Comparing Exhaust Emissions From Heavy Duty Diesel Engines Using EN 590 vs. Mk1 Diesel Fuel

Literature Study

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ABSTRACT

This literature study is fully financed by the Swedish Transport Administration (STA) with the main objective to gather information whether there still is an emission gain to be found, on a national level, from the present Swedish diesel fuel quality, focusing on the use in heavy duty on-road applications and non-road mobile machinery (NRMM).

The literature study has been carried out by AVL MTC. A reference group consisting of members from the main stakeholders from the Swedish oil industry and heavy-duty vehicle industry was formed by STA and have been contributing with material and expertise.

A large number of reports and other information material were potentially suitable for this study. More than half of the material initially collected did, however, not have enough data or the correct criteria to be included in this study. The most common imperfects was either the fuel quality (not Mk1 and EN 590 used in parallel) or engine technology (light duty diesel of pre Euro III heavy-duty engines). The material that past the criteria's and has been used in this literature study can be found in the reference list in the end of this report.

Sweden has for quite some time been ahead of most other countries in Europe when it comes to automotive fuel qualities. This is particularly true for its diesel fuel quality. Since the beginning of the 1990: ies Environmental Class 1 diesel (Mk1), according to SS 15 54 35, has been the dominating diesel fuel quality in Sweden for the transport sector. This fuel was designed to reduce regulated and un-regulated emissions compared to the standard European diesel fuel of that time and further, to open up for the use of exhaust aftertreatment devices, as example, particle filters.

Over the years the European diesel fuel quality, specified according to EN 590, has improved and today the European and Swedish fuel qualities are much closer than what was the case 15 – 20 years ago.

During the same period, emission legislations for heavy duty diesel engines have emerged from Pre-Euro up to Euro VI/EEV for on-road applications and from no legislation up to Stage IV for non-road applications.

The major questions to be answered with this literature study are; Is there still emission benefits when using Mk1 diesel fuel compared to current European diesel fuel qualities and how sensible (related to emissions) are newer technology heavy duty diesel engines for the remaining differences between Swedish Mk1 diesel and the European EN 590 diesel fuel qualities? The focus was to identify significant differences in tail pipe emission from heavy duty engines using Mk1 and EN 590 diesel fuels and also to identify any gaps in the current knowledge. A further objective was to make a quality assessment of available material.

Data from 4 engines meeting Euro III emission requirements, 5 engines meeting Euro IV emission requirements, 1 engine meeting Euro V emission requirements and 3 engines meeting Stage I emission requirements for NRMM has been used.

The conclusion is that data and experience from on-road Pre-Euro up to Euro III and non-road Stage I technologies are sufficient to conclude that Mk1 still has significant emission benefits in those applications.

The literature study has identified significant gaps in knowledge, especially for newer engine technologies. Even though engines meeting Euro IV emission requirements had the largest number of engines from the same emission category in this literature study, the knowledge bank is insufficient. Of the 5 Euro IV engines included in the study, 2 of them were prototype engines and most likely not representative for series production engines. On 1 of the others the exhaust emission aftertreatment system was modified. The 2 remaining engines are most probably not Volvo or Scania and therefore not representative for the Swedish vehicle fleet.

It is also quite clear that we are lacking information on the latest engine technologies, such as Euro V/EEV, Stage IIIA and Stage IIIB.

The study verified benefits on NO_x, PM, PAH, PN and bio reactivity when using Mk1 diesel fuel. This has been the case in most investigations and in all the engine technology covered in this literature study.

When it comes to regulated emissions, engines of different engine technologies reacted in similar ways to Mk1 diesel fuel compared to EN 590. In other word, the relative emissions benefits found when comparing the two fuels used in engines meeting emission requirements according to Euro III, IV and V respectively was quite constant. This strengthens the apprehension that fuel formulation is of vital importance for the emission performance. But as the regulated emissions have been reduced with the newer engine technologies the differences in gram per kWh between the fuels have decreased.

Looking at the un-regulated emissions and bio reactivity the influence of the newer engine technologies was not as clear. It is unclear if newer engine technologies give a real emission benefit. What is important to high light is however that Mk1 still gave substantial emission benefits also on most un-regulated emissions and reduces the bio reactivity.

The recommendation regarding further investigations on emission benefits when using Mk1 specification diesel compared to EN 590 would be to focus on Euro IV, Euro V and Stage IIIA and IIIB engines. A special focus on un-regulated emissions, particle numbers and bio reactivity would be desirable. A further continuation of this project might be the case. Focus will then be on actual testing and analyses of the exhausts to fill the identified gap of knowledge.

Measurement accuracy and repeatability

Emission regulations in general are surrounded by strict methods on how the emission tests and measurements are to be done. Compounds regulated by law have to be measured following precise methods according to regulations or directives. When the measurement equipments used together with their calibrations are in line with the descriptions in the corresponding method and the test procedure is followed otherwise, the method guarantees a sufficient accuracy for deciding pass or fail against emission limit values based on a single test.

Unregulated emission compound measurements however, are though not included in the regulations and consistent measuring methods. For these purposes different measuring methods using various measuring techniques can be applied according to praxis, good engineering judgment and chemical and biochemical expertise. In general the accuracy connected to these chemical and biological analyzing tools are considered to be less accurate than for the regulated compounds. A significant contribution to the increased uncertainty is the more complex sampling and sample preparation techniques involved for measuring unregulated compounds and biological activity.

Also, a historically widely used method when comparing different fuels uses emission test of a complete heavy duty vehicle on a chassis dynamometer. But there are no precise method described in any regulation or directive regarding heavy duty vehicle tests on a chassis dynamometer. Usually the sampling and measuring techniques prescribed for the engine tests (engine dynamometer) are used synonymously at chassis tests also, but the engine test cycles can not be applied as such on chassis dynamometer. Instead various look-alike cycles are usually applied, cycles defined by vehicle velocity against time. But as long as the vehicle configuration to be simulated (vehicle inertia, vehicle road load curve, gear box handling etc) is not specified, the actual engine load and speed and hence measured emission are closely depending on such factors.

Often the experimental design used for studies comparing different fuel qualities is based on A and B tests and also retests on A. This means that as many circumstances as possible influencing the emission results are kept constant while switching the fuel quality. The test series uses the same vehicle, the same setting for the dynamometer, the same driver, constant ambient conditions etc thereby isolating the effects depending of the fuels. But since the vehicle usually is driven by a human driver, the skill of the driver and the repeatability of the driver still influence the result. If, taking the repeatability of the test series into consideration, there still are significant differences in some of the results between two fuel qualities; these differences are based on the specific circumstances for the test series. For instance, for another chosen setting for the vehicle inertia to be simulated, the emission levels probably would have been quite different and the outcome regarding the influence of fuel quality may also have been different.

So, the A-B-A test series monitoring the relative changes when switching fuels may in general be quite accurate considering standard emission components and less accurate considering unregulated compounds involving more or less non-standardized analysing tools and methods. The absolute emission values however are depending on the test cycle and test procedure and results based on chassis dynamometer tests may suffer from lack of standardized measurement methods mainly in terms of the setting of the dynamometer.

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1 BACKGROUND

A focus on local and regional emissions was intensified worldwide in the mid to late 1970: ies. The main focus was on reducing particulate, sulphur and aromatic emissions from diesel engines and reduced lead and benzene emissions from gasoline engines. Lead free gasoline was introduced in Sweden during the 1980: ies and with the introduction of catalytic converters on gasoline fuelled vehicles in the end of the 1980:ies a drastic reduction of emissions from passenger cars in Sweden was initiated.

