuels in the transportation sector.

To sum up the development in Sweden it can be said that ethanol fuel is used in the following cases;

- low blends (about 5 vol-% of ethanol in all gasoline in Sweden).
- E85 for Flexible Fuels Vehicles (the number of FFV’s in Sweden is growing fast. As of April 2004 it was around 7 600 vehicles;
- buses fuelled with neat ethanol (totally around 400 buses in the country)

Despite Sweden being a “small” market regarding the number of vehicles, it seems to have been of interest for the manufacturers to produce ethanol fuelled vehicles and engines for this demanding market. Unfortunately the cost of designing and developing a new engine for a specific demand has become too high, if it is to be paid back from a small market. As the ethanol fuel market is growing rather fast it is becoming more interesting for the vehicle manufacturers to invest in ethanol vehicles. A growing market should create new market opportunities for many commercial actors.

The main object of this report is to present a project carried out on an ethanol fuelled compression ignition engine. The reason for carrying out the project was to examine the technical and environmental potential for the future development of engines to be run on neat ethanol. There is a strong need for the development of such engines as there is a rapid interest in developing sustainable mobility systems particularly in large cities. Therefore, it should be of great interest for environmentally demanding planners of public transport as well as for environmentally ambitious engine manufacturers to take part in the further development of such engines. Available volumes of ethanol are expanding very rapidly and therefore it is a sound rationality to direct larger volumes of ethanol to the diesel powered public transport sector. The main arguments for this are that:

- Replacement of diesel fuel with ethanol will result in larger reductions of NO_x and particles emissions than the use of the same volume of ethanol as a replacement of gasoline. Replacement of diesel fuel with ethanol will also result in fewer problems at refineries vis-à-vis the production of gasoline.

- Substitution of diesel fuelled vehicles with ethanol fuelled vehicles in high-density population areas will be an appropriate measure to be taken in order to protect health, which is of great concern for a large number of exposed individuals.

- Obtaining sustainable mobility systems in both absolute and relative terms should be of great concern for public transport planners. In order to be successful in this venue, public transport must be based as much as possible on clean alternatives to passenger cars as well as meeting the economical and availability demands. To provide information about the existence of biofuels in public transportation vehicles is a suitable way to inform the majority of the public in a broad scale.

- Introducing new fuels in dedicated vehicles and applying the fuel in captive fleets such as city buses is the easiest and most realistic way to solve the-chicken-and-the-egg-problem, since the fuel can be distributed at the depot for buses.

Especially for the health and environment and consequently also for the economy in the long run there is a benefit in the use of ethanol as an alternative to diesel fuelled engines and vehicles at a higher rate than today. As will be demonstrated by this report, adding an emission control system to an Euro III ethanol fuelled heavy duty engine resulted in the engine being able to meet the emission standards for Enhanced Environmental Friendly Vehicles (EEV). A further upgrading of such an engine to be used in city buses and other heavy duty vehicles in city traffic could be a measure to be taken in order to improve the air quality in cities.

2 THE PROJECT

In May 2003 the European commission released a directive (EU Directive, 2003) in order to promote an increase of the use of biofuels. In paragraph 22 the Commission point out that *"Promotion of the production and use of biofuels could contribute to a reduction in energy import dependency and in emissions of greenhouse gases. In addition, biofuels, in pure form or as a blend, may in principle be used in existing motor vehicles and use the current motor vehicle fuel distribution system. The blending of biofuel with fossil fuels could facilitate a potential cost reduction in the distribution system in the Community"*.

Since Sweden is making a serious effort to increase the use of renewable fuels, in order to further reduce the emissions of NO_x and particles in urban areas, in particular, and of the emission of greenhouse gases, many parties are involved in this effort. In the introduction of this report a short presentation of the situation in Sweden concerning the use of ethanol fuel was given. Since the early 1980s public transportation in Stockholm is managed by SL, (Storstockholms Lokaltrafik), and this company has been involved in the introduction of alcohol fuelled buses and is now operating about 250 buses in the public transportation system. Generally the buses run well and those who are involved in the operation of the buses have gathered valuable experience in the use of ethanol fuel in the transportation system. As a result SL is planning to purchase an additional number of ethanol fuelled buses. Public transportation authorities in other cities in Sweden operating ethanol fuelled buses have similar plans.

In the effort to increase the use of biofuels there is a problem in that no new ethanol fuelled buses have been available for purchase during the last couple of years. The BioAlcohol Fuel Foundation in Sweden which is involved in the transfer to renewable fuels has taken actions in order to ease the way to a broader international market for alcohol fuelled heavy duty engines. Today there are certain new requirements for such an engine, since it has to compete with existing diesel engines that are produced in their millions annually. One of the major advantages of an alcohol fuelled engine, except for running on renewable fuels, is that the levels of NO_x and particles are much lower in the exhaust compared with those emissions in the exhaust from a diesel engine (Egebäck, 1993). This was demonstrated at an early stage of the introduction of ethanol fuelled buses. However, it has been claimed that new technologies for emission reduction will “clean up” the diesel exhaust to an unexpected low level. In order to study what could be done in order to “clean up” an ethanol fuelled compression ignition engine design for meeting the Euro 3 emission requirement it was decided to ask a company involved in the development and production of exhaust emission control systems to carry out a project. An agreement was signed with STT Emtec a well recommended company which among other things has invented a special EGR-system for heavy duty diesel engines.

The purpose of the project was to investigate the possibility of meeting the future European emission standards for Heavy Duty Vehicles (HDV) specified in the EU DIRECTIVE 1999/96/EC when fuelling the engine with ethanol (EU Directive, 1999). The current and the future emission are specified in Table 1 and the goal for the investigation was to meet the emission limits for the years 2005 and 2008 and in addition the standards specified for Enhanced Environmentally Friendly Vehicles" (EEVs).

Table 1. Future limit values according to EU directive 1999/96/EC – ETC tests [(b)]

Row	Mass of carbon monoxide (CO) g/kWh	Mass of non-methane hydrocarbons (NMHC) [g/kWh]	Mass of methane (CH_4) [(c)] [g/kWh]	Mass of nitrogen oxides (NOx) [g/kWh]	Mass of particulates (PT) [(d)] [g/kWh]
B1 (2005)	4.0	0.55	1.1	3.5	0.03
B2 (2008)	4.0	0.55	1.1	2.0	0.03
C (EEV)	3.0	0.40	0.65	2.0	0.02

[(b)] The conditions for verifying the acceptability of the ETC tests (see Annex III, Appendix 2, section 3.9) when measuring the emissions of gas fuelled engines against the limit values applicable in row A shall be re-examined and, where necessary, modified in accordance with the procedure laid down in Article 13 of Directive 70/156/EEC.

[(c)] For NG engines only.

[(d)] Not applicable for gas fuelled engines at stage A and stages B1 and B2 .

During the planning of the project it was decided to take samples in order to determine the distribution, size and number of the particulate emissions. A research team at Luleå University of Technology was engaged to carry out the study using a Mobility Particle Sizer (SMPS). The result of the study is presented in Appendix 1.

3 ENGINE AND THE SYSTEM FOR EMISSION CONTROL

The work with the engine included adaptation, mounting and verification of their EGR-system to a 9-liter compression Scania ethanol fuelled engine. The main specification of the engine can be seen in Table 2. The engine mounted on the test bed is shown in Figure 1.

3.1 The ethanol engine

Peter Ahlvik, a former employee at Scania in the field of engine development, and today a well-known consultant, has kindly contributed with the following characterization of the Engine (Ahlvik, 2004)

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"In addition to the parameters listed in Table 2 some further comments about the engine features can be made. The Scania 9-liter engine represents a somewhat outdated engine technology compared to the most advanced engines on the market today. Its combustion system and, in particular, the injection equipment, comprising an in-line injection pump, fuel lines and injection nozzles has been succeeded by more modern systems on newer engines. State-of-the art heavy-duty diesel engines today use unit injectors. Many European and most US engine manufacturers use unit injectors on their newest heavy-duty engine families.

Common rail injection systems are extensively used on light-duty engines and they are rapidly gaining acceptance for medium-duty and heavy-duty engines as well. However, so far, the pressure level for common rail systems has been considered somewhat low for heavy-duty applications. The current maximum pressure level for the second generation common rail systems is about 1 600 bar, whereas unit injectors can reach over 2 000 bar (current maximum level is about 2 300 bar). In one of the most recently conceived and presented new heavy-duty engines (April 2004), i.e. the MAN D20 engine family (10.5 litres), the injection pressure has been increased from 1 600 bar in the rail to 1 900 bar at the nozzle by using injector valve pulsing (Bunting, A, 2004): This example shows that common rail injection is gaining interest for heavy-duty engines as well as for smaller engines.

The achievable maximum injection pressure with state-of-the art in-line pumps (e.g. Bosch P8000 series) is approximately of the same order as the previously mentioned level for common rail systems. However, the maximum pressure *is only achievable at high speed and load*, whereas common rail systems are, in theory, capable of achieving the maximum pressure at all speeds and loads, though this is not always desirable.. Furthermore, the injection event can be divided into several phases in order to reduce emissions and engine noise. It is conceivable that in-line injection pumps do not have the capability to fulfil the demands for future engines, i.e. that engines should fulfil Euro IV or US 2004 emission legislation.

Table 2. Specification of the 9-liter Scania ethanol engine

Parameter	Value	Unit
Engine model	Scania DC9 04 230	
Certification	Euro III	
Combustion system	DI, swirl supported	
Aspiration	Turbocharger & aftercooler	
Engine type	In-line 6-cylinder	
Displacement	8 974	cm^3
Cyl. dia.	115	mm
Stroke	144	mm
Valves per cylinder	2	-
Compression ratio	17:1	-
Max power	169 (230)	kW (hp)
Max torque	1 100	Nm
Rated speed	1 900	r/min
Rated torque speed	1 100 – 1 200	r/min
Mean piston speed at rated power	8,87	m/s
BMEP at max. torque	15,4	bar
Min. specific fuel consumption	201	g/kWh

It can also be noted that the Scania engine uses a 2-valve design for the cylinder head. In 4-valve engines, it is fairly simple to utilise a central nozzle without any inclination. However, in 2-valve engines, the effective valve area would have to be reduced too much to utilise a centrally positioned vertical injector. A relatively recent improvement on the *diesel-fuelled* version of the Scania 9-litre engine was that the inclination of the injector was reduced from 18° to 8°. Thus, the cylinder heads of the two engines tested at the laboratory in Luleå were different in that respect. A reduction of the injector inclination gives a more uniform distribution between the fuel sprays from each nozzle hole, which decreases the emissions (primarily particulate emissions). This modification has not yet been introduced on the ethanol engine, which has retained the 18° inclination used on previous versions of the diesel-fuelled engine. It seems likely that the reduced inclination for the new cylinder head would be a better compromise regarding exhaust emissions even for the ethanol-fuelled version of the engine.

I n conclusion of the above discussion it can be stated that the Scania 9-litre engine is no longer state-of-the-art in engine design. The results obtained on the ethanol-fuelled version of the engine must be assessed bearing this in mind. There is no doubt that further optimisation of the ethanol engine regarding exhaust emissions could be carried out, provided that the latest available technology for fuel injection and the corresponding improvements of the combustion system could be applied."

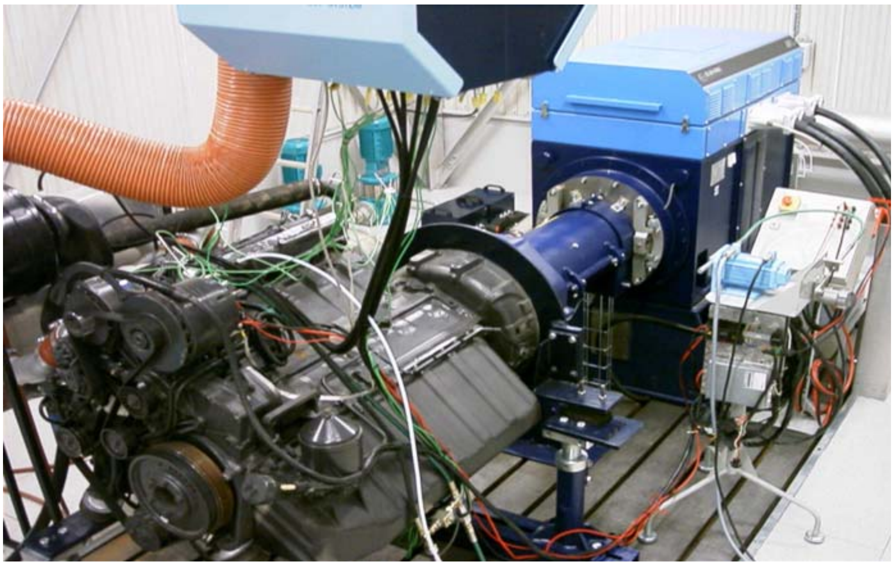

Figure 1. The Scania ethanol engine mounted on the test bed at STT Emtec.

3.2 The emission control system

STT Emtec is a Swedish company situated in Sundsvall, a city approximately 400 kilometres north of Stockholm. The company is known for having developed exhaust turbo systems and an EGR-system for diesel fuelled engines. STT Emtec is engaged in operations in two business areas**:** Emission Systems and Engine Systems. Their present day operation comprises design and construction, electronics, testing and evaluation and manufacturing of prototypes. Amongst other things the EGR-system is now produced as a retrofit device for diesel fuelled buses in traffic under the trade name “STT Emtec AB DNOx™”.

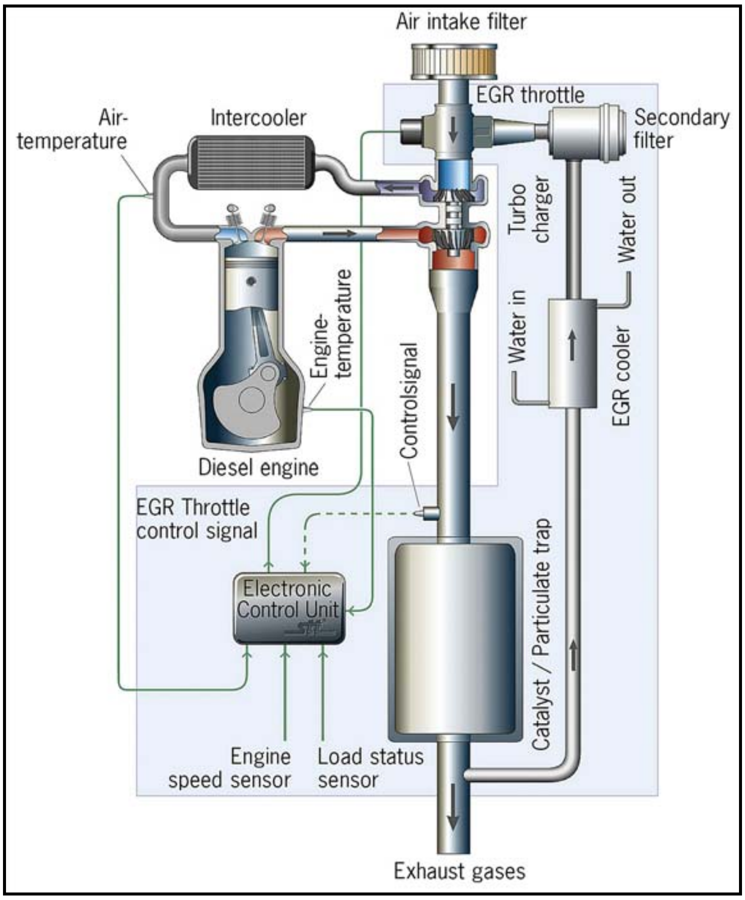

Figure 2. STT Emtec AB DNOx™.

The following three alternative exhaust control systems were used and verified during intensive engine testing and emission measurement at STT Emtec:

1. EGR-system: Trade mark: STT Emtec AB DNOx™ plus oxidation catalyst.
2. EGR-system: Trade mark: STT Emtec AB DNOx™ plus oxidation catalyst.and particulate filter.

3. EGR-system: Trade mark: STT Emtec AB DNOx™ plus particulate filter.

The main verifications were carried out with the systems 1 and 2. System 3 was tested only for an EGR-ratio resulting in 40 % NO_x reduction.

It should be stressed that neither the catalyst nor the particulate filter were designed to be used on the actual 9-litre Scania ethanol engine. Both of them were designed for other purposes – the catalyst for research at Luleå University of Technology and the filter for investigations at STT Emtec.

4 VERIFICATION OF EMISSION CONTROL SYSTEM

The basic feature for the verification was the EGR-system and after the adaptation and the investigation of the function of EGR-system the emission performance was verified, after adding on the catalyst and the particulate filter as shown above.

The adaptation and investigation of the EGR-system was conducted chiefly by engine mapping. Some of the main activities in the test cell at STT Emtec are shown in Table 3. ESC-tests were carried out parallel with ETC-tests during the emission-verification testing.

Table 3. Activities for the investigation of the Scania ethanol engine at STT Emtec.

Activity	Contents
Pre investigation work	Making a prototype EGR-system (electric and manual)
Installation test cell	Installation of engine etc. in test cell
Instrument installation	Installation of sensors etc. and calibration of the equipment.
Referens test	ESC and ETC testing of engine w/o emission control system
EGR mapping	Installation of DNOx™-system and engine EGR mapping.
Test with DNOx™-system	ESC and ETC testing of engine with emission control system
Dismounting	Demontering av provobjekt och kringutrustning.
Evaluation and reporting	Evaluating and combining test results and specifications

Of the emission test method referred to in Table 3 the:
* **ESC** test procedure is a 13 mode steady state test specified in the EU Directive 1999/96/EC.

* **ESC** test procedure is a transient test also specified in the EU Directive 1999/96/EC.xxxx

The emission verification tests were conducted according to an emission test matrix, Table 4. One emission test was carried out for each alternative marked with "**X**", totally 31 tests. The setting of the EGR ratio was based on the reduction rate of NO_x for all emission parameters NO_x, particles (PM), CO, HC and CO_2 and also for fuel consumption. The baseline for "**max**" was defined as the ratio when the EGR ratio was too high to maintain an acceptable function of the engine.

Table 4. Emission test matrix.

	Baseline		ETC emission reduction				ESC emission reduction			
Engine configuration	**ETC**	**ESC**	**40%**	**50%**	**60%**	**max**	**40%**	**50%**	**60%**	**max**
Without emission control	X	X	X	X	X	X	X	X	X	X
With catalyst	X	X	X	X	X	X	X	X	X	X
With catalyst and filter	X	X	X	X	X	X	X	X	X	X
With filter			X							

Test fuel

The ethanol fuel used had the following specification:

- Type of fuel: Etamax D
- Density: 0.817 kg/l
- Hydrogen/Carbon balance: 3.12

5 EMISSION DATA

The emission data in g/kWh for ETC and ESC test procedure respectively are presented in the following table named Table 5.

Table 5. Emission data generated according to ETC test and ESC test respectively.

