Report

Literature study – diesel fuel MK1 and EN590

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Ecotraffic

Content

1. Projektinformation (Swedish)

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Ansvarig hos beställare	Magnus Lindgren	**Projektnummer**	7059
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2. Abbreviations, acronyms and glossary

CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
EGR	Exhaust Gas Recirculation
ETC	European Transient Test Cycle
ESC	European Stationary Test Cycle
FAME	Fatty Acid Methyl Esters
FC	Fuel Consumption
HC	Hydro Carbon
NEDC	New European Driving Cycle
NOX	Nitrogen oxides (NO + NO2)
NO	Nitrogen oxide
NO2	Nitrogen dioxide
PM	Particulate Matter
PMP	Particulate Measurement Programme (the EU programme for developing new measurement methods for particle mass and number)
PN	Particle number
RME	Rasped Methyl Ester
MK1	Swedish Environmental Class 1 Diesel
PAH	Poly Aromatic Hydrocarbons
DPF	Diesel Particle Filter

3. Summary

The differences between the Swedish MK1 diesel and European diesel have remarkably been reduced and both have low content of sulphur and aromatics. There are, however, still differences, both in the specifications and in the real content in available diesel fuel. This literature study summarizes facts and lack of facts on differences in emission from MK1 and sulphur free EN590:2009.

Only a few studies compare different modern diesel qualities. The studies found cover engines of the following categories:

- Off road engines Stage I
- Light vehicles, Euro 3
- Heavy Duty engines, Euro III, Euro IV, Euro V

For many of these engine categories there is only little information of unregulated emissions. Only one Euro V engine is tested and only for regulated emissions.

There is a gap in knowledge for comparing MK1 and EN590:2009 in the following categories:

- Off road engines Stage II, Stage III A or Stage III B
- Light vehicles, Euro 1, 2, 4, 5, 6
- Heavy Duty engines, Pre Euro, Euro I, Euro II, Euro VI

For the studied engines, generally MK1 have emission benefits compared to EN590:2009. CO- and HC-levels are reduced for light vehicles and increased in most tests for heavy duty engines. NO_x are reduced by MK1 in most tests. Particle mass is reduced in most tests. Studies showed both higher and lower particle number with MK1 and MK1 gave a substantial reduction of PAH and AMES mutagenicity.

4. Work description

Scoop of work

This literature study focus on reports about diesel emissions from Swedish diesel MK1 and EN590:2009. Earlier revision of European diesel is not in focus. However studies on diesel test blends with varying levels on sulphur and aromatics corresponding to modern diesel quality are included.

This report summarizes the references and their results of emission tests on regulated and unregulated components. The purpose is to summarize knowledge of different engine generations and to identify knowledge gaps.

Background

Since 1991 Sweden has a unique diesel quality – MK1 (Environmental Class 1). When MK1 diesel appeared on the market it was the world's cleanest diesel. The content of sulphur and aromatics was much lower compared to diesel used outside Sweden. The sulphur level in MK1 diesel is around 3 mg/kg. The sulphur limit for Europe diesel was 2000 mg/kg and a normal level was around 1000 mg/kg. Since then, the European diesel, EN 590, has gone through many revisions, the content of sulphur and aromatics has decreased and the differences between the Swedish MK1 and European diesel has thereby been reduced. There are, however, still differences, both in the specifications and in the real content in available diesel fuel.

In Sweden the European diesel is classified as MK3 (environmental class 3). MK1 is the dominating fraction with almost 100 % of the market. 5 million m^3 of diesel is used annually in Sweden to cars, heavy duty engines and non-road applications. The energy taxes were 1 524 SEK/m^3 for MK1 and 1 924 SEK/m^3 for MK3 in 2011. Due to the reduced differences between MK1 and MK3 the Swedish parliament have asked the government to investigate to what extent the tax differences can be reduced.

The sulphur limit is 10 mg/kg in both MK1 and EN590:2009. The typical level differs however with MK1 having a typical level at 1-4 mg/kg and EN590:2009 a level at 5-7 mg/kg (1). The aromatic and PAH levels are a bit difficult to compare as the specification of aromatics and PAH differs. The aromatic level for MK1 diesel is 5 % and a typical level is 3-5 %. EN590 have no limit for aromatics and the typical level is 15-30 %. The PAH level in MK1 is 0.02 % and is specified for PAH´s with tree rings and larger. The PAH level in EN590 is 8 % and is specified as PAH´s with two rings and larger. In MK1, the typical level of PAH´s with two rings and larger is 0.1-0.5 %. The density, distillation point and viscosity differ also. In table 1 the specifications and differences are summarized.