None so drastic emission improving technology was on the horizon for diesel engine equipped vehicles. In an investigation initiated by The Swedish Environmental Protection Agency it was concluded that engine technology and driving conditions had large effects on emissions, but that much could also be done by improving the fuel quality. Increasingly tougher and tougher emission regulations have resulted in reduced emissions in newer engines, but it takes quite some time for a vehicle/engine fleet to be renewed. This is where environmental classification of fuel qualities comes into play. An improved fuel can give reduced emissions immediately in all engines, new and old.

In 1991 the environmental classification of Swedish diesel fuel was introduced. Diesel fuel was divided into three classes, Mk3, Mk2 and Mk1. Mk3 follows the European diesel standard, EN 590, while Mk2 and Mk1 have more stringent requirements on specific parameters, see Swedish Standard - SS 15 54 35. Mk2 was a fuel specification that some of the refineries could produce with minor upgrades, while Mk1 required large upgrades of all refineries. Within a few years Mk1 become the major diesel fuel used in Sweden and today 97% to 99% of the diesel fuel sold is of Mk1 quality.

Comparing specification for Mk1 with diesel fuel commonly used in 1990, large differences could be found for content of sulphur, aromatics (both total aromatics and PAH’s) as well as for density and the distillation curve. The density and distillation curve requirements also resulted in a difference of the viscosity for the fuel. Extensive tests and detailed investigations at the time of introduction of the improved diesel fuel showed that Mk1 diesel fuel reduced both regulated and unregulated emissions as well as the biological activity in the exhaust.

The introduction of even more stringent emission regulations for both on-road and non-road diesel vehicles/engines have meant that the engine technologies also have to be changed. These new engine technologies sometimes require improvements of the fuel quality to reach optimum performance for the combination of engine and fuel. Within the European Union work has been done, i.e. Auto Oil projects, where fuel quality requirements have been investigated.

Over the years, major changes have been made to both the European diesel standard, EN 590 and to the Swedish environmental class diesels, SS 15 54 35.

Revision history of European and Swedish diesel standards:

SS 15 54 35 was introduced 1991 and has been revised 1993, 2001 and 2006. A further revision is ongoing.

EN 590 was introduced 1993 and further revisions have been made 1999, 2004 and 2009.

European Heavy Duty Diesel Engine emission regulation history:

On-road	Non-road (represented by 130 – 560 kW engines)
1989 => Euro 0	Before 1999, no European emission regulation
1993 => Euro I	
1996.10 => Euro II (revised 1998)	1999.01 => Stage I
2001.10 => Euro III/EEV	2002.01 => Stage II
2006.10 => Euro IV	2006.01 => Stage III A
2009.10 => Euro V	2011.01 => Stage III B
2014.01=> Euro VI	2014.01 => Stage IV

Both the changes of the quality for European market fuel and the changes of engine technology will effect the emission associated with the use of Mk1 diesel compared to the European standard diesel. To compile the current knowledge and identify gaps of knowledge this project was initiated by STA. This report, the literature study, constitutes the first part of work where, the current knowledge will be summarized and recommendations given on further investigations.

Items not covered by this study

In this study only currently available information on exhaust emissions from heavy duty diesel engines when using EN 590 and Mk1 diesel are to be covered. Synthetic diesel and pure biodiesel is not elaborated. Further, exhaust emissions from diesel engines used in light duty vehicles (passenger cars) are not included in the study.

Production costs are not to be compared. No evaluation of the Swedish fuel depot systems ability to handle multiple diesel fuel qualities (summer, intermediate and winter qualities) is to be done.

2 DIESEL FUEL SPECIFICATIONS

The European Fuels Directive specifies fuel parameters with influence on climate change and air pollution. It is mandatory for the member states to implement the directive in the national legislation. The European Standard for diesel fuel (EN 590) specifies both the environmental parameters according to directive and other functionality related parameters. In some EU member states also a reference to EN 590 is made in the national legislation.

2.1 Swedish Environment Class 1 Diesel standard

As described in the background section, Sweden introduced specifications for environmental classified diesel fuel in 1991 to help reduce emissions from diesel engines, see table 1 for highlights of the first specification.

Table 1

Extracts from 1991 Swedish Mk1 Diesel Fuel Specification

Fuel Property	Unit	SS 15 54 35 Specification		Analyzing method
		Min	Max	
Cetane number		50,0		ISO 5165
Cetane index		50,0		ISO 4264
Density @ 15°C	Kg/m^3	800	820	ISO 4264, ISO 5165
Sulphur	mg/kg	-	10,0	SS 15 51 16
Aromatics	Vol%	-	5	ISO 3675, ISO 12185
PAH (tri+ aromatics =>)	Vol%	-	0,02	SS 15 51 16
Viscosity @ 40°C	cSt	1,40	4,00	ISO 3104
Distillation IBP 95% point	°C	 180 -	 - 285	ISO 3405

For complete specification see SS 15 54 35:1991 at SIS (www.sis.se)

In that specification focus was set on parameters that would reduce exhaust emissions either direct or indirect. Compared to the European standard diesel predominantly used in Sweden prior to 1991 this was the parameters that were changed:

Density: 800 – 820 kg/m^3

Decrease of density compared to European diesel at the time (820 – 860kg/m^3). This reduction of density, together with the distillation curve requirements, reduced the high boiling components and also slightly the energy content / liter (~3 – 4% in summer, less difference in winter). The reduction of high boiling components reduced soot and heavy PAH emissions.

Distillation curve: IBP ≥180℃, 95% point ≤ 285℃

The distillation curve for the Swedish Mk1 diesel was radically lighter than the European diesel at the time. In Europe no requirement for IBP was set and the 95% point requirement was ≤ 370℃. Especially the reduction in 95% point resulted in reduced soot and heavy PAH due to the reduced molecular size.

Sulphur: ≤ 10 mg/kg

This was one of the most radical differences from the “normal” diesel fuel of that time. In Europe diesel could have up to 2 000 mg/kg sulphur. Normal levels in European diesel was round about 1 000 mg/kg. As the production values in Mk1 diesel usually is roughly 3 mg/kg or less the reduction of sulphur was in the order of 500 to 1000 times.

Aromatics: ≤ 5 vol%

European diesel did not have any specification regarding aromatic content. A typical aromatic content at the time was in the order of 20 vol% to 25 vol%. Aromatics increases the PAH emissions and also to a smaller extent soot formation.

PAH (tri +): ≤ 0,02 vol% (detection limit)

The International Agency for Research on Cancer (IARC) has classified several polycyclic aromatic hydrocarbons (PAH’s) compounds into probable or possible human carcinogens. In principle, the carcinogenic potency of a given PAH compound can be assessed based on its benzo[a]pyrene equivalent concentration. At the time of introduction of the Swedish environmental class diesels no requirement for PAH’s in European diesel was existing. Three ring, and larger, PAH’s are thought to be most critical to human health and therefore the Swedish specification concentrated on them. European diesel at that time contained up to 5 vol% of tri+ PAH’s.

Cetane number: ≥ 50

Cetane number is an indication of the fuels ignition delay. The higher value the shorter ignition delay time. Increased cetane number generally decreases the NO_x emission. An increased cetane number has also been important as a mean to open the door for the modern diesel engine design with moderate geometric compression ratio and high boost. A low cetane fuel would result in difficulties starting the engine, especially cold start in winter conditions. Cetane number in Europe at the time was ≥ 45.

Viscosity: 1,40 to 4,00 cSt@40°C

With the requirements for density and distillation curve, Swedish Environmental Class 1 diesel automatically got a low viscosity. Typical viscosity values for Mk1 were between 1,9 cSt and 2,0 cSt. Typical European diesel usually has viscosity at round about 4 cSt in the summer and just below 3 cSt in the winter. The low viscosity of Mk1 diesel could cause problems in some fuel injection systems, especially if the system was worn.