NOx (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	2.96	1.98	1.62	1.38	0.81	2.71	1.63	1.36	1.2	0.76
With only catalyst	2.88	1.78	1.56	1.33	0.77	2.71	1.57	1.30	1.20	0.91
With catalyst and filter	2.85	1.74	1.45	1.24	0.72	2.76	1.60	1.30	1.07	0.70
With only filter		1.88								

Particles (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	0.059	0.073	0.085	0.097	0.205	0.030	0.032	0.035	0.040	0.077
With only catalyst	0.032	0.052	0.061	0.071	0.135	0.015	0.018	0.026	0.024	0.048
With catalyst and filter	0.008	0.002	0.004	0.003	0.006	0.003	0.001	0.001	0.001	0.002
With only filter		0.01								

CO (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	3.33	5.49	7.38	9.41	22.53	1.91	2.97	4.13	4.97	12.10
With only catalyst	0	0	0	0	0.2	0	0.02	0.02	0	0
With catalyst and filter	0	0	0	0	0	0	0	0	0	2
With only filter		6.57								

HC (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	0.54	0.57	0.64	0.75	1.91	0.44	0.43	0.45	0.46	0.83
With only catalyst	0.03	0.15	0.21	0.29	0.99	0.03	0.08	0.10	0.11	0.25
With catalyst and filter	0.04	0.15	0.23	0.33	1.28	0.04	0.08	0.12	0.17	0.62
With only filter		0.57								

CO2 (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	674	683	687	688	696	624	621	624	626	632
With only catalyst	678	697	702	711	748	639	646	654	658	673
With catalyst and filter	677	697	706	712	767	645	653	663	669	699
With only filter	672									

Table 5 and Table 6 (in section 6) are related to the matrix presented in Table 4. This matrix was used as a schedule during the process for verification of the influence on emissions of parameters. The parameters to take in account were primarily the EGR ratio (NO_x-reduction) and systems used for after treatment of the exhaust (particulate filter and/or catalyst). Actually, in this case the ratio of EGR is not measured or presented. The parameter used instead of EGR ratio is the effect of EGR on NO_x emissions, which for this investigation was set to 40%, 50%, 60% and Max respectively. "Max" is related to the function of the engine and not related to a fixed EGR ratio, which also is the case when the EGR ratio is related to a certain percentage (40%, 50% etc.) reduction of NO_x. The effect on the emissions will be discussed under section 7 "Results and discussions" with special considerations to the emission requirements for meeting the EU emission standards for year 2005 and year 2008 respectively and also for Enhanced Environmentally Friendly Vehicles" (EEVs).

6 FUEL CONSUMPTION

The fuel consumption data in g/kWh for ETC and ESC generated during the tests carried out according to the procedure ETC and ESC respectively are presented in the following table named Table 6. Also data from calculation of the fuel penalty caused by the use of EGR and the different emission after treatment systems are presented in Table 6.

Table 6. Fuel consumption data generated according to ETC test and ESC test respectively.

Fuel consumpt. (g/kWh)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	379	384	390	392	409	366	372	377	381	391
With only catalyst	384	394	398	403	428	371	379	385	388	398
With catalyst and filter	385	397	402	408	442	372	383	390	395	415
With only filter		389								

Fuel penalty (%)	ETC Driving cycle					ESC Driving cycle				
NOx reduction	**0%**	**40%**	**50%**	**60%**	**Max**	**0%**	**40%**	**50%**	**60%**	**Max**
Without after treatment	0%	1.2%	2.7%	3.4%	7.9%	0.0%	1.6%	2.9%	3.9%	6.8%
With only catalyst	1.2%	3.9%	5.0%	6.1%	12.7%	1.2%	3.5%	5.2%	6.0%	8.7%
With catalyst and filter	1.5%	4.5%	6.1%	7.6%	16.4%	1.6%	4.5%	6.5%	7.8%	13.3%
With only filter		2.6%								

Different engines may have different tolerance to the use of EGR with respect to the effect on fuel consumption. For this investigation ethanol was used as the fuel during all testing. The matter of fuel penalty will be discussed under the headings "Results and discussions".

7 RESULTS AND DISCUSSIONS

When studying the results from this investigation it should be be kept in mind that the purpose of this work was to study the effects on the emissions when using EGR on an engine, which was at one time in production and also that the after treatment devices were taken from the shelf.The Scania ethanol engine used in this project had previously been used as an object for research at Luleå University of technology. At STT Emtec no changes were made to the engine before adapting the exhaust control system. The work carried out has been specified in Table 3. Since one of the main specialities of STT Emtec is the development of EGR systems for combustion engines a thoroughly adaptation, installation and engine mapping was conducted before the verification of the emission performance. As already stated above no special investigation of the exhaust after treatment systems was carried out before the emission characterization for the verification. It should therefore be kept in mind, that the main feature of this project was to study the influence on the emissions of EGR. A study of a suitable arrangement of after treatment systems should be seen as a remaining work.

In order to understand and identify the different settings of the emission control system the following phrases are used:

* **Baseline:** No EGR and exhaust after treatment system.
* **Baseline: Without after treatment:** Zero to max EGR.
* **NOx Reduction[1]:** A ratio of EGR expressed by a specified NO_x reduction.
* **With only catalyst:** Catalyst used for all EGR ratios from zero to max.
* **With catalyst and filter** Catalyst and particulate filter used for all EGR ratios from zero to max.
* **With only filter:** Filter used for all EGR ratios from zero to max.
* **After treatment systems:** Means in this report: Catalyst, particulate filter and the combination catalyst + filter in line.

1) The setting of the EGR ratio was such that NO_x reduction would be 40%, 50%, 60% and max at steady state test.

Presentations in section 7.1 and 7.2 are focused on the actual data generated at STT Emtec. To start with it was essential to identify which of the EGR settings in combination with the exhaust after treatment systems could be used in order to meet the future EU standards. In order to identify the best alternative a number of figures presented in Appendix 2 were constructed and three of them are presented in section 7.1. The selected alternative is then presented in section 7.2.

In section 7.3 a number of figures are presented in which the emissions from the actual engine including the emission control system are compared with the future EU emission standards. In section 4 the following figures are arranged so that EU emission limits can be seen in the same figure as the result from the emission characterization.

7.1 Evaluation of the complete data package

Since there are many different figures to be presented for the evaluation, from the emission and fuel consumption point of view, the best alternatives of some of them are assembled in Appendix 2 Furthermore, the presentation has been focused on data from the transient tests, since the acual engine is supposed to be used in a city bus and consequently run in transient conditions. Figure 3 represent the group of figures in Appendix 2 and in these figures all the data for each emission component are shown and in Figure 3 the emissions of oxides of nitrogen (NO_x) when measured according to the transient test are presented.

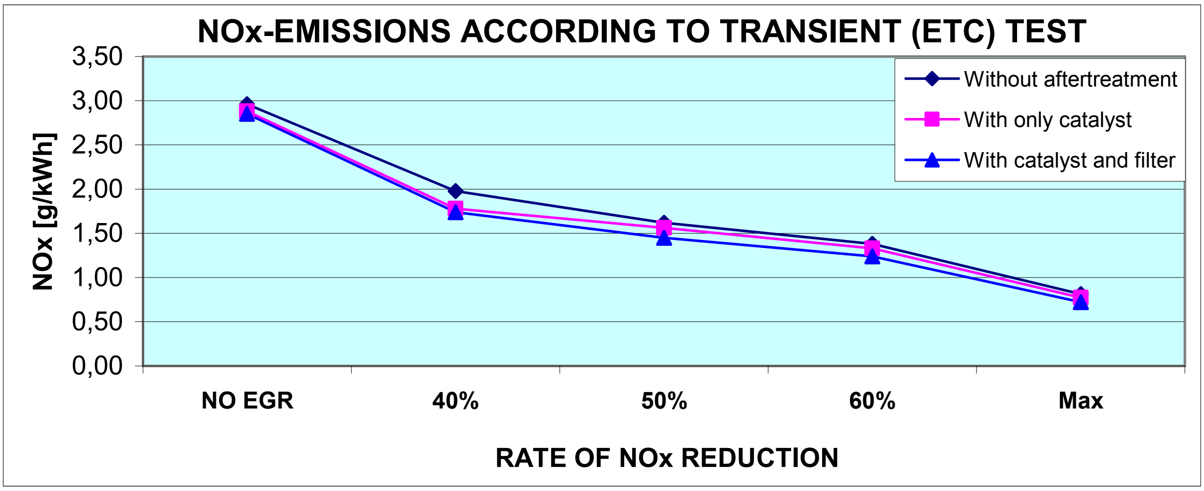

Figure 3. Emissions of NO_x as a function of the EGR ratio.

As can be seen in Figure 3 the NO_x emissions decrease when the EGR ratio increases and in fact it actually decreases from 2.8 g/kWh to around 0.75 g/kWh. If there were no negative effects of the increase of the EGR ratio, going to "Max" EGR ratio would be a more than remarkable improvement of the NO_x emission performance. At an EGR setting resulting in 60% NO_x

reduction the engine was still working well and the other negative effects were not too dramatic. With this EGR setting the level of NO_x was down to 1.38 g/kWh, which means that a level of about 1.0 g/kWh could certainly be reach with a suitable exhaust after treatment system.

It is well known that the use of EGR tends to increase the emissions of particles, which is what has happen even here as shown in Figure 4.

In Figure 4 it can be clearly seen that that EGR has a negative influence on the particulate emissions especially at higher EGR ratios. The positive message that the figure gives is that the combination of catalyst plus filter very effectively reduces the particulate emissions, which could lead to the conclusion that the EGR ratio could be increased close up to "Max". Fortunately, the level of particles can be kept really low, despite the fact that it increased up to 0.097 at 60% NO_x reduction and to 0.205 at max EGR. When using the combination catalyst and particulate filter the level of particulates were kept at a level of under 0.04 g/kWh except at the setting "Max" when it crept up to 0.06 g/kWh.

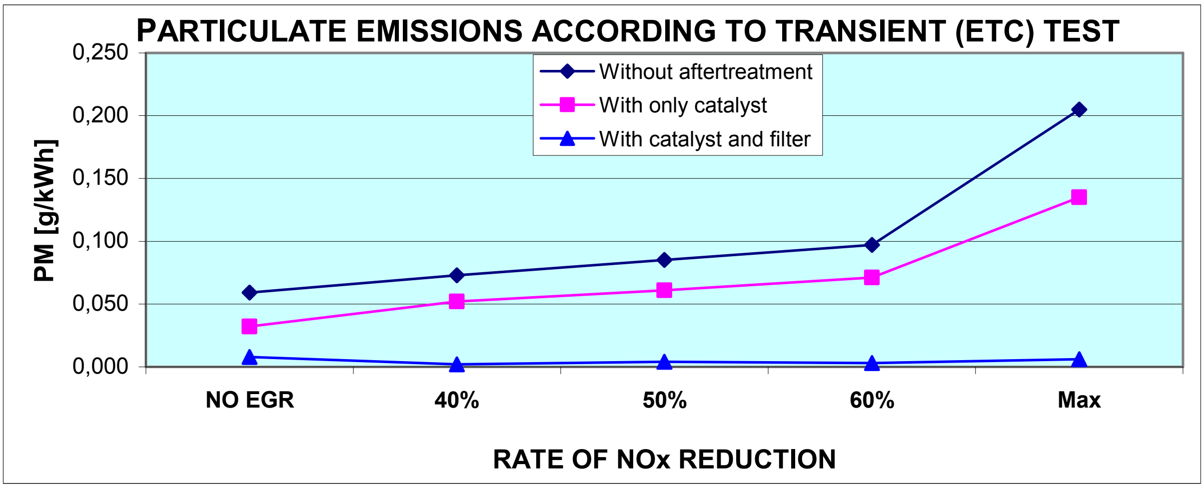

Figure 4. Emissions of particles as a function of the EGR ratio.

However, there is at least one additional negative effect to consider when designing an efficient emission control system. The negative effect in mind is the influence on the fuel consumption, which has to seriously be considered, since it increases the operating costs of the vehicle. The fuel consumption penalty related to the EGR ratio can be seen in Figure 5.

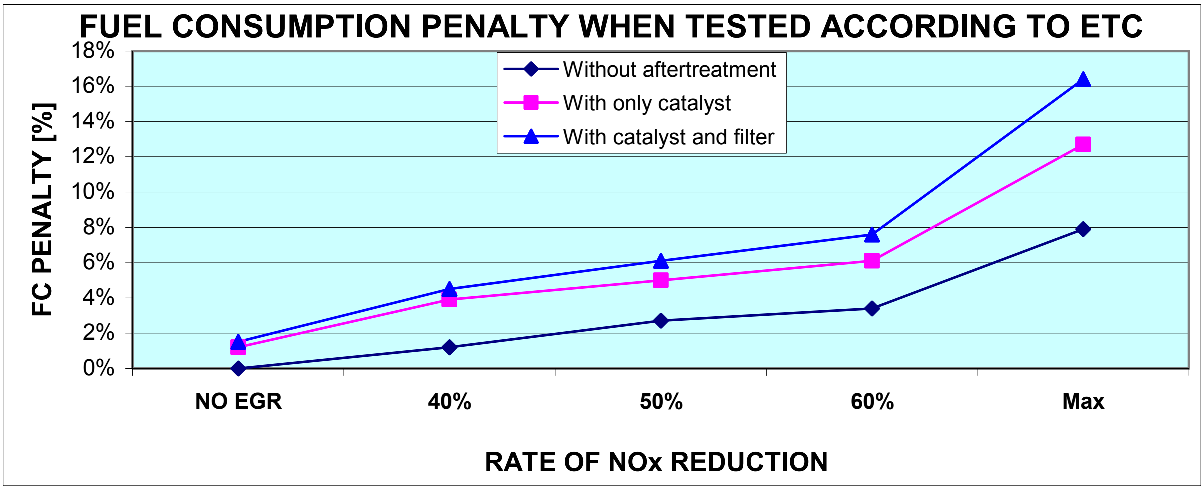

Figure 5. Fuel penalty as a function of the EGR ratio.

Figure 5 clearly illustrate the influence on fuel consumption not only of the EGR ratio – which could be considered as not too dramatic, max approximately 8% – but also the effect of the systems used for after treatment of the pollutants in the exhaust. From the figure it also can be seen that there is a minor difference in the fuel consumption penalty when using both the catalyst and the particulate filter when compared with "only catalyst". However, according to Figure 5 the fuel consumption penalty is at least dubbled when using the exhaust after treatment devices. Furthermore, the figure shows that the catalyst is the main after treatment device causing the increase of fuel consumption in this study.

7.2 Identification of the favoured alternative

The objective of this project was to study whether or how much a not too costly adaptation of a emission control system could reduce the emission from a ethanol fuelled engine originally developed in order to meet the Euro 3 standards presented in Table 7. The actual engine a Scania 9 litre ethanol fuelled engine was produced as a bus engine and a number of ethanol fuelled buses in Stockholm are equipped with this engine. When tested at STT Emtec the engine without catalyst met the Euro 3 standards for all emission components presented in Table 7.

Table 7. Emission standards according to Euro 3.

Regulation	**To be in force**	**Particles g/kWh**		**NO_x g/kWh**	**HC g/kWh**		**CO g/kWh**		**Opacity m^{-1}**
		ESC	ETC		ESC	ETC	ESC	ETC	ELR
EURO 3	2000	0.10	0.16	5.0	6.66	0.78	2.1	5.4	0.8

When studying the results presented in Table 5 and especially Figure 3, Figure 4 and Figure 5 it was obvious that the further evaluation should be focused on "40% NO_x reduction". No other EGR setting resulting in a specified NOx reduction can meet the goal to fulfil the emission requirements for Enhanced Environmentally Friendly Vehicles (EEV). In addition it was seen that with the actual engine in combination with EGR and the exhaust after treatment system which was used the fuel consumption penalty was seen to be unacceptable high. Therefore the further evaluation here will be focused on this combination. This does not mean that other alternatives could be of no interest. A refined system including the engine and emission control system could certainly even lower emission limits with fewer components in the system.

The following five figures in this section show the effect on the emissions when adding the different exhaust after treatment systems to the engine operated with a certain EGR setting. In addition the fuel consumption and the fuel penalty for the different alternatives are shown two figures. Since different alternatives for control of the emissions are presented in the report, it should be underlined that all of the five figures presented in this section include **EGR** with the setting which resulted **in 40% NO_x reduction.**

Figure 6 to 10 show the emission performance from tests at an EGR setting resulting in a 40% NOx reduction without and with after treatment systems. Figure 6 shows that the after treatment systems "With EGR only catalyst" and "With catalyst and filter" reduced the emission of NO_x to some extent. The alternative "With only filter" shows only a minor reduction of NO_x whereas the two other alternatives include EGR.

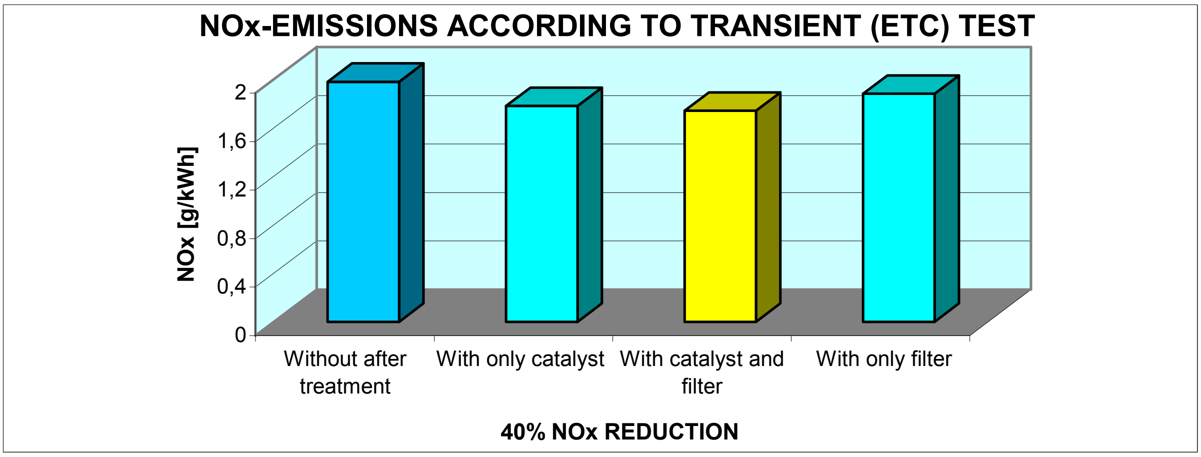

Figure 6. Emissions of NO_x at 40% NO_x reduction and when adding the different after treatment systems.

The particulate emissions increased from 0.059 g/kWh up to 0.73 g/kWh when using EGR at the ratio that resulted in a 40% NO_x reduction. Figure 7 shows that the catalyst reduced the emissions but not to the level 0.03 or 0.02 g/kWh. Fortunately the combination catalyst and filter had a dramatic influence on the particles. Furthermore, even this particle filter reduced the emissions to a great extent 0.014 g/kWh, meaning that the 0.02 g/kWh standards could be met with a good margin.