The reduction of sulphur content in diesel has two main positive effects, firstly the acidification in the environment is reduced, secondly it enables the use of advanced after-treatment technology (sulphur is a poison to catalyst material). There is also a positive side effect; in the process to remove sulphur from the fuel, the concentration of aromatics is also reduced.

Table 1. Comparison of Swedish MK1 diesel and European diesel EN590 (1, 4).

Fuel property	Unit	Swedish MK1 SS 15 54 35		European diesel EN 590:2009	
		Specification	Typical content	Specification	Typical content
Sulphur	mg/kg	10	1-4	10	5-7
Aromatics	vol %	< 5	3-5	-	15-30
PAH (tri+ aromatics)	vol %	< 0,02	No data	-	0,2-0,7
PAH (di+ aromatics)	vol %	-	0,1-0,5	< 8,0	No data
Density	Kg/m^3	800-830		820-845	
Viscosity (40 °C)	cSt	1,4-4		2-4,5	
Distillation IBP 95 % point	°C	 180 340		 360	

According to the report "Comparing exhaust emissions from heavy diesel engines using EN590 vs. MK1diesel fuel" (4) there are differences in both emissions and health effects when using older euro-classes of heavy duty engines and non road engines. Information regarding newer engines is not included.

Methodology

Information is derived from the below mentioned databases and personal contacts:

- Stockholm University database. Search done by Roger Westerholm.
- Chalmers Technical University. Search done by Börje Gevert.
- SAE Database
- Dieselnet
- Contacts with Preem and Statoil Sweden
- Contacts with Statoil Norway
- Contacts with Marit Låg, Folkehelseinstitutet, Norway
- Contacts with SPBI
- Contacts with Erik Fridell, IVL
- Contacts with Felix Köhler, TUV NORD, Germany

5. Results

Overview of relevant studies

There are a lot of emission reports regarding earlier diesel qualities. But for modern diesel quality there is a gap in knowledge and only a few studies compare different modern diesel qualities. Working according to the methodology explained above some reports of interest have been found. These studies cover modern engines but not the latest. For older vehicles and for the latest engine technology there are no studies.

The reports we examined are the following.

1. Fridell, 2006. En kunskapssammanställning av partikelutsläpp från dieselfordon. IVL-rapport. För Svenska Statoil.
2. Thomson et al, 2004. Fuel Effects on Regulated Emissions From Advanced Diesel Engines and Vehicles. SAE paper.
3. Rantanen et al, 2005. NexBTL – Biodiesel Fuel of the Second Generation. SEA paper.
4. Danielsson et al, 2010. Comparing Exhaust Emissions From Heavy Duty Diesel Engines Using EN590 vs. MK1 Diesel Fuel. AVL MTC 0015.
5. Lindberg, D, 2007. Jämförelse mellan svavelfri Europadiesel och MK1. Emissioner från en tung motor utan avgasrening. Lunchseminarium 2007-04-24. Svenska Statoil.

Some other reports that were of interest are referred to in the reports above.

Short summary of relevant studies

Reference 1 (Fridell 2006) is a literature study written by IVL Swedish Environmental Research Institute for Statoil Sweden. The focus is on the two diesel qualities MK1 and “sulphur-free” EN590 and emissions of particles and CO_2 but also studies with other diesel qualities are taken into account. A study from 1998 (Lee et al) shows that sulphur content have an impact on particles on heavy duty engines (no figures shown). It also shows that reduced polyaromatic content gives fewer particles on older engines (no figures or engine class shown). On newer engines they find no clear effect. Another study (Kweon et al) shows that heavy duty diesel (no class indicated) give higher $PM_{2,5}$ with high aromatic level at high load (no figures shown). The effect was not found at low load. A study from 2003 (Bielaczyc et al) show that sulphur content have a clear effect on particles (no figures shown). In the World Wide Fuel Charter from 2002 is shown that sulphur content have an impact on particles (no figures shown). Also the polyaromatic content is of importance. A reduction from 9 % polyaromatics to 1 % reduced the particle emissions by 6 % for light duty and 4 % for heavy duty engines. This is an average for a large number of vehicles in a study done in the mid 90´s. The sulphur content is of great importance to particle emissions, and it was also shown in some studies that polyaromatic content has an impact on the particle emissions. The most important method to reduce particles is, however, to use particle filters. The total emissions of particles from the cars in Sweden (2006) will be higher with EN590:2009. The difference will decrease with the shift to cars with particle filter. There may be a negative aspect with higher aromatic content even for engines with particle filter. The filter will get a higher load and it could mean shorter service interval or more frequent filter failures. Catalyst for reducing NO_x is likely to be standard in the future. Then it´s important with as low content of sulphur as possible. Today MK1 have a sulphur content of 1-4 mg/kg and EN590:2009 have 5-7 mg/kg. The sulphur will reduce the capacity of the NO_x catalyst.