After the introduction of the Swedish Environmental Class 1 diesel, SS 15 54 35, has gone through a couple of revisions. Today SS 15 54 35:2006 is active, see table 2, but a revision is expected before end of 2010.

In 1993, requirements for lubricity were added to the specification since it was found that the severe hydrotreatment needed to reduce the sulphur levels down below 10 mg/kg also affected the ability of the fuel to lubricate injectors and fuel pumps. A requirement for lubricity using a HFRR test was added and the required value in that test is less than 460 µm.

In 2001 the specification was adjusted to reflect the increased cetane requirement in Europe, EN 590, The cetane number was increased from minimum 50 to minimum 51.

In 2006 adjustments was made to be able to blend FAME (Fatty Acid Methyl Ester) into Swedish Mk1 diesel fuel. A parameter was added allowing for a maximum of 5 vol% FAME in the fuel and the 95% distilled point was increased from maximum 285℃ to maximum 320℃, this to make it possible for the high boiling FAME components to be added.

Table 2

Extracts from 2006 Swedish Mk1 Diesel Fuel Specification

Fuel Property	Unit	SS 15 54 35 Specification		Analyzing method
		Min	Max	
Cetane number		51,0		ISO 5165
Cetane index		51,0		ISO 4264
Density @ 15°C	Kg/m^3	800	820	ISO 4264, ISO 5165
Sulphur	mg/kg	-	10,0	SS 15 51 16
Aromatics	Vol%	-	5	ISO 3675, ISO 12185
PAH (tri+ aromatics =>)	Vol%	-	0,02	SS 15 51 16
Viscosity @ 40°C	cSt	1,40	4,00	ISO 3104
Fatty Acid Methyl Ester (FAME)	Vol%	-	5	EN 14078
Lubricity (HFRR)	µm	-	460	ISO 12156-1
Distillation	°C			ISO 3405
IBP		180	-	
95% point		-	320	

[1]This Swedish Standard specifies PAH's as the content of tri+-aromatic hydrocarbons
For complete specification see SS 15 54 35:2006 at SIS (www.sis.se)

In 2009, the EN 590 specification increased the permissible content of FAME to maximum 7 vol%. SS 15 54 35 is to follow in the same foot steps requiring further adjustments to the specification. The draft SS 15 54 35 specification, planned to be released late 2010 has proposed an increase of maximum density to 830 kg/m^3 and 95% point to 340℃.

2.2 European Diesel standard

The quality of European diesel fuels is specified by the EN 590 standard. While these specifications not are mandatory, they are observed by all fuel suppliers in Europe. Beginning from the late 1990s, several diesel fuel properties - including cetane number, sulphur content and FAME biodiesel content—are also subjected to environmental regulations.

The EN 590:1993 included a sulphur limit of 0.2% (wt.), which became effective from October 1994 *[Directive 93/12/EEC]*. This sulphur limit was applicable to all gas oils, including diesel fuel. Extract from the EN 590:1993 specification are found in Table 3.

Table 3

Extract from 1993 European Diesel Fuel Specification

Fuel Property	Unit	EN 590 Specification		Analyzing method
		Min	Max	
Cetane number		49,0		ISO 5165
Cetane index		46,0		ISO 4264
Density @ 15°C	Kg/m^3	820	860,0	ISO 4264, ISO 5165
Sulphur	% (wt.)	-	0,20	EN 24260 / ISO 8754
Viscosity @ 40°C	cSt	2,00	4,50	ISO 3104
Distillation	°C			ISO 3405
65% point		250	-	
85% point		-	350	
95% point		-	370	

For complete specification see EN 590:1993 at SIS (www.sis.se)

Some of the important revisions of the EN 590 standard were:

- EN 590:1993—The first EU diesel fuel specification. It established a sulphur limit of 0.2% (2000 mg/kg) for on road and non road diesel fuels.
- EN 590:1999—This standard reflected the sulphur (350 mg/kg) and cetane (51) specifications by Directive 98/70/EC.
- EN 590:2004—Sulphur limits of 50 mg/kg (so called Euro IV) and 10 mg/kg (Euro V) as regulated by Directive 2003/17/EC. FAME content of max. 5%.
- EN 590:2009—FAME content of max. 7% as regulated by Directive 2009/30/EC. This directive also adopts mandatory biofuel requirements for refiners and introduces a sulphur limit of 10 mg/kg in non road fuels effective 2011.

Table 4

Extracts from 2010 European Diesel Fuel Specification

Fuel Property	Unit	EN 590 Specification		Analyzing method
		Min	Max	
Cetane number		51,0		ISO 5165
Cetane index		46,0		ISO 4264
Density @ 15°C	Kg/m^3	820,0	845,0	ISO 4264, ISO 5165
PAH (di+ aromatics =>)	Vol%	-	8,0	EN 12 916
Sulphur	mg/kg	-	10,0	ISO 14596, ISO 4260
Viscosity @ 40°C	cSt	2,00	4,50	ISO 3104
Fatty Acid Methyl Ester (FAME)	Vol%	-	7,0	EN 14078
Lubricity (HFRR)	µm	-	460	ISO 12156-1
Distillation	°C			ISO 3405
65% point		250	-	
85% point		-	350	
95% point		-	360	

[1]The European Standard specifies PAH's as the content of di-aromatic and tri+-aromatic hydrocarbons.
For complete specification see EN 590:2009+A1 2010 at SIS (www.sis.se)

2.3 Remaining differences

When the Swedish Environmental Class 1 diesel appeared on the market it was clearly the world's cleanest diesel. No other diesel, except from experimental volumes of synthetic diesel, was anywhere near the same quality. Diesel fuel specified in accordance with EN 590 has gone thru a remarkable transition from 1993 up until the latest revision 2009 (2010). There are, however, still some differences between the two fuels. There is a need to compare the differences both related to the specification and also related to the typical commercial available diesel fuel on the market. In table 5 the current specification differences are summarized.

Table 5
Comparison of remaining differences between Mk1 (SS 15 54 35:pr 2010) with European diesel (EN 590:2009+A1 2010)

Fuel Property	Unit	SS 15 54 35 Specification		EN 590 Specification		Analyzing method
		Min	Max	Min	Max	
Density @ 15°C	Kg/m^3	800	830	820,0*	845,0	ISO 3675, ASTM D4052
Aromatics	Vol%	-	5	-	-	ISO 3675, ISO 12185
PAH (tri+ aromatics =>)	Vol%	-	0,02	-	-	SS 15 51 16
PAH (di+ aromatics =>)	Vol%	-	-	-	8,0	EN 12 916
Viscosity @ 40°C	cSt	1,40	4,00	2,00	4,50	ISO 3104
Distillation	°C					ISO 3405
IBP		180	-	-	-	
95% point		-	340	-	360	

*Arctic quality of EN 590 are allowed to go down to 800 kg/m3

2.3.1 Typical commercial available diesel fuel on the market.

Density; In Sweden the typical values have been around 815 kg/m^3 while typical density values in Europe (summer) often is around 840 kg/m^3.

Total aromatics; In Sweden typical aromatic values are 3,0 vol% to 5,0 vol%. Due to the introduction of low sulphur levels in the European diesel the corresponding hydrotreatment has resulted in a reduction of aromatics also in Europe even though they still do not have introduced any requirement in the specification. Today a typical European diesel aromatic content is in the range of 15 vol% to 30 vol%.