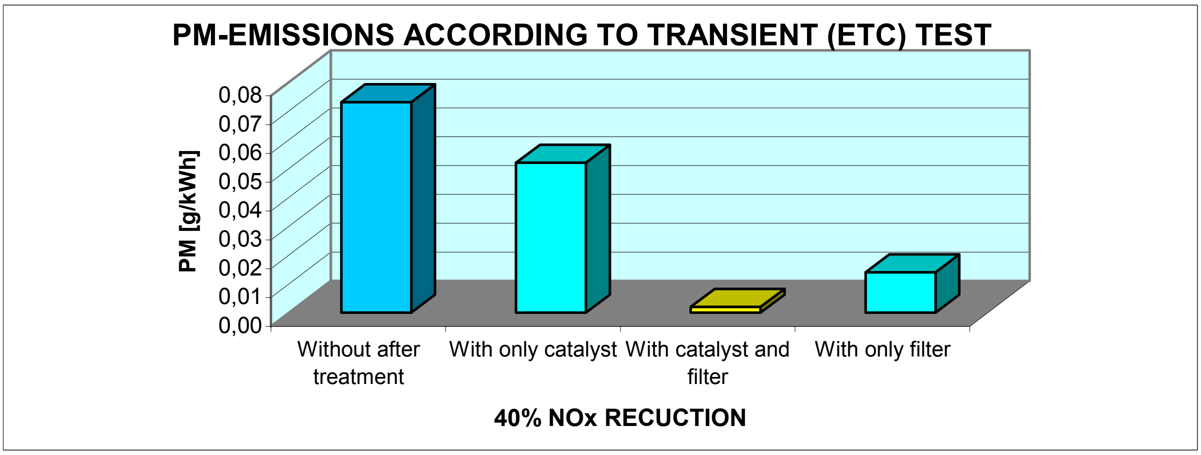

Figure 7. Emissions of particles at 40% NO_x reduction and when adding the different after treatment systems.

At an EGR setting resulting in a 40% NOx reduction only the alternatives ”With only catalyst and filter” and “With catalyst filter” could meet the standards, Figure 8. However, the HC standards are rather mild and for gas fuelled engines range from 1.1 down to 0.65 g/kWh which compared with the standards for other engines, which range from 0.55 down to 0.40, according to Table 1. If such exemptions should be applied also for ethanol fuelled vehicles and engines, higher HC levels could be accepted for these vehicles and engines. A research team at Luleå University of Technology found that between 60 to 90 per cent of HCs detected with a FID (used for measurement of hydrocarbons in motor vehicle exhaust) were not hydrocarbons (Haupt et al., 1997).

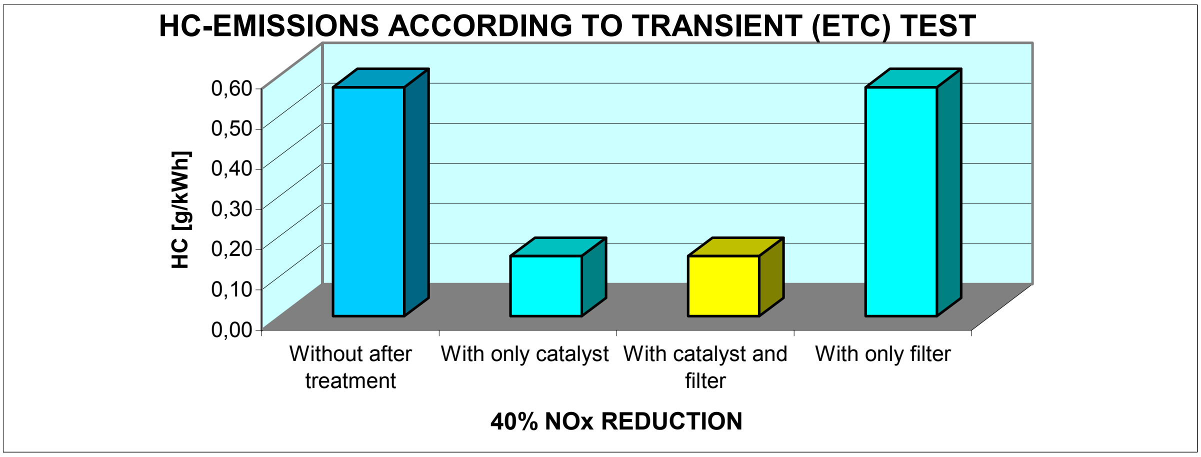

Figure 8. Emissions HC at 40% NO_x reduction and when adding the different after treatment systems.

Generally the emission of carbon monoxide (CO) from motor vehicles of today is at such levels that CO is regarded as not to be a serious problem. However, the use of EGR tends to increase the level of CO in the exhaust and therefore it may have to be reduced. As shown in Figure 9 the level of CO is rather high and from Table 5 it can be seen that the emission of CO increases with a function of the EGR-ratio. On the other hand using the catalyst or the combination catalyst plus particle filter reduced the CO emission remarkably. Whether the emission level should be regarded as to be zero or a positive figure is of less interest here (see Table 5). The procedure for measurement of automotive emissions is not complete accurate and therefore there are some uncertainties in the figures (g/kWh) or g/km) representing the actual emissions levels.

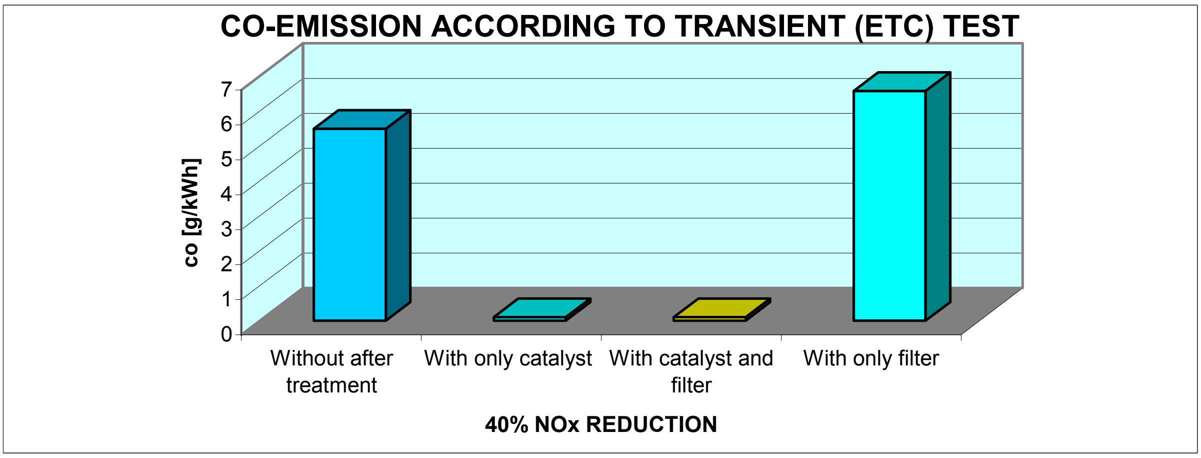

Figure 9. Emission CO at 40% NO_x reduction and when adding the different after treatment systems.

CO_2 emission is linked to fuel consumption and then affected by the EGR ratio and of the system used for exhaust after treatment. This can be more clearly seen in Figure 5 than in the following figures, Figure 10, Figure 11 and Figure 12, since these figures are limited to showing the data generated at an EGR setting resulting in a 40% NOx reduction. Since the ethanol fuel used is based on renewable biomass only a part of the emitted CO_2 will contribute to the increase of the greenhouse gases. Therefore in reality it is favourable to use bio ethanol despite the volumetric consumption being higher compared to the use of a fossil fuel. It should be underlined that all ethanol fuel used in Sweden is bio based.

The fuel consumption is of concern, since an increase will to a certain rate increase the operation cost for the vehicle owner. Therefore it should be of high priority to design the engine and the emission control system in a manner that minimise the fuel consumption penalty. Taking into account that the energy content in one litre of neat ethanol is 21.4 MJ/l and that the energy content in one litre of Swedish MK 1 diesel oil is 35.4 MJ/l the fuel penalty in energy terms compared with diesel oil can be calculated in addition to the fuel penalty shown in Figure 12.

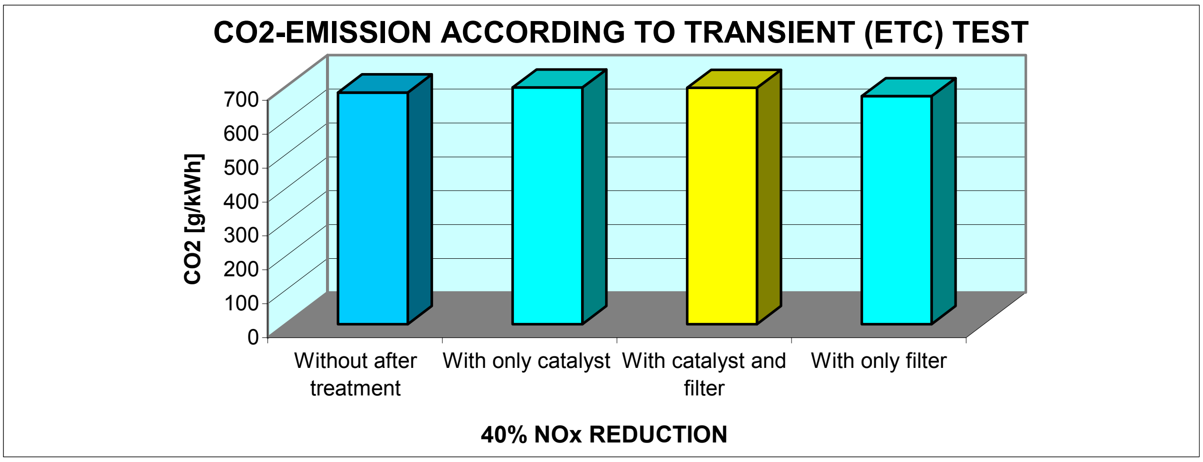

Figure 10. Emission of CO_2 at 40% NO_x reduction and when adding the different after treatment systems.

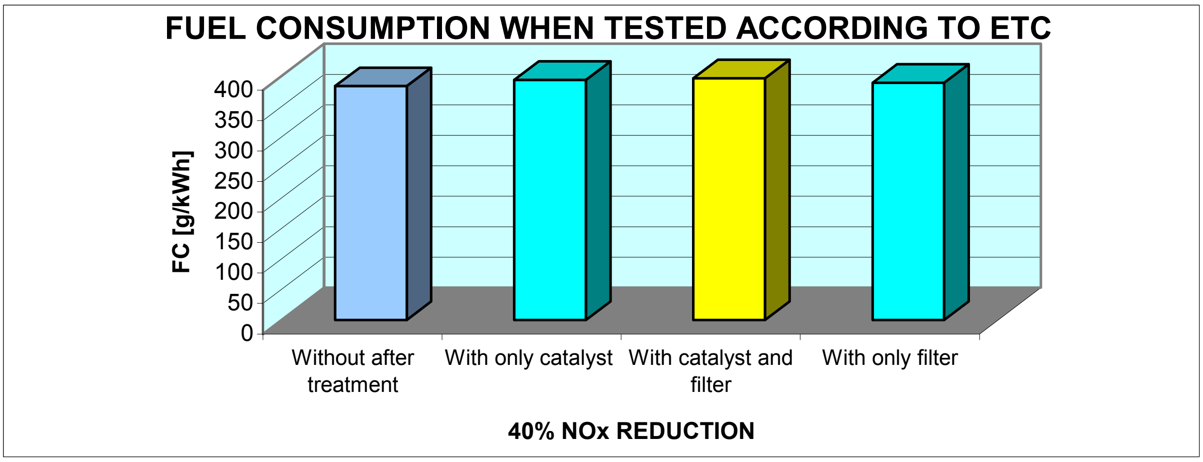

Figure 11. Fuel consumption at 40% NO_x reduction and when adding the different after treatment systems.

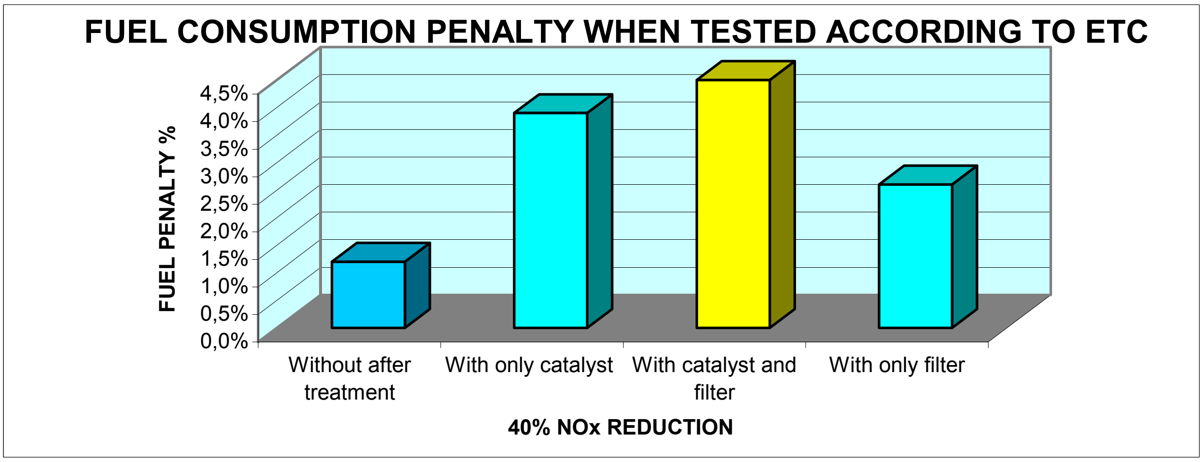

Figure 12. Fuel consumption penalty at 40% NO_x reduction and when adding the different after treatment systems.

Since data from tests according to ESC on the same type of Scania 9 litre engine fuelled with Swedish MK 1 diesel oil was available, these data have been used in order to show the fuel consumption penalty when comparing the use of ethanol with the use of MK 1, Figure 13.

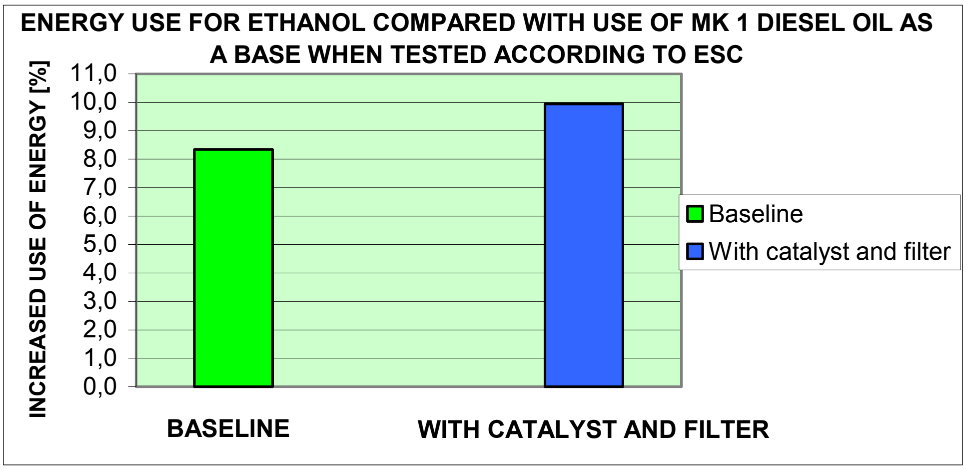

Figure 13. Fuel consumption penalty at 40% NO_x reduction and when adding the different after treatment systems when compared with the use of MK 1 diesel oil.

When using data from the above mentioned measurements on the diesel fuelled Scania 9 litre engine tested according to ESC, the use of energy could be calculated to be 9.14 and 9.40 MJ/kWh for "Baseline" and "With catalyst and filter" respectively. This figures for used energy has then been used as a base for comparison of the used energy for the ethanol fuelled engine when tested according to ESC for the baseline and with an EGR ratio resulting in "40% NO_x reduction". Consequently the calculated use of energy for the ethanol fuelled engine is based on data in Table 6 (ESC driving cycle). The increased use of energy for the ethanol fuelled engine when compared with the diesel fuelled engine are 8.3% and 9.9 % for "Baseline" and "With catalyst and filter" respectively. There was no data generated from test of the diesel fuelled engine according to ESC for the alternatives "With only catalyst" and "With only filter". Figure 13 shows a considerable increase in the use of energy for the ethanol fuelled engine as calculated. However it is believed that this penalty of the fuel consumption can be reduced to great extent if a more precise adjustment of the engine to the fuel is carried out and with careful adaptation of the emission control system.

7.3 Emission levels compared with future EU emission standards

I order to get a good view of the effect on the emission levels when using a certain ratio of EGR in combination with some different sets of systems for after treatment of the exhaust two sets of figures have been constructed. In this section one set of these figures is presented showing the actual emission levels for the baseline engine and different combination used for the control of emissions. In the same figures even the future EU emission standards defined in the EU Directive1999/96EC as B1 (2005), B2 (2008) and EEV are included for reasons of comparison.

In the following figures the baseline emissions "Without emission control", the emissions with EGR but "Without after treatment" and the emissions when using the exhaust after treatment systems "only catalyst", "catalyst and filter" and "only filter" are presented. The presentation is done this way in order to make it easy to compare the emission levels with the future EU emission standards defined as "B1 "(2005)", "B2 (2008)" and "C (EEV)" in Table 1.

Figure 14 shows that all alternatives presented in the figure meet the EU limits for NO_x year 2005 according to Directive 1999/96/EU. The only alternative meeting the emission requirement for "B2 (2008)" and EEV is the alternative EGR in combination with catalyst and filter (40% NO_x reduction) if the need for including a certain safety margin is taken into account.

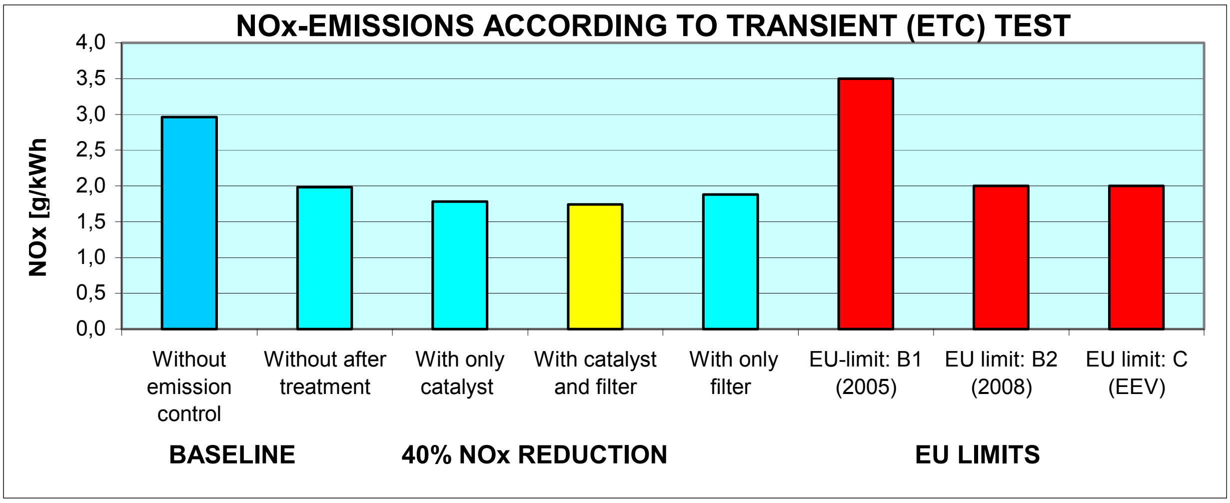

Figure 14. NO_x emissions for baseline and emission control compared with EUs NO_x- limits.