“Comment on reference 1 - some of the referred studies is quite old and there´s a lack of information of figures from them. Without data like sulphur content and engine class it´s difficult to validate and make conclusions. Despite this the study has a lot of valuable facts and explains the scientific background to formation of particles"

Reference 2 (Thomson et al 2004) is an SAE paper describing emission tests done as a part of CONCAWE´s contribution to the EU “PARTICULATES” consortium. Two advanced light-duty and three heavy-duty diesel engines covering Euro 3 to Euro 5 were tested. The fuels tested covered a range of sulphur content, aromatics and polyaromatics. Among the fuels were MK1 (without FAME) with a sulphur content of 3 mg/kg, 1,7 % monoaromatics and no polyaromatics, called D5 in the report, and a sulphur free diesel (without FAME) equivalent to EN590:2009, with a sulphur content of 8 mg/kg, 14,1 % monoaromatics and 4,3 % polyaromatics, called D4. For the light duty cars, NEDC cycle, steady state and driving cycles according to the ARTEMIS project were used. For heavy duty engines, the relevant EST and ECT cycles and extended steady state modes were used. Regulated emissions were analyzed. Several differences in the emissions were found. For the heavy duty engines the differences for most emission categories were small or the levels were very low. D5 gave about 15 – 20 % higher HC emission (in ECS from 0.25 to 0.3 g/kWh, in ETC from 0.3 to 0.35 g/kWh) than D4, about 10 % lower NO_x (in ECS to 4.5 g/kWh, in ETC to 5 g/kWh) and 20 % lower PM (in ECS to 0.05 g/kWh, in ETC to 0.065 g/kWh) with the Euro 3 engine. Euro 4 and 5 engines had HC levels at zero or close to zero. For NO_x and PM the differences were similar to Euro 3 but on a lower level. The light duty vehicles were car A, a Euro 3 level with oxidation catalyst and car B, a Euro 3 level with DPF (particle filter). D5 gave lower CO emissions though only significant in car A (from 0.1 to 0.05 g/kWh), lower HC emissions (50 % on car A, 30 % on car B) with levels around 0.01 g/kWh and no or very small difference on NOx. On car A D5 reduced PM emissions with around 40 % from 0.04 g/kWh to 0.025 g/kWh in a high speed test cycle. Car B had extremely low PM emissions and differences were not significant.

Reference 3 (Rantanen et al, 2005) is an SAE Paper describing emissions from MK1 and “sulphur-free” EN590 with different blends of the advanced biodiesel NexBTL in three light duty diesel cars. Test was performed by Technical Research Centre of Finland (VTT Processes). Only one of the cars, car A, was tested with both MK1 and EN590 without NexBTL. The Euro class was not indicated but the model year is 2000 so we can assume that it was Euro 3 (which came into effect in 2001). It was tested with and without catalyst. Without the catalyst we assume the car would correspond to pre-euro class. MK1 had a sulphur content of 1 mg/kg, 5.4 % total aromatics and <0.03 % polyaromatics. EN590 had a sulphur content of 6 mg/kg, 19 % total aromatics and 0.07 % polyaromatics. The European test cycle NEDC was used. Regulated emissions, several individual hydrocarbons, PAH´s and Ames mutagenicity were measured. MK1 gave lower emissions both with and without catalyst. For example without catalyst MK1 compared to EN590 gave 12 % lower CO (0.59 g/km), 14 % lower PM (0.031 g/km), 31 % lower benzene (2.2 mg/km), 70 % lower PAH_{sum} (1.1 µg/km) and 63 % lower mutagenicity (7 krev/km). With catalyst the levels were lower but relative difference was in the same order, except for PAH. MK1 gave 15 % lower CO (0.25 g/km), 21 % lower PM (0.027 g/km), 27 % lower benzene (1.3 mg/km), same emission of PAH_{sum} (1.1 µg/km) and 50 % lower mutagenicity (4 krev/km).