PAH’s; It is not possible to do a direct comparison on PAH content in Mk1 diesel fuel with EN 590 by using the specification values. This is due to a difference in how the two specification defines PAH’s. In the Mk1 specification tri+ aromatics is specified while EN 590 specification has opted for di+ aromatics. Looking at typical analyses values, the PAH Di+ in Mk1 is around 0,1% - 0,5% (EN 590 specifies maximum 8%), while PAH Tri+ in EN 590 is around 0,2% – 0,7% (Mk1 specifies maximum 0,02%).

Viscosity; With the introduction of FAME in the Swedish Environmental Class 1 diesel, the viscosity has increased slightly. It would be expected that typical viscosity values for B7 - Mk1 diesel fuel to be at, or just above 2,0 cSt. Typical European diesel still has viscosity at around 4 cSt in the summer and just below 3 cSt in the winter.

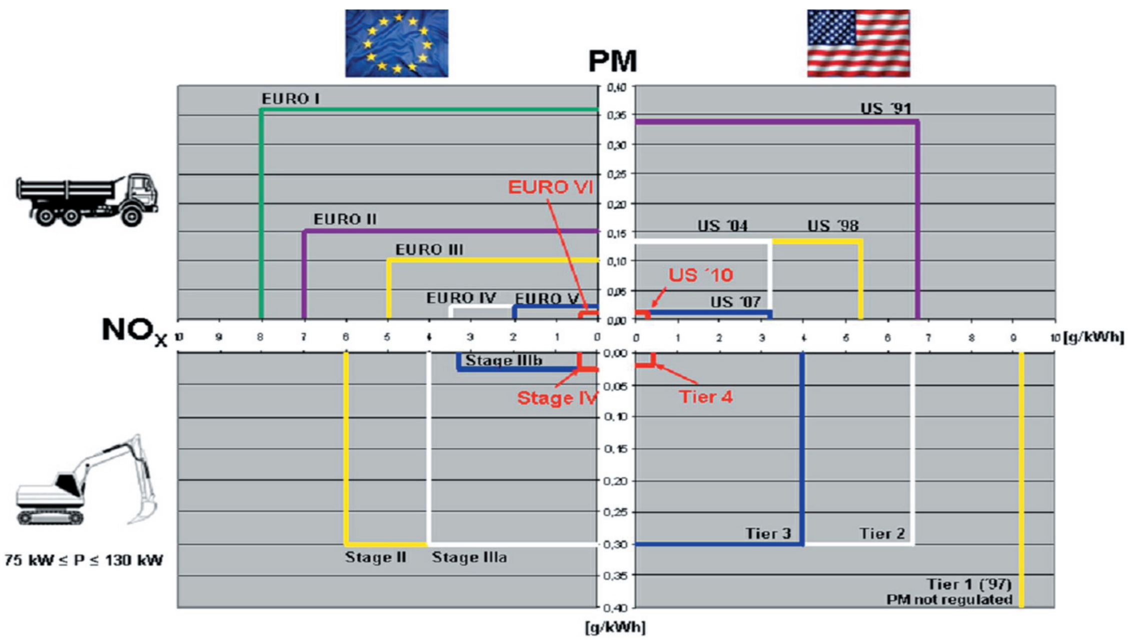
Carbon to hydrogen ratio; The reduction of aromatics in diesel fuel has meant that the carbon – hydrogen ratio has been reduced. As the aromatic components have been reduced, the amount of hydrogen in the fuel has increased. This shift to higher hydrogen content is true for EN 590 due to the hydrotreatment required when reducing sulphur, but still Mk1 have even higher hydrogen content. This results in less carbon / kWh in the fuel.

3 EUROPEAN HEAVY DUTY DIESEL ENGINE EMISSION REGULATION

The evolution for engine technology for heavy duty diesel engines over the last 10 to 20 years has been mostly driven by more and more stringent emission regulations and the effort from manufacturers to reduce fuel consumption by making engines more fuel efficient. The size of the development can be illustrated by looking at a graph 1 where the changes to regulation of NO_x and PM emissions that has been implemented from 1989 and onwards can be seen.

Graph 1

European and North American NO_x and PM Emission history



3.1 European emission regulations for on-road applications

Euro emission regulation for on-road diesel engines was introduced in 1989. Euro 0, I and II used a test cycle according to ECE R49 witch was a 13-mode steady state cycle. With the introduction of Euro III that cycle was replaced by two steady state cycles, ESC and ELR, and a new dynamic test was introduced, ETC. Euro III has been followed by Euro IV and Euro V and a new emission regulation, Euro VI, is to be introduced in 2014.

Table 6
European HD diesel engine On-Road emission regulation

Dates for first registration, entry into service	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	Particles [g/kWh]
Euro 0 – 1989 – 1993 ECE R49 13-mode steady-state	11,2	2,4	14,4	-
Euro I – 1993 – 1996.09 ECE R49 13-mode steady-state < 85 kW > 85 kW	4,5 4,5	1,1 1,1	8,0 8,0	0,61 0,36
Euro II - ECE R49 13-mode steady-state 1996.10 1998.10	4,0 4,0	1,1 1,1	7,0 7,0	0,25 0,15
Euro III – 2001.10 – 2006.09 European Stationary Cycle (ESC) and European Load Response (ELR) European Transient Cycle (ETC)	2,1 5,45	0,66 0,78	5,0 5,0	0,1 0,16
Euro IV – 2006.10 – 2009.09 European Stationary Cycle (ESC) and European Load Response (ELR) European Transient Cycle (ETC)	1,5 4,0	0,46 0,55	3,5 3,5	0,02 0,03
Euro V - 2009.10 – 2013.12 European Stationary Cycle (ESC) and European Load Response (ELR) European Transient Cycle (ETC)	1,5 4,0	0,46 0,55	2,0 2,0	0,02 0,03
Euro VI[1] - 2014.01 – European Stationary Cycle (ESC) and European Load Response (ELR) European Transient Cycle (ETC)	1,5 4,0	0,13 0,16	0,4 0,4	0,01 0,01

3.1.1 On road engines used in literature study material

In the reports used in this literature study 10 heavy duty on road diesel engines have been used. They span from 4 up to 6 cylinders and engine size from just above 4 litres to 12 litres. Below is a table with engine data. More information can be found in appendix 1 to 12.

[1] Euro VI will also include maximum particle number requirements but they will be defined at a later stage

Table 7
On road engines used in literature study material

Emission class	Reference	Number of cylinders	Total displacement [dm^3]	Engine power	Emission control system	Test conducted in
Euro III	1	6	-	309 kW	Injection pressure/timing	Vehicle on chassis dyno
Euro III (Euro II mod)	3	6	-	255 kW @ 1900 rpm	Injectors, ECU, Cam	Engine test cell
Euro III	4	6	12	-	-	Engine test cell
Euro III	9	-	9	-	Ox. catalyst (removed in test w/o cat)	Vehicle on chassis dyno
Euro IV	4	6	11	-	EGR + CRT	Engine test cell
Euro IV	6	4	4,6	103 kW	EGR (+PM-KAT)	Engine test cell
Euro IV	7 & 13	5	9	228 kW	Cooled EGR	Engine test cell
Euro IV	8	-	-	-	SCR	Vehicle on chassis dyno
Euro IV	9	-	10,5	-	Particle oxidation catalyst	Vehicle on chassis dyno
Euro V	4	6	12	-	SCR	Engine test cell

3.2 European emission regulations for non-road mobile machinery

Stage I emission regulation for non-road diesel engines was introduced at different times depending on engine power and application. Generally the regulation came into effect during 1999 for most applications. Stage I has been followed by Stage II and onwards. Currently Stage IIIb is being introduced and Stage IV is on its way, see table below for further information.