According to Figure15 it seems necessary to use a particulate filter in order to fulfil the future EU particulate standards. If the whole system including the engine the EGR system and other parts included in the whole system are refined it may be possible to meet the 0.02 g/kWh standards with a catalyst alone.

Keeping in mind that the future emission standard for year 2008 and EEV according to the EU Directive 1999/96/EC concerning NO_x is 2.0 g/kWh it can be seen that the NO_x emissions (1.98 g/kWh) are under the standards at 40% NOx reduction even without after treatment system. However, a safety margin of 10 to 15% from the actual engine emission level up to the standards may be required, since there will be a variation of the emission level from engine to engine. Therefore in this case two of the three after treatment systems gave the necessary safety margin.

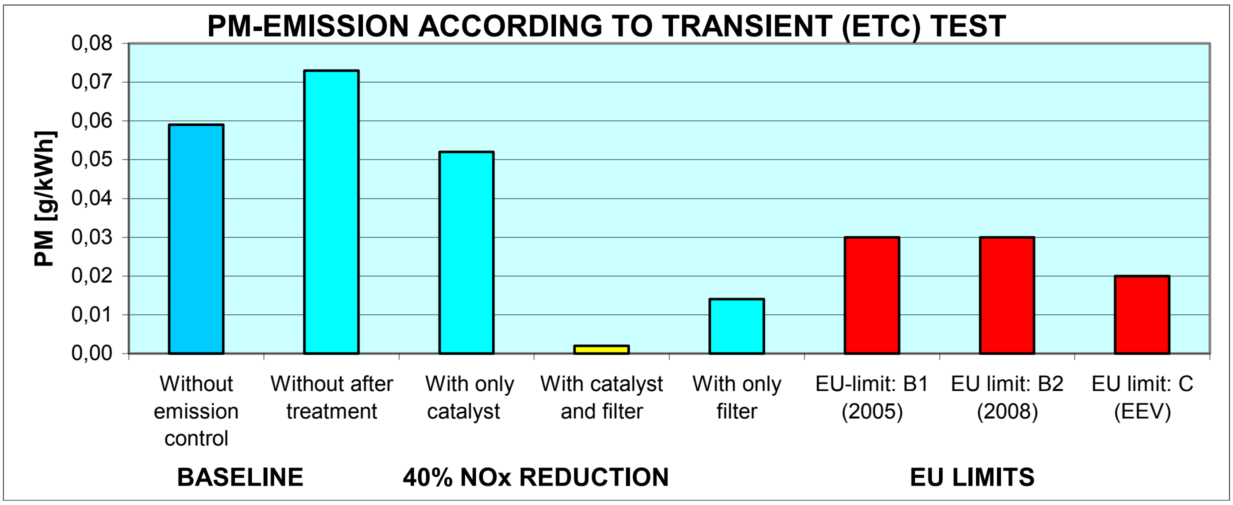

Figure 15. PM emissions for baseline and emission control compared with EUs PM-limits.

The HC standards according to the EU Directive 1999/96/EC for not "gas fuelled engines" are 0.55, 0.55 and 0.40 g/kWh for B1 (2005), B2 (2008) and EEV respectively according to Table 1.

Figure 16 clearly illustrate the advantage of including a catalyst in the system. It seems to be unnecessary to use two separate systems i.e. both a catalyst and a particulate filter. Therefore the most economic alternative would be to use a particulate filter, which has a rather efficient catalytic function. Obviously the filter used in this application does not have any strong catalytic function, since as can be seen of the figure there is a very large difference between the HC emissions when using the catalyst alone compared with the HC emissions when using the particulate filter alone.

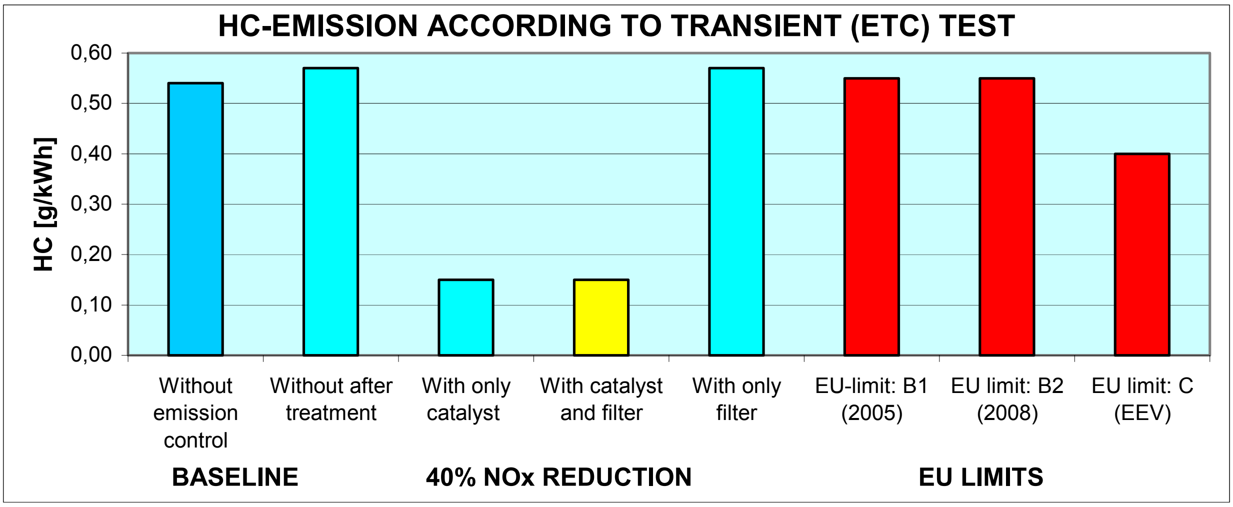

Figure 16. HC emissions for baseline and emission control compared with EUs HC-limits.

When comparing Figure 17 with Figure 16 it can be seen that the patterns of these figures are almost the same except for two test cases. This verifies the observation that the catalytic function of the filter was very limited if it exists at all. On the other hand the oxidation function of the catalyst seems to be very strong since the levels of the CO emission was reported to be zero according to Table 5.

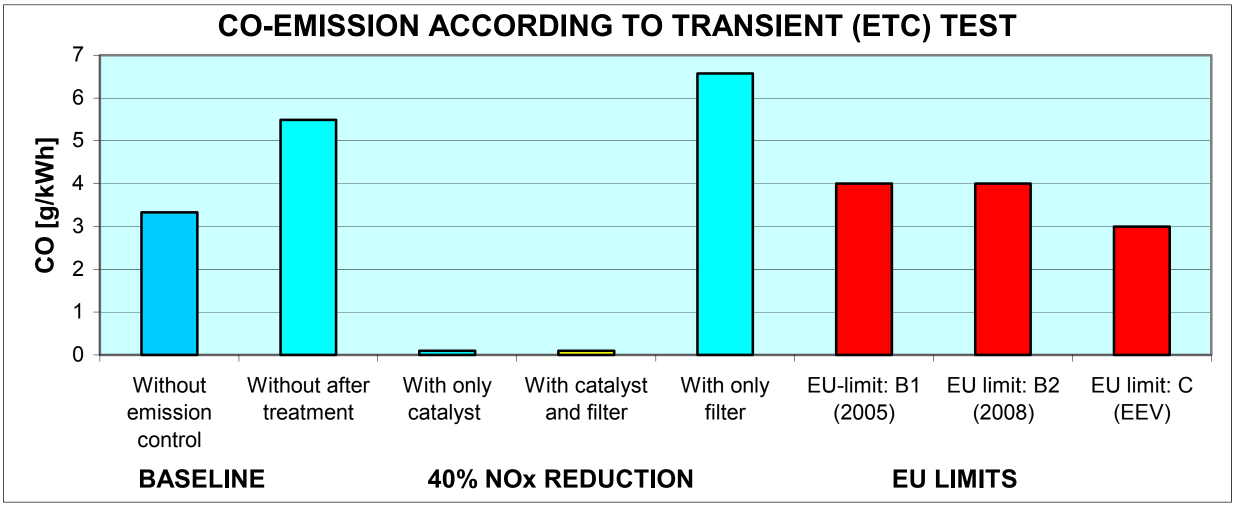

Figure 17. CO emissions for baseline and emission control compared with EUs CO-limits.

Figure 18 shows that the use of an emission control system influences the emission of CO_2 negatively except in the case of particulate filter. Comparing the baseline CO_2 emission, 674 g/kWh, with the highest level of the CO_2 emission presented, 697 g/kWh, result in a calculated increase of 3.4 %. It would be of interest to know how large a part of the CO_2 emission can be regarded as not having an impact on the environment by means of greenhouse gases. However, such an evaluation is not within the scope of this investigation.

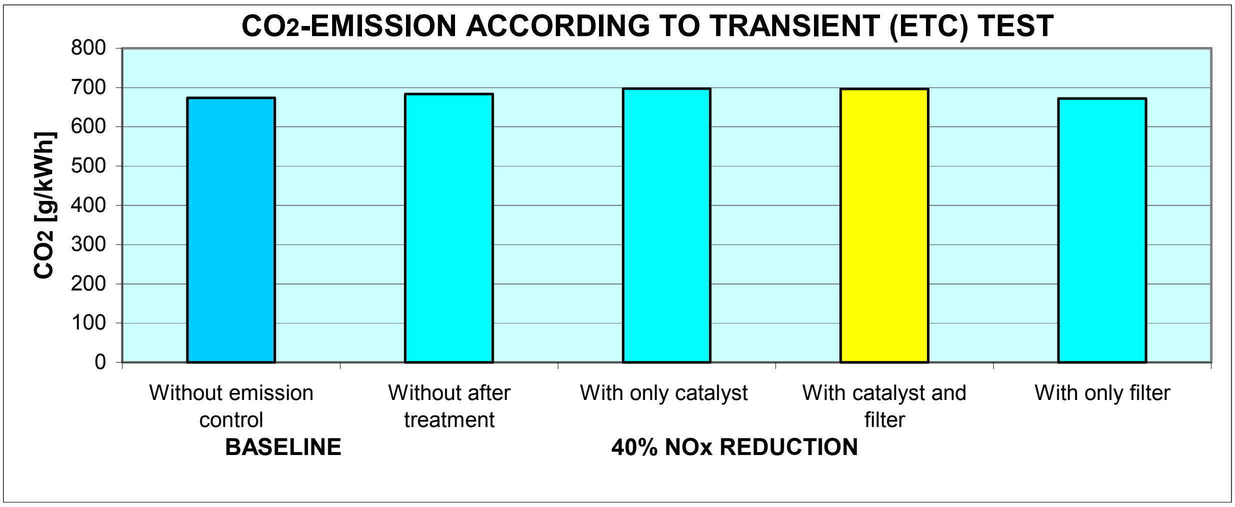

Figure 18. CO_2 emissions for baseline and emission, control.

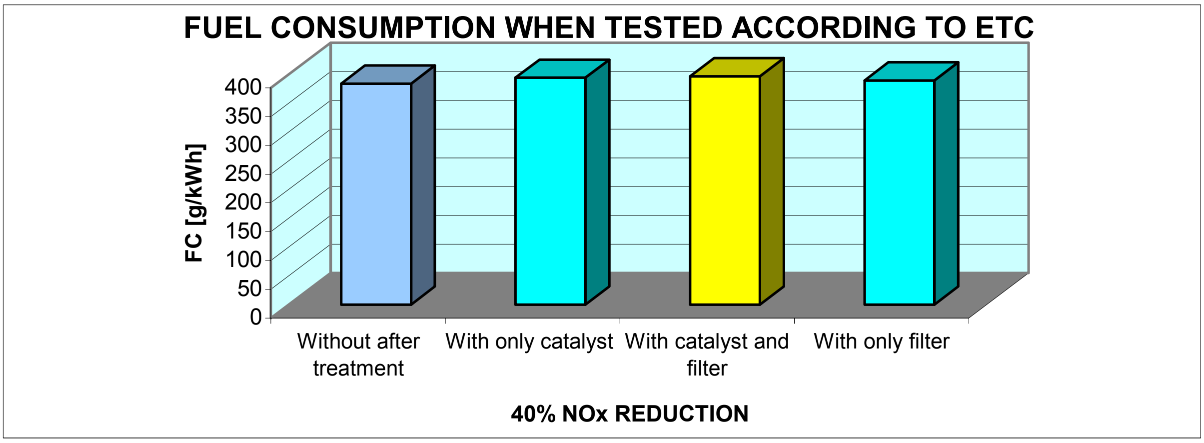

Figure 19. Fuel consumption for baseline and emission control alternatives

The patterns of the increase of fuel consumption shown in Figure 19 and the fuel penalty according to Figure 20 seems to be logical despite there being a decrease in fuel consumption when using EGR as has been reported elsewhere. It must be kept in mind that different engines may have a negative or positive EGR tolerance. The use of exhaust after treatment systems such as catalysts and particulate filters also have a negative influence on fuel consumption since they increase the back pressure in the exhaust system. It has been noted that the level of fuel penalty is somewhat higher 4.5 (Figure 20) than the increase of CO_2 emission, 3,4% (Figure 19).

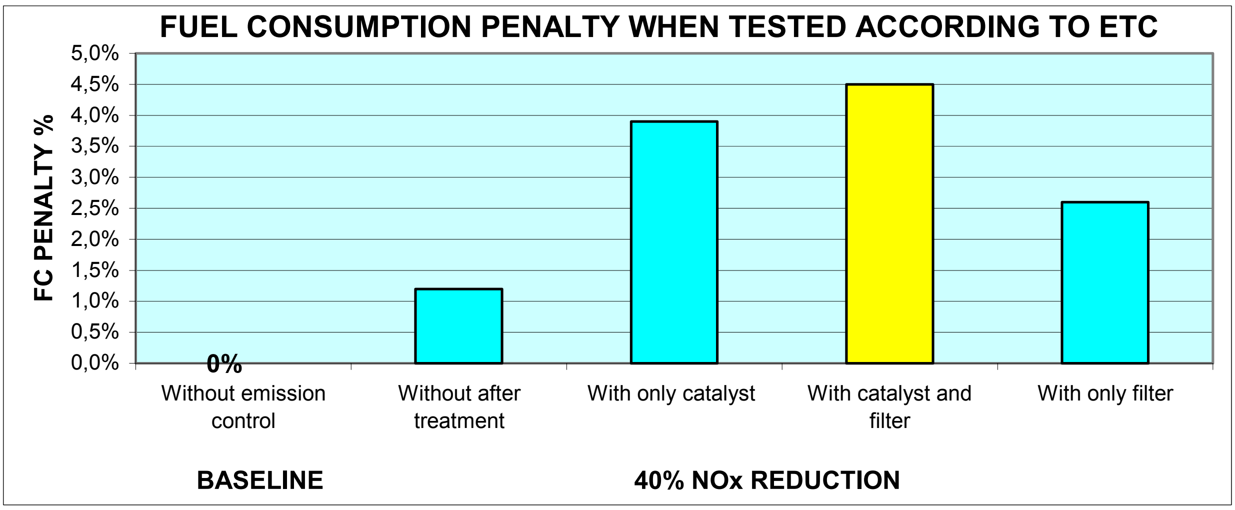

Figure 20. Fuel consumption penalty for baseline and emission control alternatives.

7.4 Safety margin up to EU standards

Emission standards in the USA specify a safety margin denoted as a deterioration factor. Such a factor was also included in the earlier Swedish emission regulations. The reason for including a deterioration factor is that it has been shown that the emission performance of a vehicle or an engine deteriorate by a certain rate during the use or operation in traffic. There are two types of deterioration factors a) factors developed by testing or investigations and b) a type of optional factors designed by the environmental authority. The deterioration factors are linked to a certain age and/or mileage of the vehicle or engine. Depending on the emission component the factor can be in the range of 1.0 to 1.3 meaning that the vehicle or engine, in the worst case, has to meet an emission level which is 30% lower than the limit value according to the standard.

However, as has already been stated above, no deterioration factors are applied to the emission standard for EU. Since there always are some variation in the production of the vehicle/engine and even uncertainties in the procedure used for determination of the emissions during certification of type testing a certain safety margins has to be applied when designing the engine and emission control system. When examining the following figures this fact should be kept in mind.

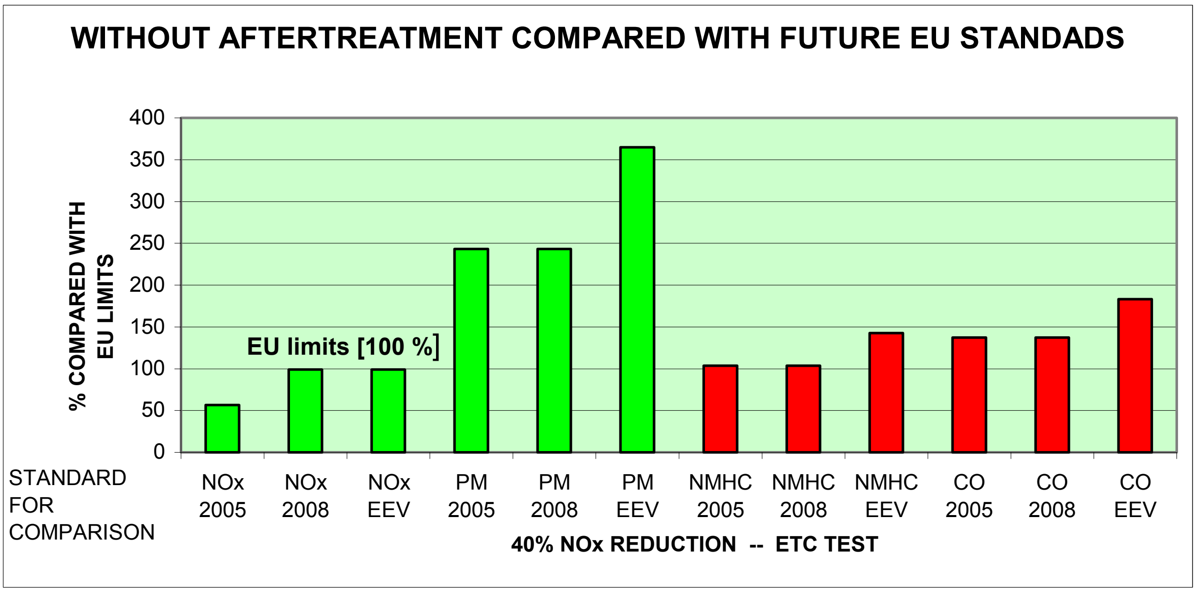

Figure 21. Level of baseline emissions compared with EU emission standards

The only emission component that in reality is lower than the standards (the 100% limit) is NO_x when compared with the 2005 level. The level of PM for example is approximately 3.6 times too high in order to meet the EEV level, Figure 21.

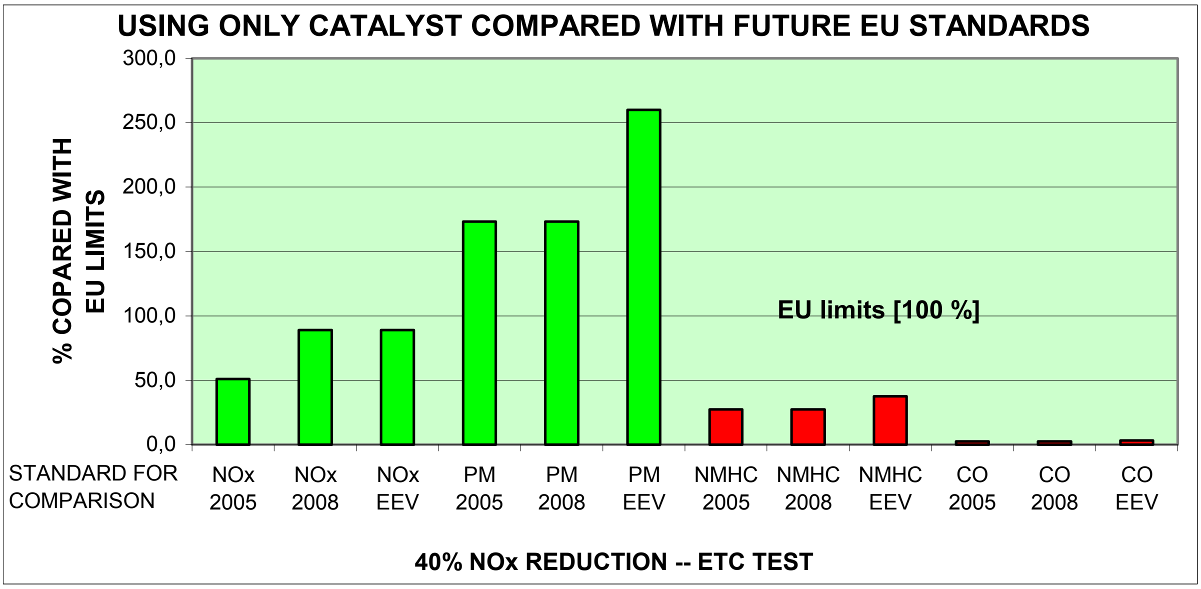

Figure 22. Emission level when using only catalyst compared with EU emission standards.

Using the catalyst seems favourable for the reduction of especially HC and CO. In combination with EGR even the standards for NO_x can be met. The possibility of using a catalyst for reduction of particles depends on the composition of the particles. If they are mainly composed by soot, which is likely when using EGR, then it is uncertain whether they can be treated with a catalyst especially if the goal is to meet the EEV limit. As can be seen of Figure 22 the actual PM level is approximately 2.6 times higher than the EEV limit.

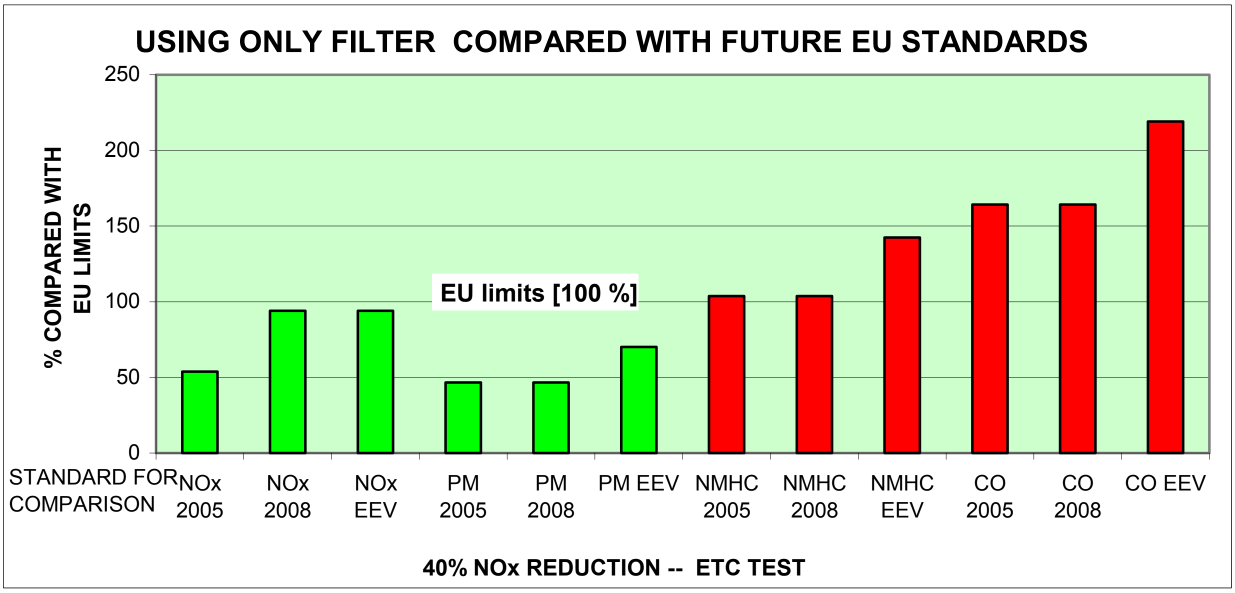

Figure 23. Emission level when using only filter compared with EU emission standards.

From Figure 23 it can easy be seen that it will not be possible to meet the EU standards with a filter alone except for the emission of particles and NO_x, but there is a question as to whether NO_x will meet the 2.0 g/kWh standard. In reality the safety margin seems to be insufficient for NO_x in order to meet these standards valid for 2008 and EEV.

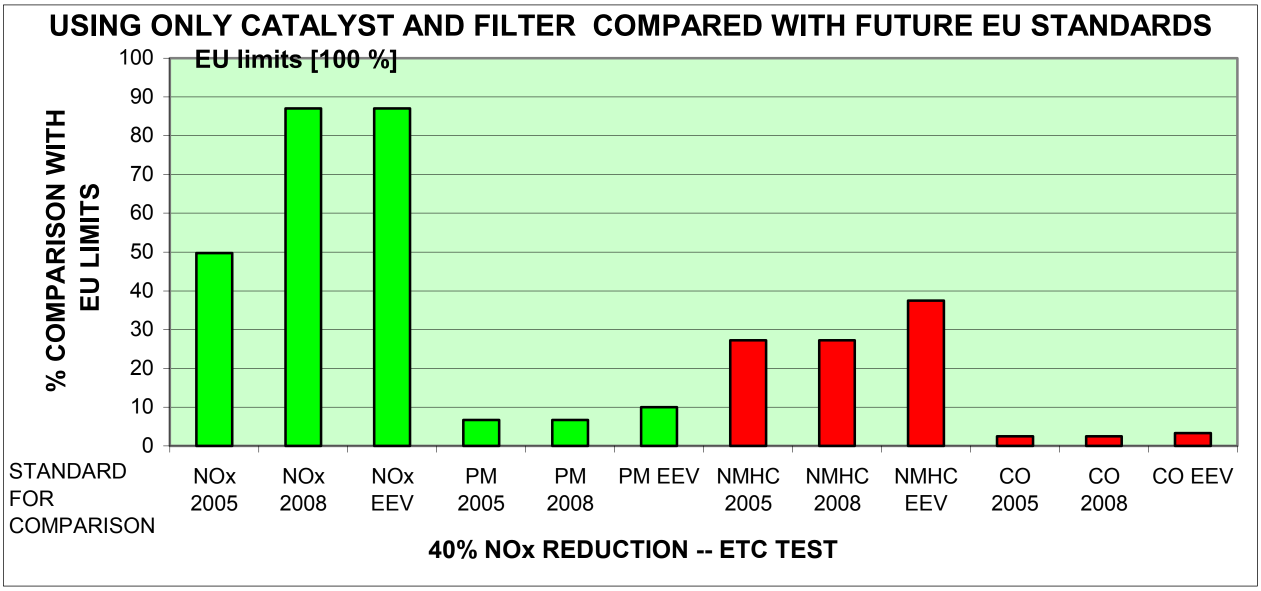

Figure 24. Emission level when using catalyst and filter compared with EU emission standards.

Figure 24 clearly indicates that it will be possible to meet all the future emission standards defined in Directive 1999/96 EC with the actual engine and the EGR setting resulting in 40% NO_x reduction when using the combination "Catalyst and filter". A higher EGR ratio and a correct matching of the whole system especially the system for after treatment of the exhaust would certainly result in an even lower emission level for NO_x. Future programs should include an updated engine, a good matching of the EGR system to that engine and an after treatment system which efficiently reduces emissions of particles, HC, CO and has a positive influence on NO_x.

8 PROPOSED NEW EURO EMISSION STANDARDS

Since the European Commission will propose a new emission standard in Spring 2005 discussions are going on between different interested parties initiated by European Commission (DG Enterprise) in order to prepare a base for standards. Two of the parts involved are the Member States and the Motor Vehicle Emission Group (MVEG). In 2003 UBA (Germany) published the following proposal for new Euro V and Euro VI emission standards for heavy-duty engines (European Federation for Transport and Environment, 2004)

Table 8. UBA proposal concerning future emission limits for heavy-duty vehicles.

Proposed limit values for emissions from heavy.duty engines (UBA, 2003) (limit values for series production)				
	EURO V 1999/96/EG from 2008/09		**EURO VI from2010**	
	ESC	ETC [1) 2)]	ESC	ETC [1) 2)]
	g/kWh	**g/kWh**	**g/kWh**	**g/kWh**
CO	**1.5**	**4.0**	**1.5**	**4.0**
HC	**0.46**		**0.46**	
NMHC		**0.55**		**0.55**
Methane		**1.1** [3)]		**1.1** [3)]
NO_x	**1.0**	**1.0**	**0.5**	**0.5**
Particulates	**0.002**	**0.003**	**0.002**	**0.003**

1) Additional transient test for diesel engines with exhaust after treatment systems.
2) For gas engines transient test only. 3) For natural gas engines only.

The Euro V limits according to the UBA proposal are regarded to be achievable with a refined emission control system of about the same type as the system tested during this project. The main problem seems to be the penalty of fuel consumption since it raises steeply after the EGR-ratio resulting in 60 % NO_x reduction according to Figure 5. Since at least of fuel penalty is caused by the particulate filter in combination with the catalyst a great part of the work must be laid down for a proper matching of the exhaust after treatment system. An upgrading of the engine and especially the fuel system is needed.

In order to meet the proposed emission limits "from 2010" the use of a more thoroughly developed engine and the emission control system is deeded. The engine and the emission control system must be matched to each other, meaning that this is to be a case for an engine manufacturer. The main difficulties with these standards are to meet the requirement for NO_x and at the same time minimize the fuel penalty. One way to reduce the cost of the fuel could be to develop the engine in a way to make it possible to use an alternative to the ignition improver used today as an additive in the ethanol fuel. Two of these candidate ignition aids are spark plugs and glow plugs and both of these, but they have also been used in different trials or test fleets of alcohol fuelled engines.

CONCLUSIONS

The purpose of this investigation was to study whether an ethanol fuelled heavy duty engine which was already in production for use in city buses could be equipped with an exhaust control system, and that it could be verified at what level the future EU emission standards can be met or surpassed if this emission control system is used. The engine was taken to a company named STTEmtec, working in the field of automotive engines and emission control.

At STT Emtec the engine was installed on an engine test bed and equipped with a system for exhaust gas recirculation (EGR) named DNO_x™ and with different systems for exhaust gas after treatment. An extensive program especially for emission testing, designed by STT Emtec was carried out, evaluated and summarized in a short report. The report has been subject to further evaluation sponsored by the BioAlcohol Foundation (Baff) in Sweden. This report is the result of the further evaluation. The purpose of the evaluation of the data and the preparation of the report has been to clearly present what has been achieved by the program at STT Emtec and what could possibly be achieved with further development of especially the system for after treatment of the exhaust in combination with a further developed engine.

When considering the positive influence on the emissions of EGR and the after treatment devices used and the negative effect on the fuel consumption, it is obvious that the most favourable alternative for this engine is an EGR ratio related to 40% NO_x combined with an exhaust after treatment system. Furthermore, during the evaluation it became clear that the goal of meeting the future EU emission standards defined as "B2 (2008)" and "C (EEV)" in Table 1 during this investigation could only be reached with the combined exhaust after treatment system including a catalyst plus filter. Therefore the further evaluation was focused on this combination. That does not mean that no other alternative could be of interest.

A refined system including the engine and emission control system could certainly result in even lower emission limits being achieved with fewer components in the system.

Especially when retrofitting an engine or a vehicle there is a need to keep the cost at a minimum. In this case it may be possible to use an exhaust after treatment system with only one component instead of two. Based on the evaluation of the data generated during this investigation it seems likely that a particulate filter with a rather efficient catalytic function could meet the emission standards defined in Directive 1999/96 EC. On the other hand there are some uncertainties as to whether all of these emission limits can be met using only a catalyst. It is likely that the particles formed during the combustion process in the engine when using EGR will form carbonaceous particles. In that case it may be difficult to treat the particulate emissions using only a catalyst. An efficient filter may be needed.

To sum up the result of the work including the adaptation of the EGR system and the testing it has proved to be successful in that:

*The function of the EGR system was really good even at higher EGR ratios

*The particulate emissions could be kept to a really low level, despite the fact that the systems tested for after treatment of exhaust were not adapted to the engine and not tested in order to select the best design when considering their ability to treat the emissions of high priority.

*Despite the fact that the program for the investigation was primarily limited to study the influence on the emissions of EGR, the future emission standards can be met with a limited setting of the EGR ratio and if the actual engine adapted after treatment system.

*The fuel consumption penalty was moderate with the selected setting of the EGR ratio "40% NO_x reduction" and could certainly be reduced by an optimal matching between the base engine and the EGR.

*The results and experiences achieved show that even lower emission levels, especially for $NO_{x,}$ could be reached with an ethanol fuelled engine.

Looking beyond the emission standards defined in Directive 1999/96 EC, work is going on within a subgroup of the Motor Vehicle Emission Group (MVEG) with the purpose of developing new emission standards within the European Commission. A Proposal for new Euro V and Euro VI emission standards have been published by UBA in Germany. The proposal includes both light duty-vehicles and heavy-duty engines. The outcome of the work within MVEG will certainly be of interest for all of these involved in the development of automotive engines and emission control systems.

The question is what the outcome of the work initiated by European Commission (DG Enterprise) will be in terms of new standards and what may be needed to meet the standards. The time schedule for these standards is that they will be in force from 2008/2009 for Euro V and from 2010 for Euro VI.

With regard to the status of the ongoing engine development and the emission control technology available today the limits proposed by UBA will certainly be reached with a number of diesel fuelled engines within the proposed time frame. Concerning alcohol fuelled heavy-duty compression ignition engines it will certainly be easier to meet the emission limits proposed by UBA. The reason for this is that both the "engine out" critical emission parameters NO_x and particles from an alcohol fuelled engine have been shown to be on a lower level than from a diesel engine. Therefore it is believed that the effort and cost for the development of an alcohol fuelled engine meeting the future emission standards will be considerably less than for the development of a diesel engine meeting these standards.

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APPENDIXES

APPENDIX I
Results from measurements of particle size and distribution

APPENDIX II
Figures showing emission levels and fuel consumption for different alternatives.

APPENDIX III
Figures, prepared by Charlie Rydén, Protima AB, showing the development of emission limits over time.

APPENDIX 1. PARTICLE NUMBER AND SIZE.

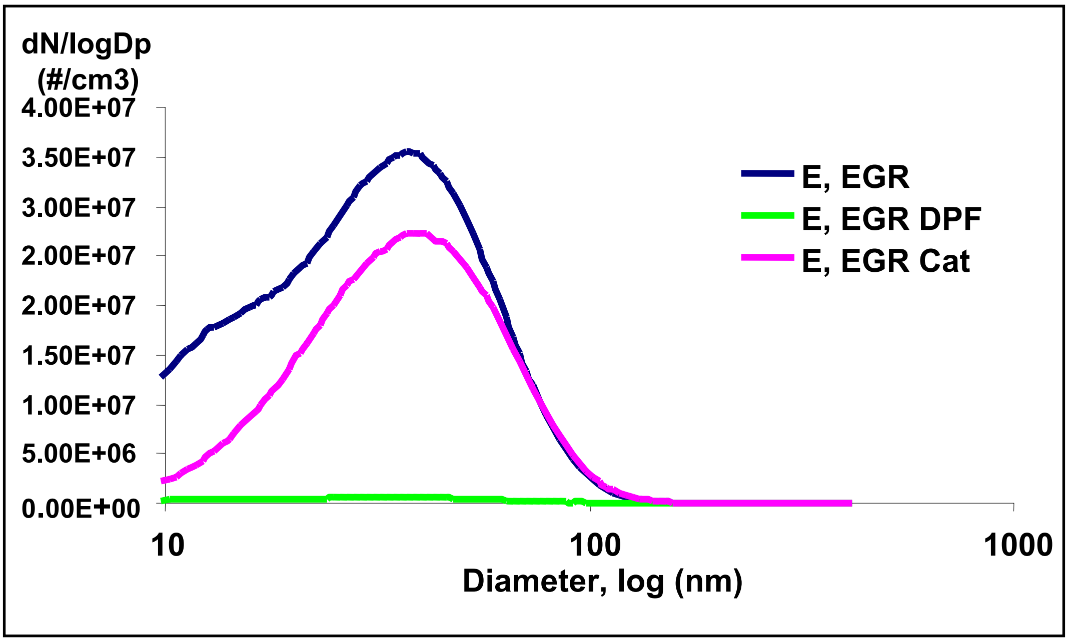


Figure A: Normal particle distribution

Figure A shows the weighted distribution of particles detected during test in accordance with ESC. As can be seen the catalyst used for this investigation had only a moderate influence on the particle emission.

No visible reduction occurs for particles larger than approx. 65 nm. The largest reduction occurs for particles smaller than 20 nm. The reduction using the particulate filter was too great to enable a comparison between the different alternatives for exhaust emission control. Consequently a supplementary figure with a logarithmic scale was constructed and is shown in Figure B.