Table 8
European Non-Road emission regulation

Engine Power	[kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	Particles [g/kWh]
Stage I - 1999.01	$130 \leq P < 560$	5,0	1,3	9,2	0,54
Stage II - 2002.01	$130 \leq P < 560$	3,5	1,0	6,0	0,2
Stage III A - 2006.01	$130 \leq P < 560$	3,5	4,0[1]		0,2
Stage III B - 2011.01	$130 \leq P < 560$	3,5	0,19	2,0	0,025
Stage IV - 2014.01	$130 \leq P < 560$	3,5	0,19	0,4	0,025

[1] NO_x + HC

3.2.1 Stage I engines used in literature study material

Make	Volvo TD40GJE	Volvo TD63KDE	Valmet 420 DWRE
Production year			
Emission class	Stage I	Stage I	Stage I
Engine power	75 kW	93 kW	84 kW
Rated speed	2200 rpm	2200 rpm	2000 rpm
No of cylinders	4	6	4
Displacement (litres)	4,0	5,48	4,4
Literature study	2	2	2

4 CONCLUSION

A conclusion of this literature study is that diesel fuel of Mk1 specification still have a positive effect on most of the measured emissions. NO_x, PM, PAH and PN emissions still benefits from the use of Mk1 diesel even in engine using later emission control technologies. However, to get the full picture additional analyses of PAH emissions and PN measurements must be carried out on engines using technology for meeting emission requirements for Euro V and Stage IIIB. Bio reactivity, measured as TCDD receptor affinity test and AMES´s test, was only carried out for engines designed to meet Euro III emission regulations. Therefore no conclusions regarding biological activity can be drawn for later engine technologies.

For the regulated emissions (CO, HC, NO_x and particle matter) tests has been carried out on engines designed to meet emission requirements for Euro III, IV, V (for on-road applications) and Stage I (for non-road mobile machinery). It is important to emphasise the need of additional tests to fill the knowledge gaps highlighted in this study. The current knowledge is valid for older engine technologies but for newer technologies the knowledge bank is not solid enough. See chapter 5 for more information.

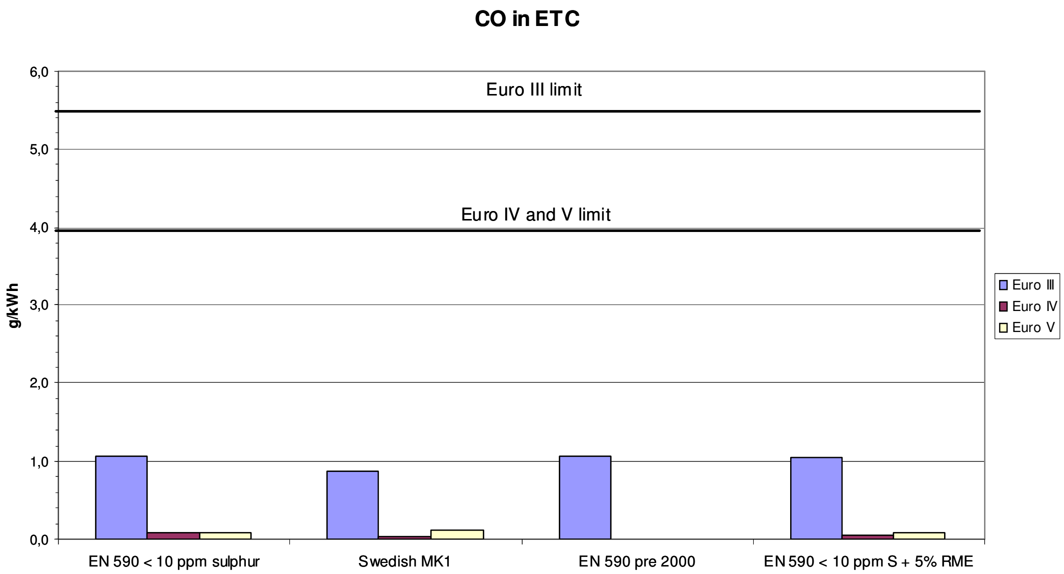
Reported values from the studied literature can be found in Appendices 1 to 12.

4.1 Regulated emissions

4.1.1 CO

In most cases the CO emission during steady state testing increased when using Mk1 diesel fuel compared to EN 590. Transient testing of engines designed for Euro III and in some cases also for Euro IV gave reduced CO emissions when using Mk1 diesel. But generally CO emissions seem to increase when diesel fuel meeting Mk1 specification is used compared to diesel meeting EN 590 specification. Since the working principal for diesel engines are combustion with a surplus of air, emissions of CO is generally not a problem. Therefore when testing diesel engines according to the set regulations the emissions of CO is far below the limit values. Graph 2 can be seen as an example of this. The data for the graph comes from reference 4.

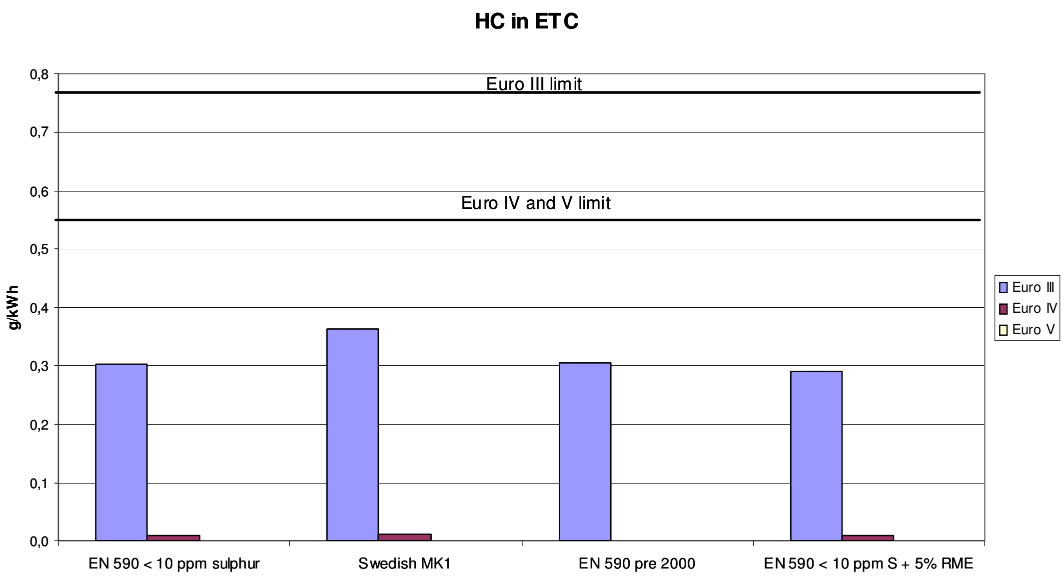
Graph 2
Example of CO emissions compared to legislative limits



4.1.2 HC

The trend for HC emissions was that the difference between Mk1 and EN 590 fuels were reduced when going to more modern engine technology. The HC emissions from the Euro V engine included in this study gave emissions under the detection limit regardless if Mk1 or EN 590 diesel fuel was used. Also for earlier engine technologies, i.e. Euro III and Euro IV the diesel engine working principal, combustion with a surplus of air, generally results in low HC emissions. Therefore when testing diesel engines according to the set regulations the emissions of HC is far below the limit values. Graph 3 can be seen as an example of this. The data for the graph comes from reference 4.