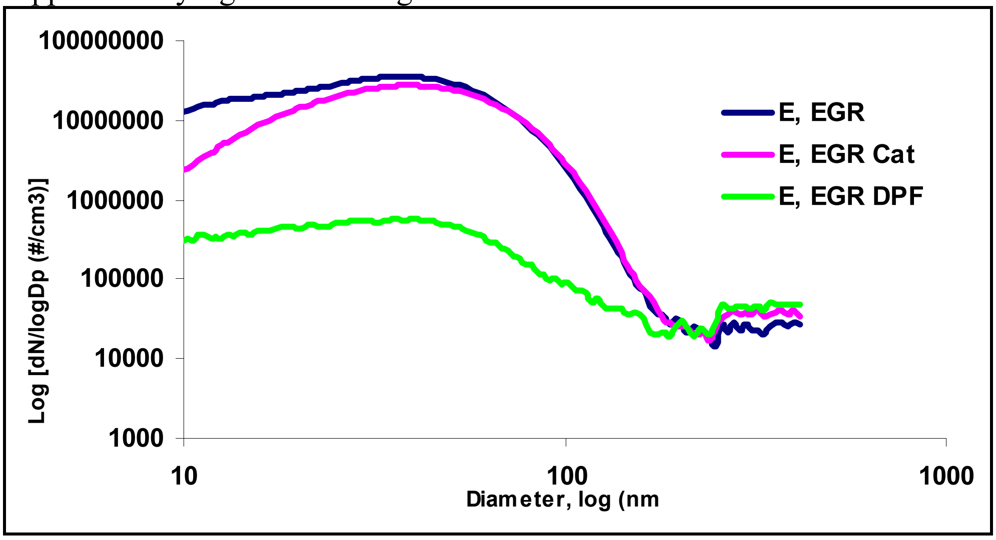


Figure B Particle distribution, Logarithmic scale, x-, y-axle

Figure B clearly validates the above mentioned effect observed during the measurement of particles, namely that particles smaller than approx. 65 nm were reduced by the catalyst, which also can be seen in Figure B by comparing E, EGR; E, EGR Cat; and E, EGR DPF with each other. With the particulate filter as an exhaust emission after treatment device a strong reduction of the number of particles occurred and the particles being reduced by several decades, see Figure B. It should be underlined that the particle mass is not influenced to the same degree as the number of particles. Since the number of larger particles increases for both the catalyst and the particulate filter the result of the exhaust gas treatment could be that the mass of particles increases. Therefore Figure C and Figure D were constructed in order to collect and present more information about the function of the exhaust after treatment systems. In Figure C the number of particles is presented and in Figure D the estimated mass of particles emitted.

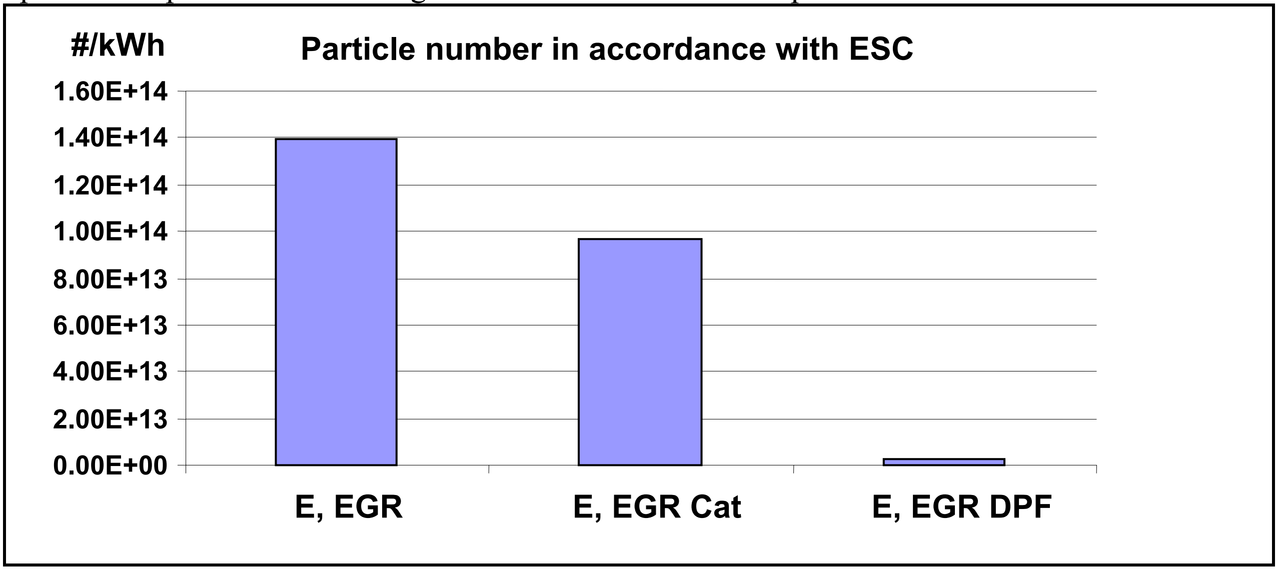


Figure C. Particles emitted from the actual engine tested according to ESC.
Data as presented in the figure: 1.40 10^{14} #/kWh, 9.69 10^{13} #/kWh, 2.57 10^{12} #/kWh.

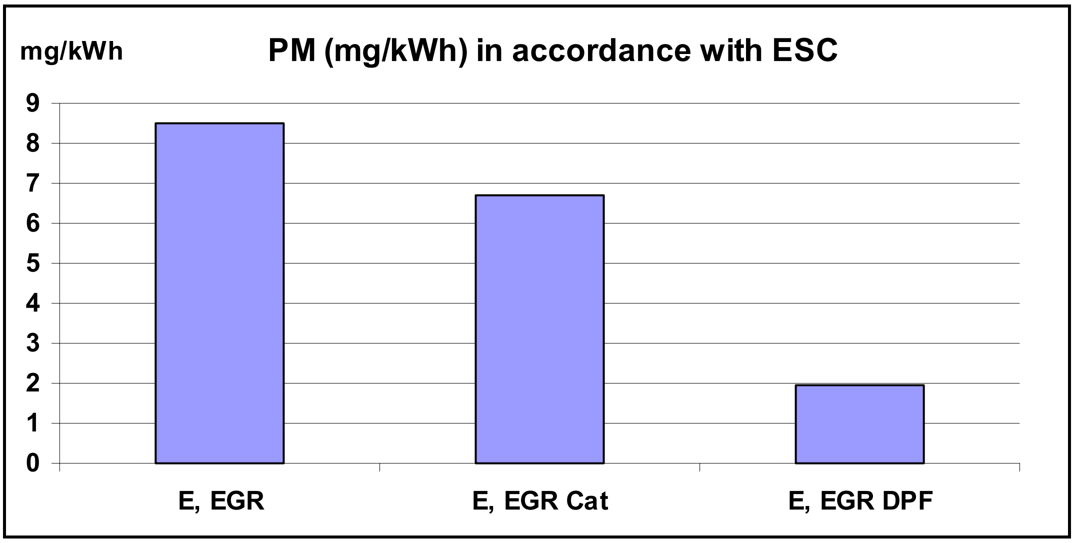
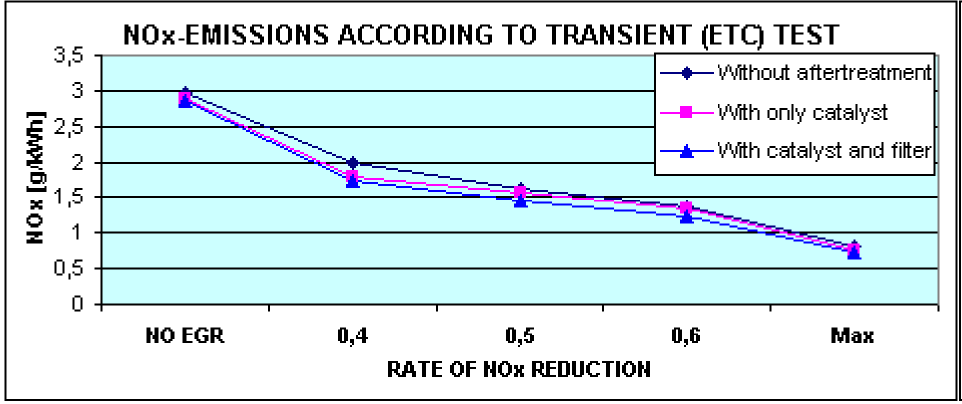
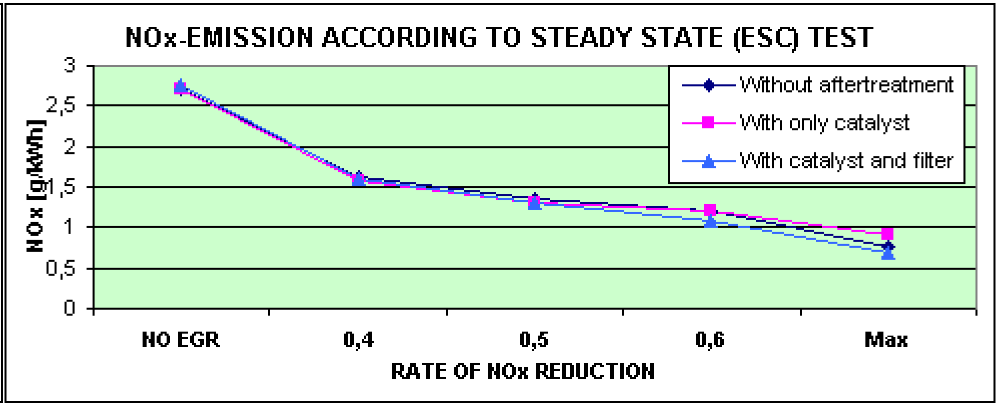


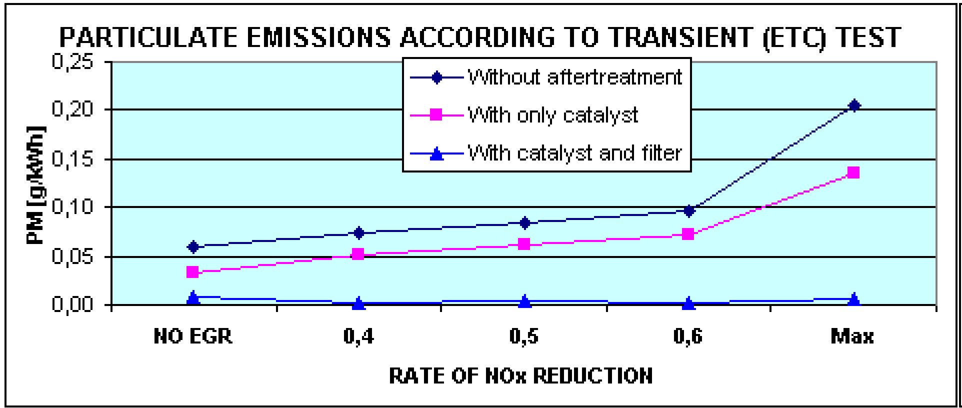
Figure D: Estimated particle mass emitted from the engine when tested according to ESC. Data as presented in the figure: 8.50 mg/kWh, 6.71 mg/kWh, 1.93 mg/kWh

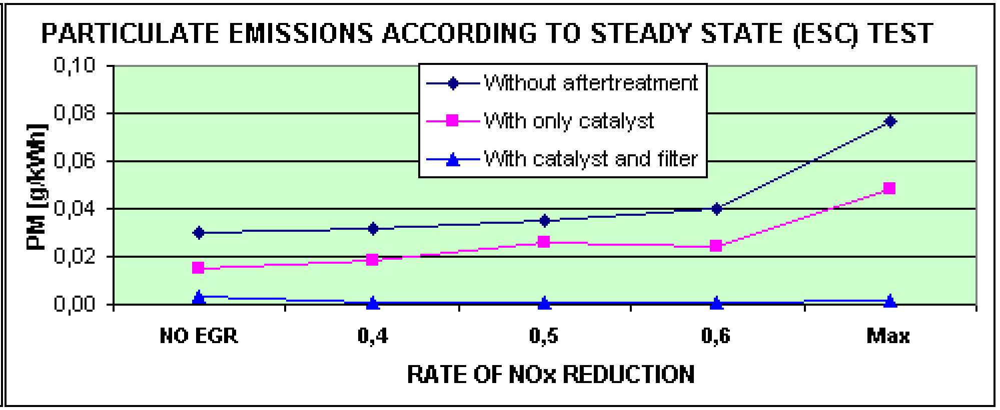
In order to sum up the findings of the investigation it can be said that this study confirmed the previously found facts that the use of EGR results in an increase of the particulate emissions. For comparison, results from research on the same type engine showed that this engine emitted approx. six times more particles with EGR than without EGR (SAE paper 2004-01-1987). Furthermore, another study presented in the same SAE paper showed that a somewhat similar engine diesel engine fuelled with diesel oil, Swedish MK 1, emitted 1.5 times more particles without EGR compared to the ethanol fuelled diesel engine in this study with EGR. When the ethanol engine was running in accordance to ESC, see figure D, the particle mass emissions was reduced by up to 77% with a diesel particulate filter but only by 21% when a catalyst was used. Corresponding figures for the particulate number emissions, see figure C, were reductions up to 98%, with the DPF and up to 31% with the catalyst.