Graph 3
Example of HC emissions compared to legislative limits

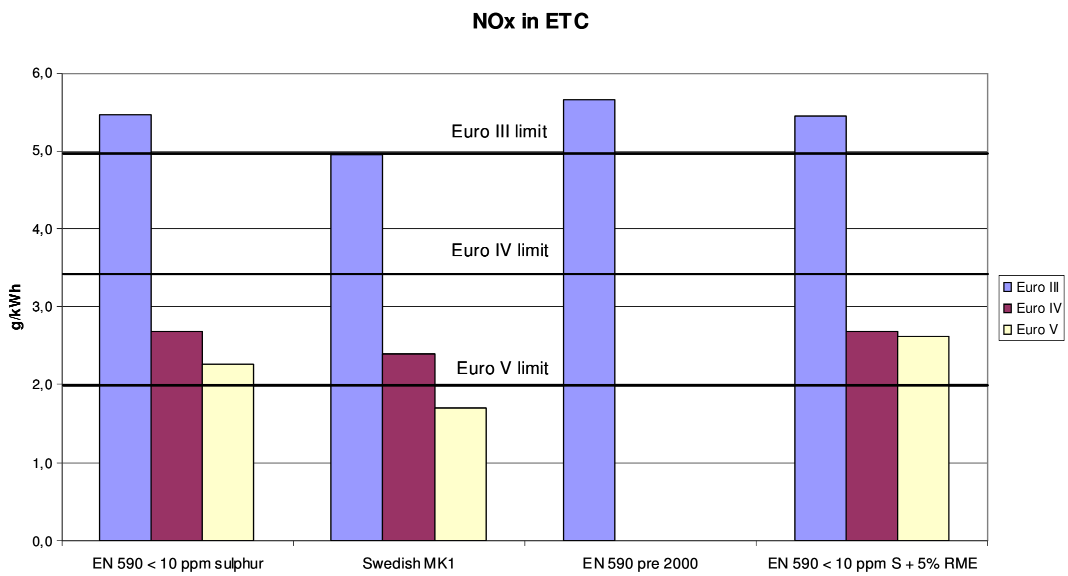


4.1.3 NO_x

NO_x emissions were generally lower when using Mk1 diesel fuel compared to EN 590. The NO_x reduction was somewhere in the order of 10%. In the Euro V engine the reduction tended to be even more significant. But it is of course important to consider that the total amount of NO_x emitted in the emission test cycles from the latest diesel engines is considerably lower than what was the case just 10 years ago, but still most of the diesel engines were very close to the limit values for NO_x. Graph 4 can be seen as an example of this. The data for the graph comes from reference 4. NO_x formation is proportional to temperature, pressure and time in the combustion chamber. The higher the temperature and pressure and the longer the time the more NO_x is produced. At the same time higher temperature and pressure generally increases the engines energy efficiency.

Graph 4

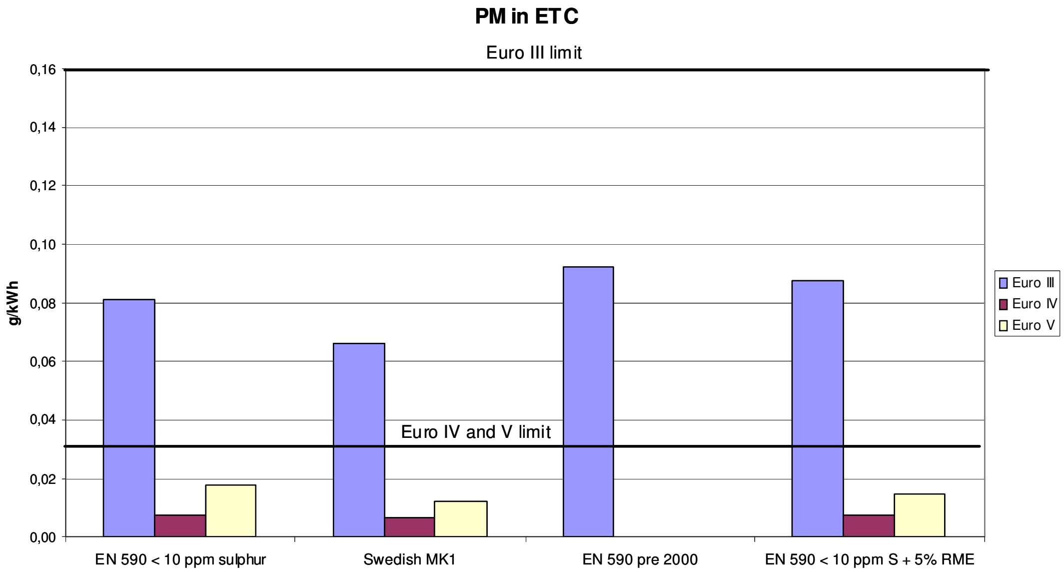
Example of NO_x emissions compared to legislative limits



4.1.4 Particulate Matter (PM)

Particulate matter were generally reduced when using Mk1 diesel fuel instead of EN 590. The reduction was often in the order of 10% to 30%. The only two exceptions in this study was one of the Stage I engines and the ESC test with the Euro V prototype engine. In the ETC test the same Euro V engine had a PM reduction of app. 30% when using Mk1, so it was not an engine technology feature. The working principal for diesel engines combustion is prone to produce particles. With the introduction of aftertreatment equipment on diesel engines a major step has been taken. Graph 5 can be seen as an example of this. The data for the graph comes from reference 4.

Graph 5
Example of PM emissions compared to legislative limits



4.2 Un-regulated emissions

4.2.1 PAH

In appendix A9, reference 9, it can be noted that the absolute PAH emission levels do not seem to be reduced with newer engine technology. It seems to be quite constant from one engine generation to the next. Therefore the fuel quality related emission reduction is very important. Available literature shows that PAH emissions was reduced when using Mk1 diesel instead of EN 590. The reduction was significant and in the order of 40% to 90%. This was the case regardless of engine technology. However, no data have been found from test of engines designed to meet Euro V emission requirements or latest technology for non-road engines since they have not been tested for PAH emissions.

4.2.2 Particle Number (PN)

Result from measurement of particle number for engines designed for non-road applications has not been available. In three of the investigations, covering Euro III and IV engines, the result pointed out that particle number emissions was reduced over the whole measuring range when using Mk1 diesel fuel compared to EN 590. In one investigation using a Euro II engine (modified to meet Euro III requirements), Mk1 produced more particles in the 50 µm to 150 µm particle size area. The general trend was that Mk1 reduces PN when compared to EN 590 diesel fuels.

4.3 Bio reactivity

4.3.1 TCDD receptor affinity test

TCDD evaluation has only been carried out for one Euro III engine. In the Braunschweig cycle TCDD reactivity was similar between the Mk1 and EN 590 fuels. It might be worth pointing out that in that test a low blend of RME reduced the reactivity in both base fuels.

4.3.2 AMES´s test

AMES evaluation has only been carried out for Euro III engines. In appendix A10, reference 10, the mutagenic effects of the particle extract were determined by the AMES method. Results from the tested fuels showed that mutagenicity of Mk1 extracts was 20 to 45% lower than the two EN 590 extracts. In the Braunschweig cycle, (appendix A2, reference 1) AMES reactivity was clearly lower for Mk1 diesel fuels compared with EN 590. The reduction was approximately 30%. The conclusion is that mutagenicity according to AMES´s test was clearly lower when using Mk1 compared to EN 590 diesel fuel.

5 FURTHER WORK NEEDED

Since the main objective with this study is to find literature presenting differences in the exhaust emissions when diesel fuels meeting Swedish Mk 1 specifications and EN 590 specification, the available material has been limited and mostly originated for tests and projects carried out in Scandinavia. Most material dates back to the time when the Swedish Environmental Class 1 diesel fuel (Mk1) was introduced and to the time when the first major improvements was made of the European diesel fuel specification expressed in EN 590. This literature study has found areas where there are no data available, areas where data is extremely scares and areas where additional data is needed to be able to fully evaluate the emission benefits found with Mk1 in this literature study.

Especially tests with modern engine technology are missing. Euro IV (many of the engines used in the literature study material was prototype engines), Euro V and engines meeting the latest non-road emission classes, Stage IIIA and IIIB is needed. Un-regulated emissions, particle numbers and bio reactivity should be given special focus.

Our recommendation is to gather more data through emission tests within the following areas:

- Comprehensive tests programs has to be developed for NRMM engines meeting Stage IIIA and IIIB
- Comprehensive tests programs has to be developed for engines meeting Euro V emission requirements, making sure to cover differences in aftertreatment equipment

- Added test programs for series produced engines meeting Euro IV emission requirements
- Emission data covering PAH, particle number and bio reactivity on emission classes Euro IV and V and Stage IIIA and IIIB is needed to understand how those emissions from the Swedish heavy duty vehicle/engine fleet will evolve as those fleets are renewed.

A cooperation between the Swedish Transport Administration (STA), oil industry and engine developing OEM’s is strongly recommended when setting up test matrix’s to gather the missing emission information.

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ABBREVIATIONS

95% point	The temperature where 95% of the fuel has been evaporated
AMES's test	Test that measures the mutagenic effects of various components on Salmonella bacteria's
Braunschweig cycle	Low speed/ load emission cycle that is designed to simulate City/Buss driving
BTL	Biomass To Liquid – synthetic fuel
CO	Carbon monoxide
CO_2	Carbon dioxide
CRT	Continuously Regenerating Trap,
CVS	Constant Volume Sampler
ECE R49	UNECE Vehicle Regulations - 1958 Agreement: Regulation No. 49 - Emission of pollutants of heavy vehicles
ECU	Engine Control Unit
EEV	Enhanced Environmentally Friendly Vehicle
EGR	Exhaust Gas Recirculation
ELR	European Load Response
EN 590	Automotive fuels. Diesel. Requirements and test methods
ETC	European Transient Cycle
ESC	European Stationary Cycle
EU	European Union
Euro I - VI	European on road emission regulation, for heavy duty diesel engines
FAME	Fatty Acid Methyl Ester
Gas oils	Distilled crude oil
GTL	Gas To Liquid, synthetic fuel
HC	Hydrocarbon
HFRR	High Frequency Reciprocating test Rig
IARC	International Agency for Research on Cancer
IBP	Initial Boiling Point

Mk1	Environmental Class 1 diesel as described in SS 15 54 35
Mk2	Environmental Class 2 diesel as described in SS 15 54 35
Mk3	All diesel fuel not fulfilling Mk1 or Mk2 but fulfilling EN 590
NExBTL	Neste Oil process to produce BTL fuel
NO_x	A generic term for the mono-nitrogen oxides NO and NO_2
NRMM	Non-Road Mobile Machinery
OEM's	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbons
PAH di+	PAH's with two or more aromatic rings
PAH tri+	PAH's with three or more aromatic rings
PM	Particulate Matter
PM-KAT®	Continuous, self-regenerating, Particle Separation System (MAN)
PN	Particle Number
prSS 15 54 35:2010	Preliminary version of the Swedish Environmental Class 1 and 2 specification
RME	Rapeseed Methyl Ester
rpm	Rotations Per Minute
SCR	Selective Catalytic Reduction
SMPS	Scanning Mobility Particle Sizer
SS 15 54 35	Swedish Standard for Environmental Class 1 and 2 diesel
STA	Swedish Transport Administration
Stage I - IV	European non road emission regulation, for heavy duty diesel engines
TCDD receptor affinity test	Measures the affinity of dioxin components to enzymes of rat liver
UREA	Organic compound with the chemical formula $(NH_2)_2CO$.

ANNEX 1: EMISSION DIFFERENCES

Below is a summary of the findings from the different papers[2] used in this literature study. The summary focuses on the different emission classes from Euro III through to Euro V for on road applications and additionally Stage I non road mobile machinery.

A1.2 Euro III

In four of the papers studied, emissions from engines designed to meet Euro III emission requirements were used. Four different engines were used, three of them being engines in series production while one being an engine originally designed to meet Euro II emission requirements but modified to meet Euro III. Summaries of the four papers can be found in appendix 1, 3, 4 and 8.

In reference 1 and 3 the main objective was to evaluate emission differences between Mk1 and EN 590 and to determine if low blends of RME would alter the findings. Regulated and unregulated emissions were examined together with mutagenicity. Reference 1 used the "Braunschweig" city driving cycle while reference 3 run both ESC and ETC test cycles.

Reference 4 and 5 focused on determining the emission differences due to engine development and fuel quality. Regulated emissions and particle numbers were measured. The test was run using both ESC and ETC test cycles.

Reference 9 compared PAH emission from fuels containing different amount of aromatics. However, in this paper neither of the fuels meets the specification for Mk1 so the results can not be used when doing a direct comparison between Mk1 and EN 590. Still the results from this paper are interesting and support the findings from other literatures. The test was run according to the ESC test cycle.

A1.2.1 Regulated emissions

A1.2.1.1 CO

In the Braunschweig cycle CO emissions decreased when using Mk1 diesel compared to EN 590 fuel. The reduction is in the order of 10% to 15%.

In the ESC cycle the CO emissions are increased in one of the papers (appendix A5) when using Mk1 diesel compared to EN 590 fuels, while it is reduced in the other paper running the same test (appendix A4). The increase and reduction is about 10%.

[2] Summaries of each paper can be found in the appendix 1 to 12.

In the ETC cycle both papers (appendix A4 and A5) show reduced CO emission when using Mk1 diesel compared to EN 590. The reduction is in the order of 10% to 20%.

A1.2.1.2 HC

In the Braunschweig cycle HC emissions were close to the detection limit for the analysing equipment. The results from the different fuels differed from 0,2 g/km to 0,4 g/km but the uncertainty in the figures makes it impossible to make any comparison.

In the ESC and ETC cycles the HC emissions are increased when using Mk1 diesel compared to EN 590 fuel. The increase is in the order of 10% to 30%.

A1.2.1.3 NO_x

In the Braunschweig cycle NO_x emissions was quite equal between the Mk1 and EN 590 fuels.

In the ESC and ETC cycles the NO_x emissions are reduced when using Mk1 diesel compared to EN 590 fuel. The reduction is around 10%

A1.2.1.4 Particulate Matter (PM)

In the Braunschweig cycle PM emissions was reduced when using Mk1 diesel compared to EN 590 fuel. The reduction was in the order of 30%.

In the ESC and ETC cycles the PM emissions are decreased when using Mk1 diesel compared to EN 590 fuels. The reduction is in the order of 20%.

A1.2.2 Un-regulated emissions

A1.2.2.1 PAH's

In the Braunschweig cycle PAH emissions was reduced when using Mk1 diesel compared to EN 590. The reduction was in the order of 60%.

In the ETC cycle the PAH emissions are reduced when using Mk1 diesel compared to EN 590. The reduction is in the order of 40%.

A1.2.2.2 Particle Number (PN)

In the Braunschweig cycle PN was reduced when using Mk1 diesel compared to EN 590. The reduction was in approximately 18%. The reduction was found in all particulate size bands that were analyzed, from 7 nm up to 3786 nm.

In the ETC cycle PN are increased when using Mk1 diesel compared to EN 590. The increase is approximately 3%.