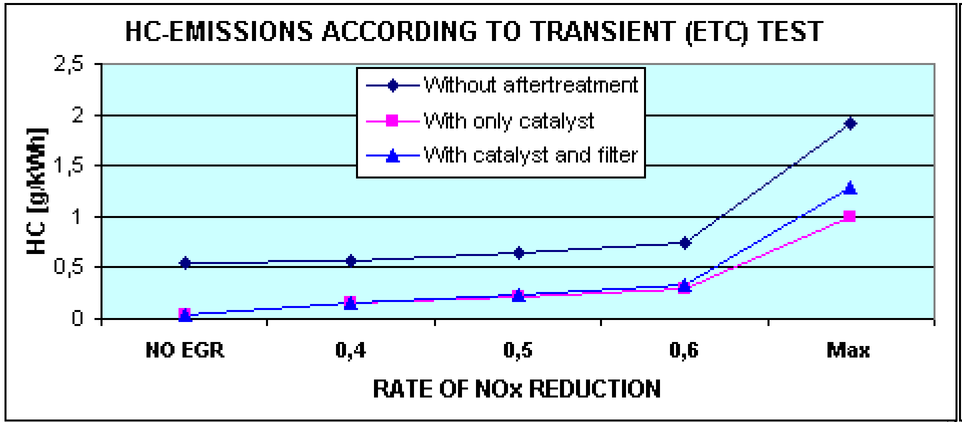
APPENDIX 2. RESULT FROM EMISSION TEST ACCORDING TO ETC AND ESC RESPECTIVELY

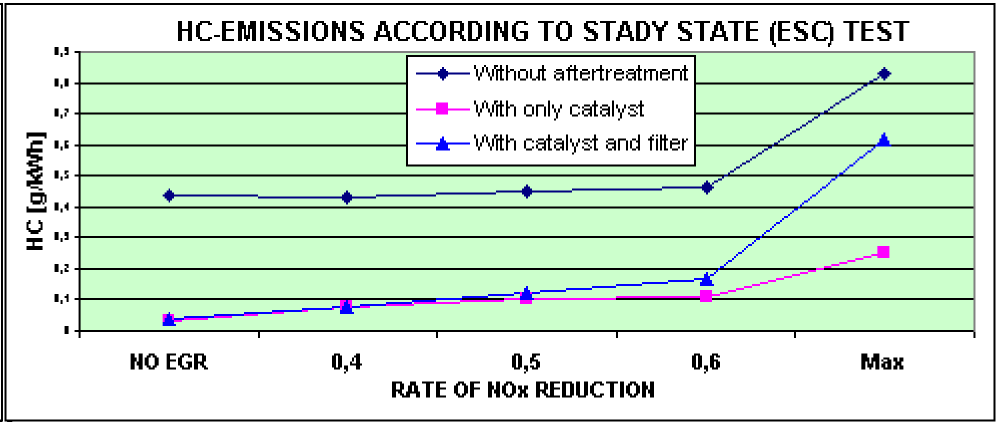


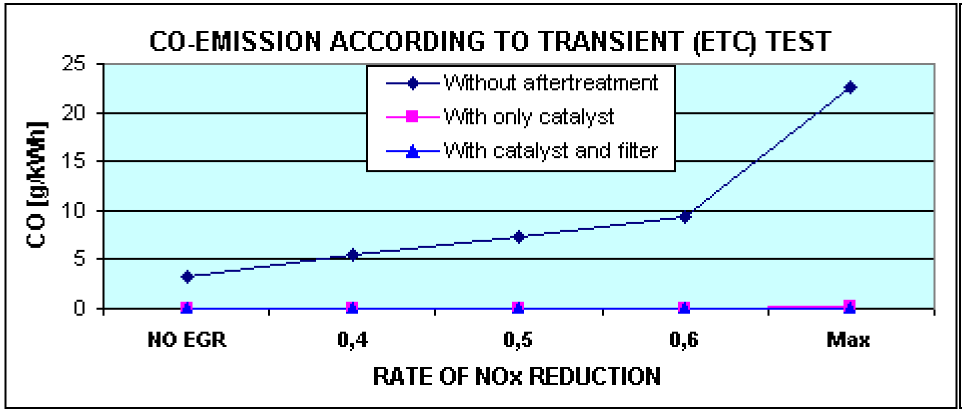


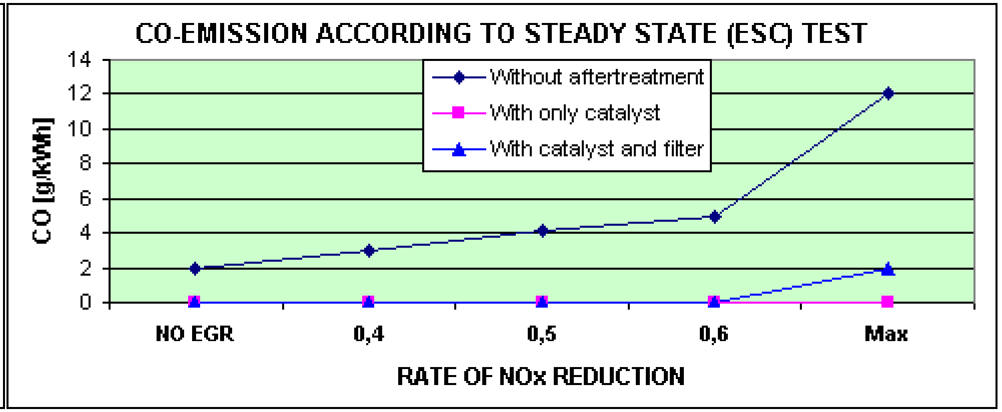


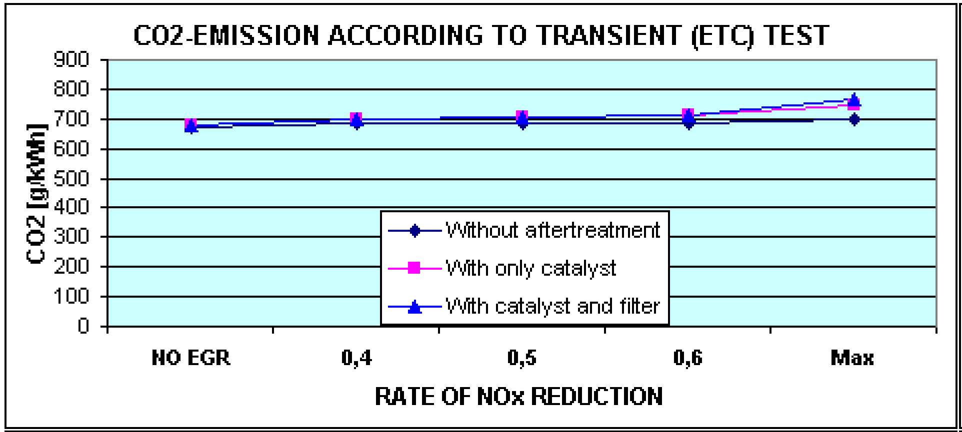


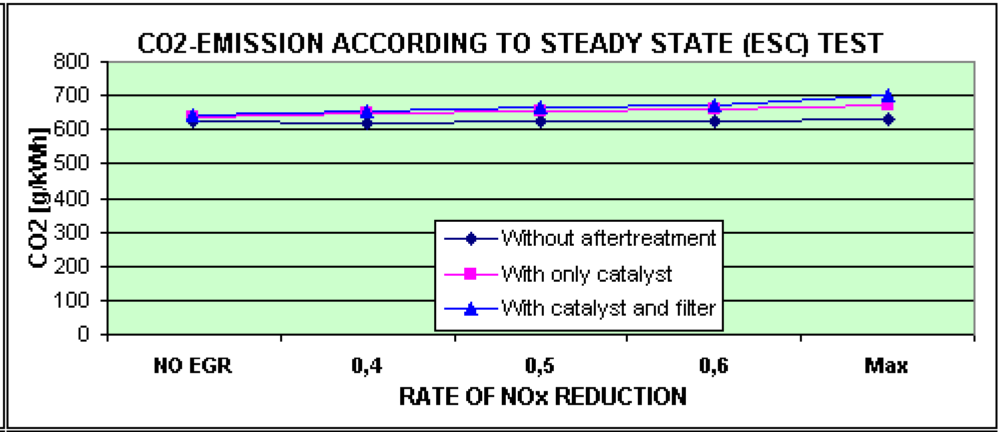


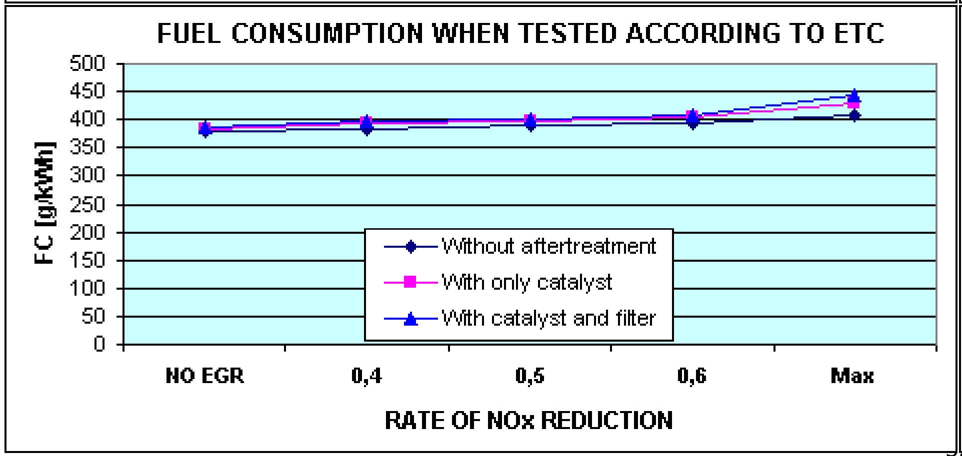


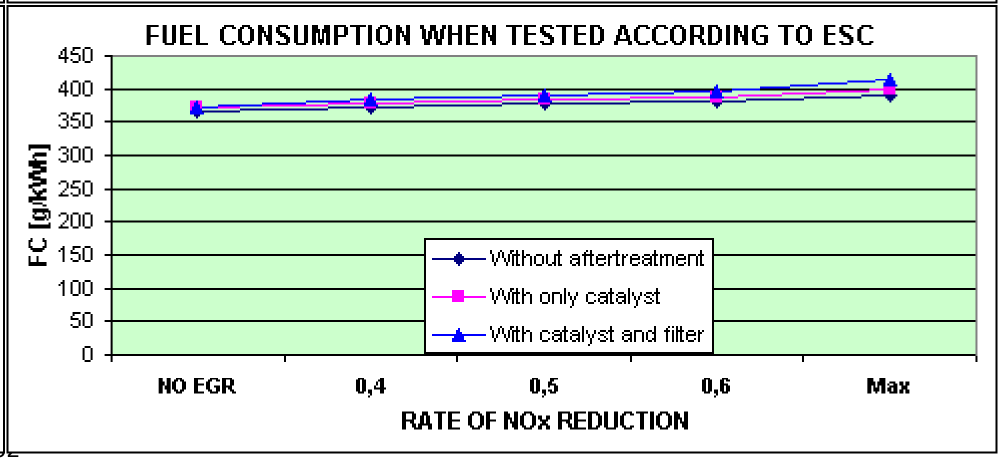

CO-EMISSION ACCORDING TO TRANSIENT (ETC) TEST
CO [g/kWh]
25
20
15
10
5
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

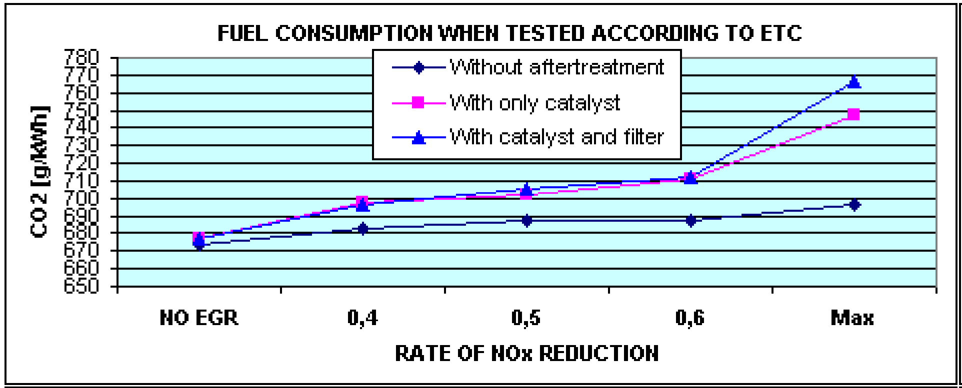

CO-EMISSION ACCORDING TO STEADY STATE (ESC) TEST
CO [g/kWh]
14
12
10
8
6
4
2
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

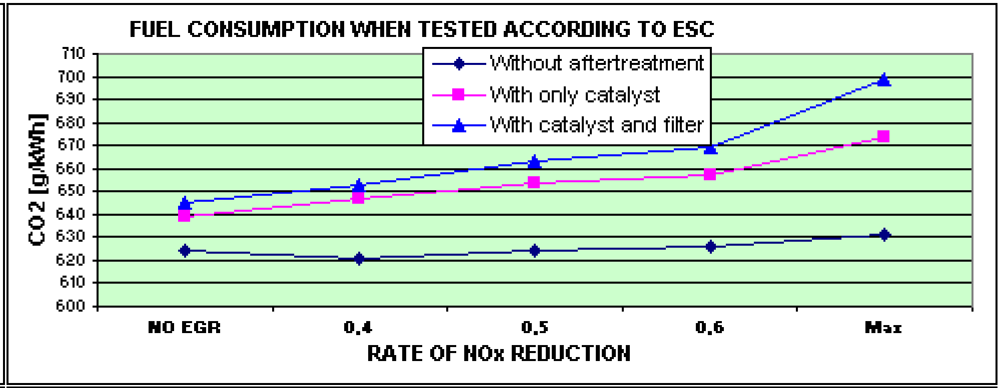

CO2-EMISSION ACCORDING TO TRANSIENT (ETC) TEST
CO2 [g/kWh]
900
800
700
600
500
400
300
200
100
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

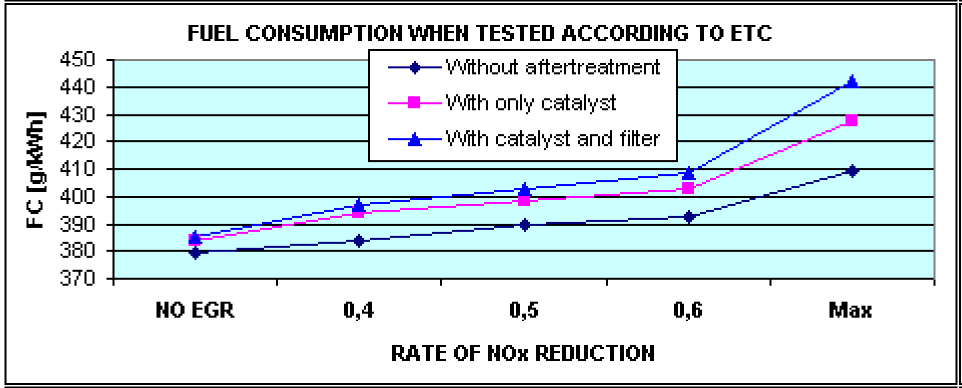

CO2-EMISSION ACCORDING TO STEADY STATE (ESC) TEST
CO2 [g/kWh]
800
700
600
500
400
300
200
100
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

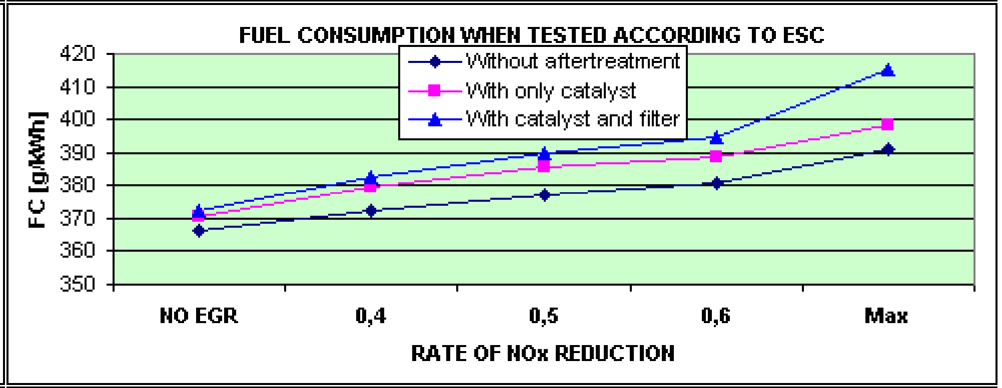

FUEL CONSUMPTION WHEN TESTED ACCORDING TO ETC
FC [g/kWh]
500
450
400
350
300
250
200
150
100
50
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

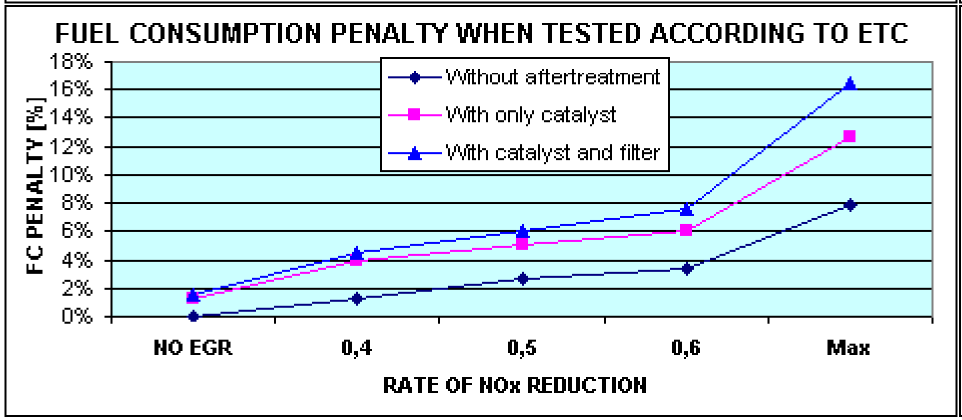

FUEL CONSUMPTION WHEN TESTED ACCORDING TO ESC
FC [g/kWh]
450
400
350
300
250
200
150
100
50
0
Without aftertreatment
With only catalyst
With catalyst and filter
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

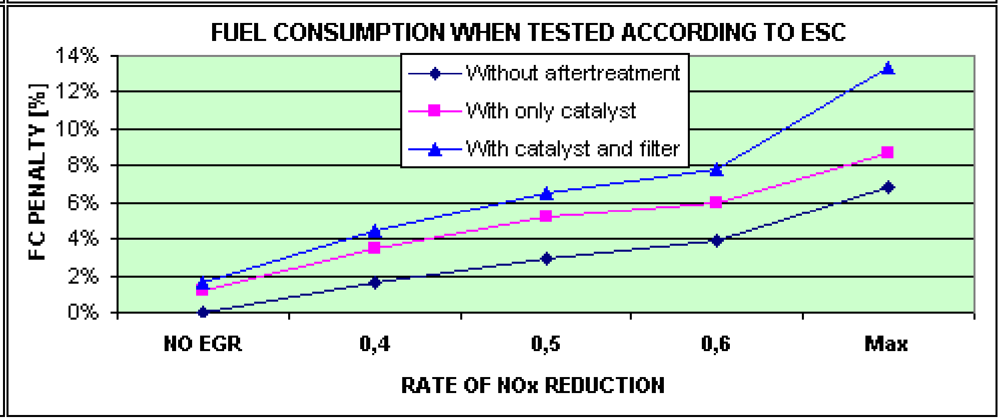

FUEL CONSUMPTION WHEN TESTED ACCORDING TO ETC
Without aftertreatment
With only catalyst
With catalyst and filter
CO2 [g/kWh]
780
770
760
750
740
730
720
710
700
690
680
670
660
650
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION


FUEL CONSUMPTION WHEN TESTED ACCORDING TO ESC
Without aftertreatment
With only catalyst
With catalyst and filter
CO2 [g/kWh]
710
700
690
680
670
660
650
640
630
620
610
600
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

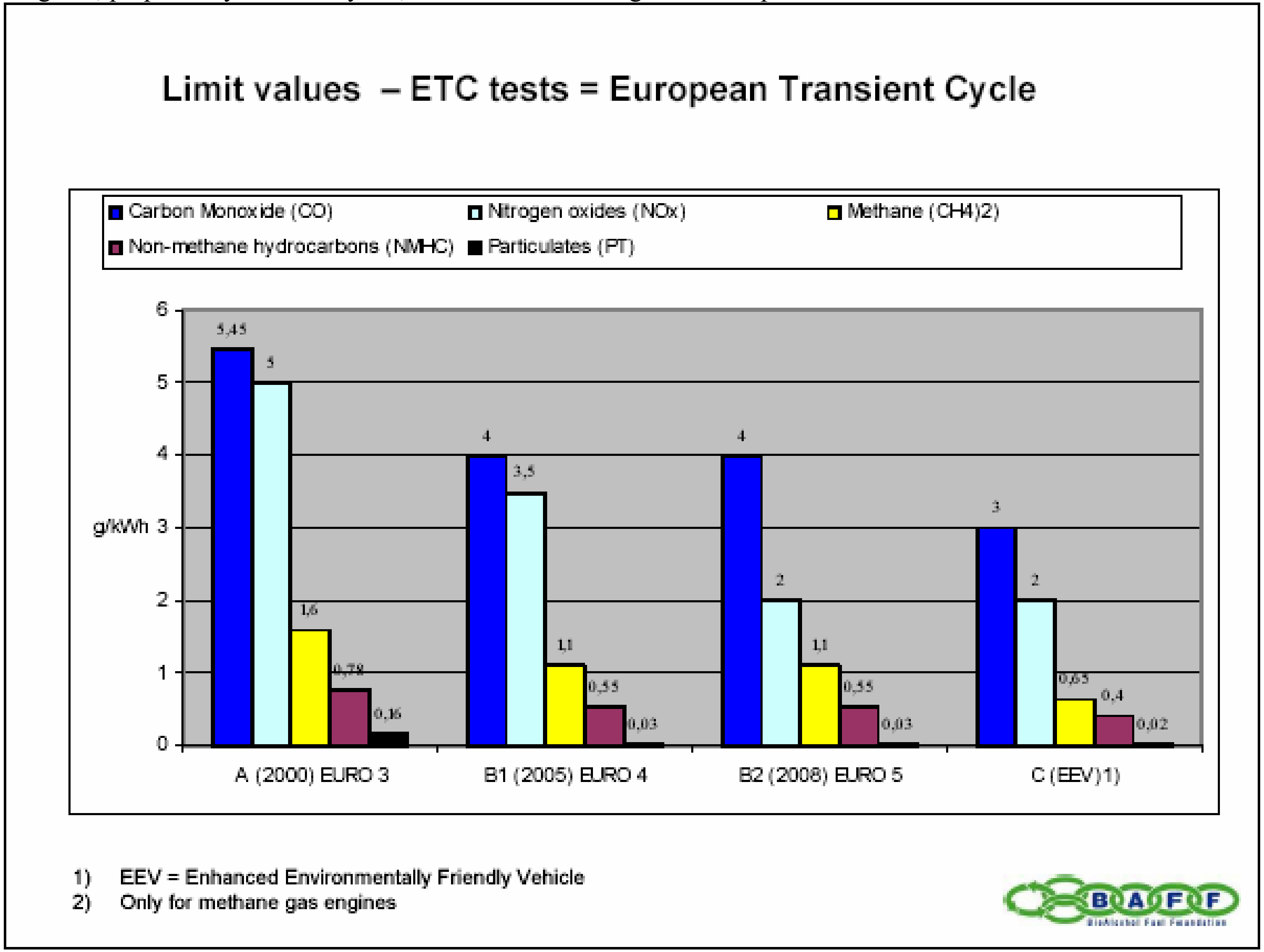

FUEL CONSUMPTION WHEN TESTED ACCORDING TO ETC
Without aftertreatment
With only catalyst
With catalyst and filter
FC [g/kWh]
450
440
430
420
410
400
390
380
370
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