A1.2.3 Bio reactivity

A1.2.3.1 TCDD receptor affinity test

In the Braunschweig cycle TCDD reactivity was quite equal between the Mk1 and EN 590 fuels. It might be worth pointing out that low blend of RME reduced the reactivity in both base fuels.

A1.2.3.2 AMES´s test

In the Braunschweig cycle AMES reactivity was significantly lower for Mk1 diesel fuels compared with EN 590. The reduction was approximately 30%.

A1.3 Euro IV

In six of the papers studied, emissions from engines designed to meet Euro IV emission requirements were used. Five different engines were used, three of them being engines in series production while two being prototype engines. One of the three production engines were tested with the normally supplied aftertreatment device removed. Summaries of the six papers can be found in appendix 4, 5, 6, 7, 8 and 12.

Reference 4 and 5 focused on determining the emission differences due to engine development and fuel quality. Regulated emissions and particle numbers were measured. The test was run using both ESC and ETC test cycles. The Euro IV engine in this paper used EGR and a particulate filter to meet the emission regulation.

In reference 6 the main objective was to compare emissions from NExBTL with conventional diesel meeting specifications according to EN 590 and Mk1. The test was run according to the ESC test cycle. The Euro IV engine in this paper used EGR but the PM-Kat® originally installed was removed during the test.

In reference 7 a comparison of emission benefits when using BTL diesel fuels was done. The comparison was made against EN 590 and Mk1. In this report the usual ESC and ETC test cycles was joined by a full load power curve test. The Euro IV engine in this test used only cooled EGR.

In reference 8 the main objective was to verify real life fuel consumption and emissions. In the part of the work included in this study, EN 590 and Mk1 diesel fuel was used. The test was carried out with a vehicle with a gross vehicle weight of 60 ton simulated half loaded. That corresponds to a total weight of approximately 45 ton. The Euro IV engine in this paper used SCR.

In reference 9 the main objective was also to compare PAH emission from fuels containing different amount of aromatics. However, in this paper neither of the fuels meets the specifications for Mk1 and therefore the results can not be used when doing a direct comparison between Mk1 and EN 590. Still the results from this paper are interesting and support the findings from other literatures. The test was run according to the ESC test cycle. The Euro IV engine in this paper used a particle oxidating catalyst.

In reference 13 emissions were a compared when EN 590 and Mk1 diesel fuels were used. Both fuels were used as "pure" hydrocarbon and with a blend of 5% RME. The tests were run according to both ESC and ETC test cycles. The Euro IV engine in this paper used only cooled EGR.

A1.3.1 Regulated emissions

A1.3.1.1 CO

In the ESC test CO emissions is equal or increased when using Mk1 diesel compared to EN 590. The increase is in the order of 0% to 18%.

In the ETC test the spread in results are even larger. In one paper the CO emissions are reduced when using Mk1 while in two other papers the CO emission is increased. The results differ from a reduction of approximately 50% to an increase of up to 19%.

In the power curve test Mk1 increased the CO emissions with 10% to 17%.

A1.3.1.2 HC

In the ESC test HC emissions results can both be reduced and increased when using Mk1 compared to EN 590. The results in one paper points towards a 10% reduction of HC emissions when using Mk1 while three other papers indicates an increase of HC emissions with between 5% and 30%.

In the ETC test the spread in results are still present. In one paper the HC emissions are reduced when using Mk1 while in two other papers the HC emission is increased. The results differ from a reduction of approximately 4% to an increase of up to approximately 30%.

In the power curve test Mk1 increased the HC emissions with 6% to 14%.

A1.3.1.3 NO_x

In the ESC and ETC tests NO_x emission is reduced when using Mk1 compared to EN 590. The reduction is reported to be between 4% and 17%. In the power curve test Mk1 reduces the NO_x emission with app. 9%.

In a test simulating a half loaded 60 ton truck a substantial NO_x reduction of some 25% was recorded for a SCR equipped engine.

A1.3.1.4 Particulate Matter (PM)

In the ESC and ETC tests PM emission is reduced when using Mk1 compared to EN 590. The reduction is reported to be between 10% and 30%. In the power curve test Mk1 reduces the PM emission with 5% to 13%.

In a test simulating a half loaded 60 ton truck a PM reduction of 15% to 20% was recorded for a SCR equipped engine.

A1.3.2 Un-regulated emissions

A1.3.2.1 PAH's

In the ESC and ETC cycles PAH emissions are approximately 70% lower with Mk1 compared to EN 590.

A1.3.2.2 Particle Number (PN)

In ESC test the PN emission from Mk1 was reduced in all particulate size bands that were analyzed.

A1.4 Euro V

In only one of the papers studied emissions from engine designed to meet, Euro V emission requirements were used. The engine used was an AVL prototype engine equipped with SCR aftertreatment equipment. A summary of the paper can be found in appendix 4.

Reference 4 and 5 focused on determining the emission differences due to engine development and fuel quality. Regulated emissions and particle numbers were measured. The test was run using both ESC and ETC test cycles. The Euro V engine in this paper used SCR.

A1.4.1 Regulated emissions

A1.4.1.1 CO

In the ESC test cycle the CO emissions are increased when using Mk1 compared to EN 590 diesel. The increase was approximately 8%.

In the ETC test cycle the CO emissions are increased using Mk1 compared to EN 590 diesel. The increase was approximately 30%.

A1.4.1.2 HC

In ESC and ETC tests the HC emissions was under the detection level for both Mk1 and EN 590 fuels.

A1.4.1.3 NO_x

In the ESC and ETC test cycles the NO_x emissions are reduced when using Mk1 compared to EN 590 diesel fuel. The reduction is approximately 25%.

A1.4.1.4 Particulate Matter (PM)

In the ESC test cycle the Euro V engine does not show any PM emission difference between Mk1 and EN 590 diesel fuel.

In the ETC test cycle the PM emissions are reduced when using Mk1 compared to EN 590 diesel fuel. The reduction is approximately 30%.

A1.5 Stage I

In only one of the papers studied, engines designed for non road applications were used. The three engines that were used were all designed to meet Stage I emission requirements. A summary of the paper can be found in appendix 2.

In reference 2 the main objective was to study and compare the influence of traditional and alternative diesel fuels on emissions from diesel engines in large off-road machines. Test was performed according to "test cycle C1 – off road vehicles" as described in ISO 8178-1996. Two Volvo engines and one SISU-Valmet engine was used. None of the engines used any kind of aftertreatment devices

A1.5.1 Regulated emissions

A1.5.1.1 CO

No emission impact on the Volvo engines, while CO emissions are reduced with app. 20% when using Mk1 compared to EN 590 in the SISU-Valmet engine.

A1.5.1.2 HC

HC emissions are increased when using Mk1 fuel compared with EN 590. The increase is between 8% and 30%.

A1.5.1.3 NO_x

NO_x emissions are quite equal regardless of specification for fuel. Results from one of the engines do not meet the emission requirements for Stage I.

A1.5.1.4 Particulate Matter (PM)

One of the three engines did not record any PM emissions during the test on EN 590 fuel and can not be used in the PM emission comparison. The second engines did not show any PM emission change when going from Mk1 to EN 590 diesel fuel quality, while the third engine showed a considerable PM emission reduction when using Mk1 compared to EN 590 diesel fuel. The reduction for that engine was close to 40%.

A1.5.2 Un-regulated emissions

A1.5.2.1 PAH's

PAH emissions are decreased when using Mk1, both when measuring PAH di+ and PAH tri+. The reduction in PAH di+ emissions compared to EN 590 is between 48% and 60% and the PAH tri+ emissions with between 72% and 94%.