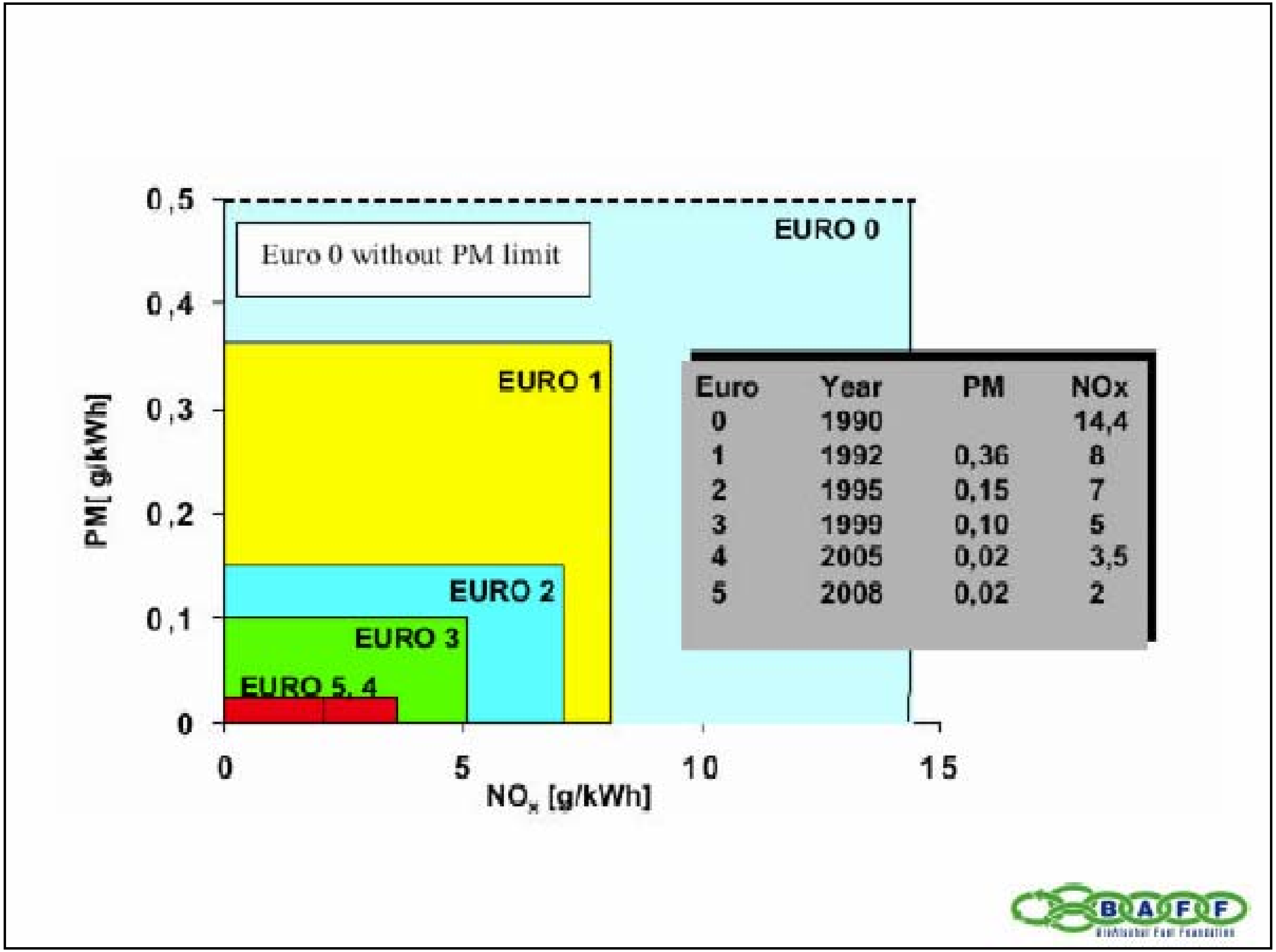

FUEL CONSUMPTION WHEN TESTED ACCORDING TO ESC
Without aftertreatment
With only catalyst
With catalyst and filter
FC [g/kWh]
420
410
400
390
380
370
360
350
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION


FUEL CONSUMPTION PENALTY WHEN TESTED ACCORDING TO ETC
Without aftertreatment
With only catalyst
With catalyst and filter
FC PENALTY [%]
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION


FUEL CONSUMPTION WHEN TESTED ACCORDING TO ESC
Without aftertreatment
With only catalyst
With catalyst and filter
FC PENALTY [%]
14%
12%
10%
8%
6%
4%
2%
0%
NO EGR
0,4
0,5
0,6
Max
RATE OF NOx REDUCTION

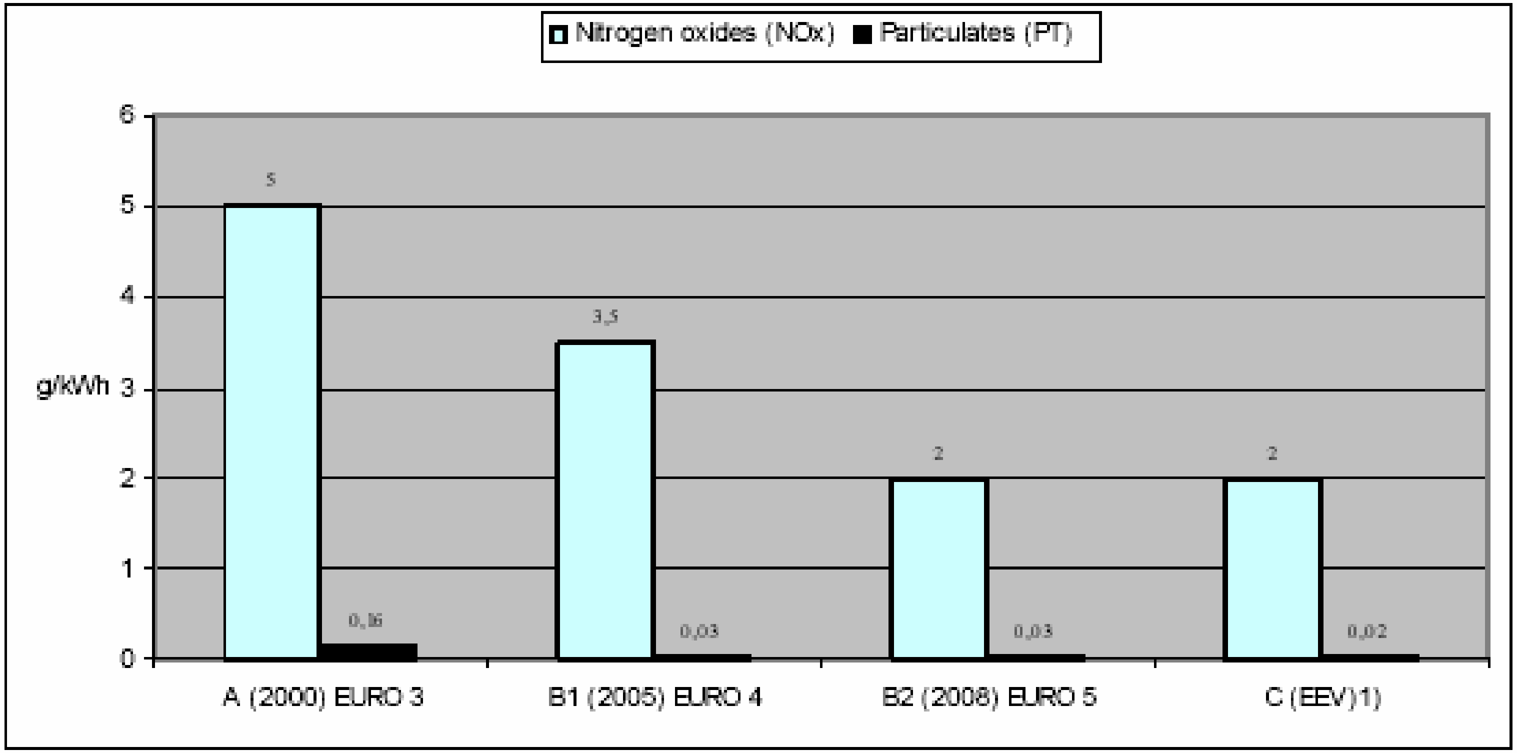
APPENDIX III: Figures, prepared by Charlie Rydén, Protima AB, showing the development of emission limits over time etc.



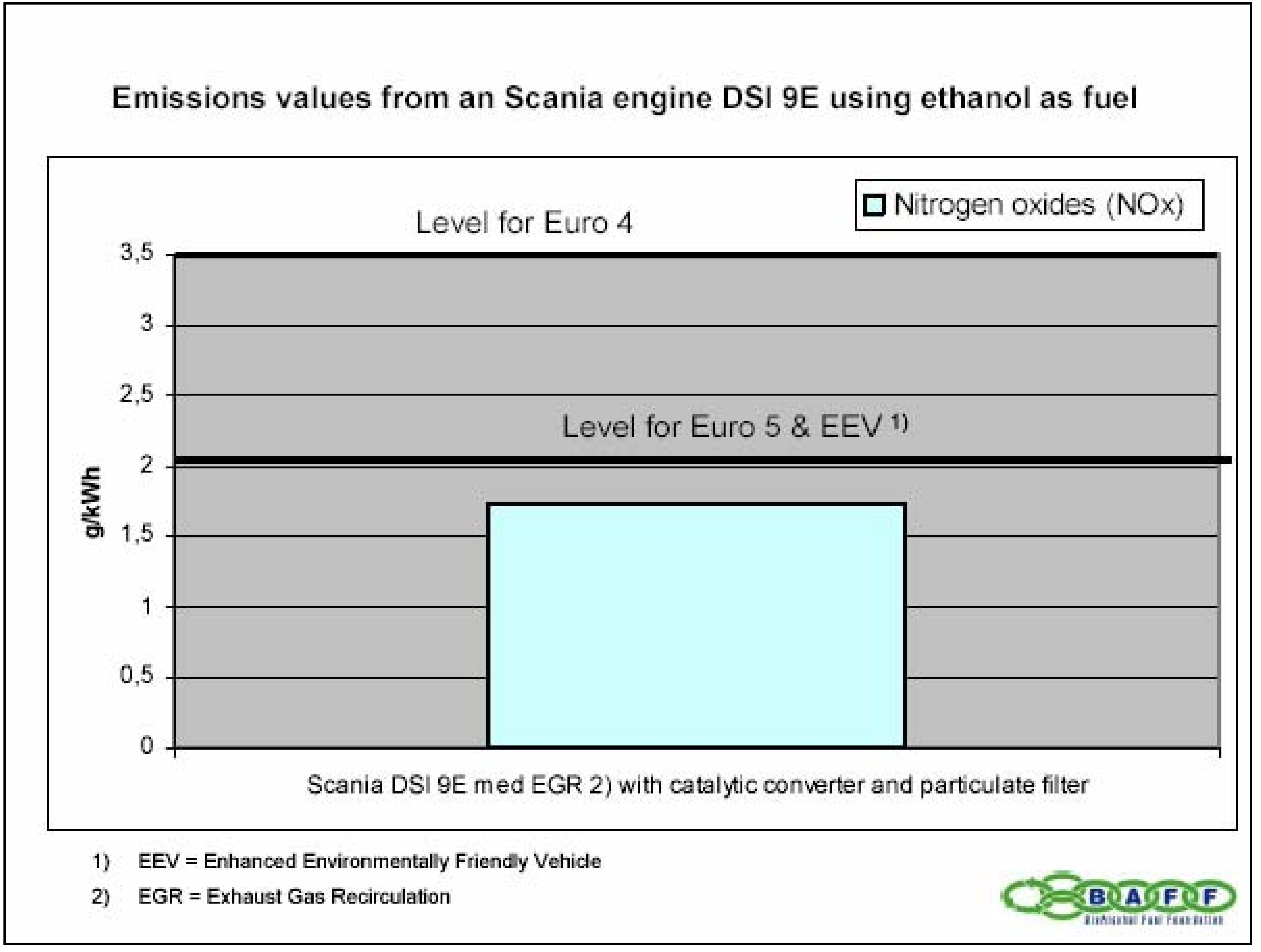


0,5
0,4
0,3
0,2
0,1
0
PM[g/kWh]
Euro 0 without PM limit
EURO 0
EURO 1
EURO 2
EURO 3
EURO 5, 4
0
5
10
15
NO_x [g/kWh]
Euro Year PM NOx
0 1990 14,4
1 1992 0,36 8
2 1995 0,15 7
3 1999 0,10 5
4 2005 0,02 3,5
5 2008 0,02 2
BAFF

Limit values – ETC tests = European Transient Cycle

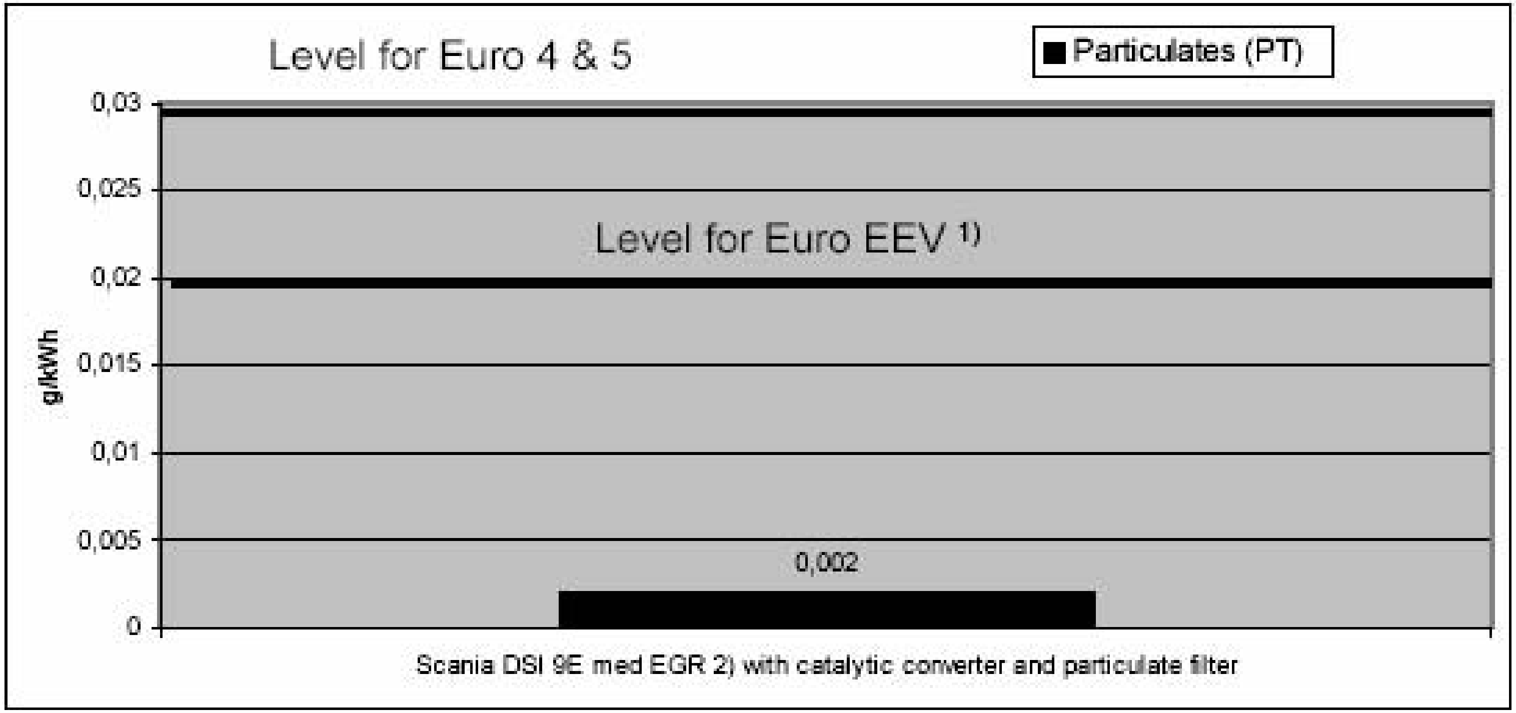


1) EEV = Enhanced Environmentally Friendly Vehicle
2) Only for methane gas engines



Emissions values from an Scania engine DSI 9E using ethanol as fuel
Nitrogen oxides (NOx)
Level for Euro 4
Level for Euro 5 & EEV 1)
g/kWh
3,5
3
2,5
2
1,5
1
0,5
0
Scania DSI 9E med EGR 2) with catalytic converter and particulate filter
1) EEV = Enhanced Environmentally Friendly Vehicle
2) EGR = Exhaust Gas Recirculation

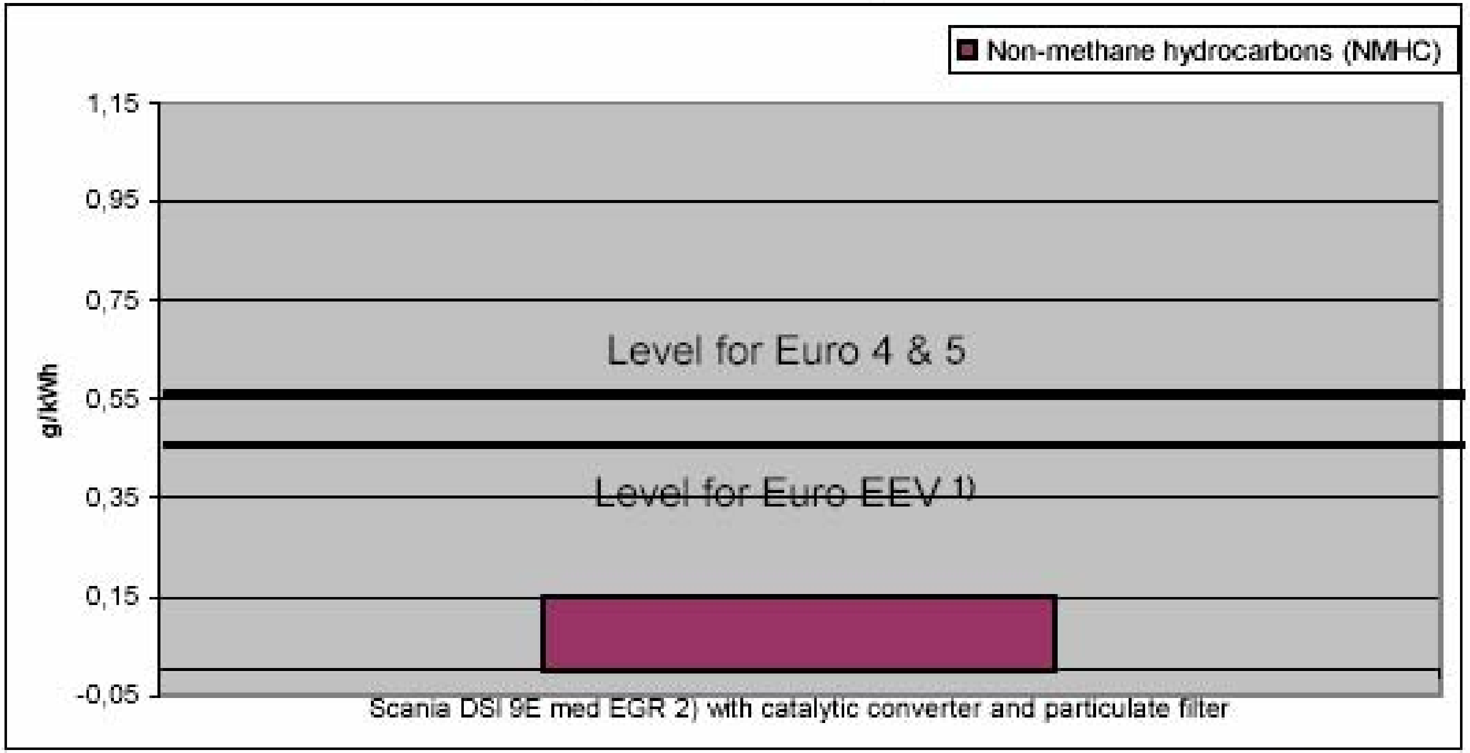
Emissions values from an Scania engine DSI 9E using ethanol as fuel



1) EEV = Enhanced Environmentally Friendly Vehicle
2) EGR = Exhaust Gas Recirculation

Emissions values from an Scania engine DSI 9E using ethanol as fuel

Limit values – ETC tests = European Transient Cycle



1) EEV = Enhanced Environmentally Friendly Vehicle

2) EGR = Exhaust Gas Recirculation