Reference 4 (Danielson et al, 2010) is a literature study written by AVL for the Swedish Transport Administration. The focus is on differences in emissions between MK1 and “sulphur-free” EN590 in heavy duty engines and non-road mobile machinery, NRMM. In the study material there were 11 on-road engines and 3 non-road Stage I engines. The on-road engines were 4 Euro III engines, 5 Euro IV engines and one Euro V engine. One of the references seems to be similar to our reference 2. The studies include several test cycles whereof some are specified in this summary. The overall conclusion is that MK1 still have significant benefits in regulated emissions and most un-regulated emissions and bio-reactivity for on-road Pre-Euro up to Euro 3 and non-road Stage I. MK1 gave lower emissions also on newer engines covered by the study but the engines were not fully representative for the Swedish fleet. For newer engine technologies there is a gap of knowledge. There is few absolute emission data in the study, the focus is on relative percentage differences. Generally CO increases when using MK1 instead of EN590 but in some cases it decreases. The emission of CO is far below the limit values. In the non-road engine study the CO level was the same in two engines and was reduced by 20 % in one engine. HC emission is also generally low and for the Euro V engine in the study it was under detection limit. HC emission increases with MK1 diesel by 10 – 30 % in Euro III engines. For euro IV engines one study find a 10 % reduction and two other studies reports increases up to 30 %. In the Stage I engines HC emissions are increased by 8 – 30 %. NO_x are reduced when using MK1 compared to EN590. For Euro III engines the reduction is from zero to around 10 %. For euro IV the reduction is between 4 and 25 % in different test cycles in the studies. For Euro V the reduction is 25 %. For Stage I-engines the level is the same. PM is reduced in the order of 20 – 30 % when using MK1 instead of EN590 in Euro III engines. The reduction is in the order of 5 – 30 % in Euro IV and 0 – 30 % in Euro V engines. For the Stage I engines the reduction was between zero and 40 %. PAH emissions was measured for Euro III, Euro IV and Stage I engines. PAH decreases for all tested engines when using MK1 compared to EN590. The reduction is 40 – 94%. Particle number, PN, was measured for some engines. A Euro III engine showed a reduction by 18 % in the Braunschweig cycle (low speed/load, simulating city/bus driving) and an increase by 3 % in the ETC cycle when using MK1 compared to EN5990. In Euro IV engines in ESC cycle PN was reduced. The Euro V and Stage I engines was not tested for PN. Bio reactivity was only tested for Euro III engines. TCDD evaluation was carried out on one Euro III engine and the reactivity was similar between MK1 and EN590. AMES mutagenicity was reduces in different test cycles by 20 – 45 % when using MK1 compared to EN590.

Reference 5 is documentation from a seminar by Björn Lindberg, product quality director at Statoil Sweden. It describes the results of a test of a heavy duty engine, a 12 L Scania Heavy duty truck (DC1201), upgraded to Euro 3, without emission control. In two work cycles, ESC and ETC, regulated emissions were measured. In cycle ETC PAH and aldehydes was measured. MK1 reduced PM from 0.035 to 0.03 g/kWh in ESC and from 0.145 to 0.123 g/kWh in ETC but a little higher PN. This means MK1 gives more of the small particles. MK1 gave a little lower NOx and a little higher HC. MK1 reduced PAH from 310 to 190 µg/kWh but increased the aldehydes from 46 to 53 mg/kWh.

Summary of results, emissions

Table 2 summarizes the results in the studied reports. The most important results of differences (or lack of differences) in emission between MK1 and EN590:2009 are presented. The table also clearly indicates where there is lack of knowledge.

Table 2. Summary of the emission changes when using MK1 instead of EN590:2009. The reference numbers are indicated in the right column.

Engine class	"name" of engine in ref	Emission changes when using MK1 instead of "sulphur-free" EN590							ref
		CO	HC	NO_x	PM	PAH	Bio	Other	
Off road									
Stage I	2 Volvos, Sisu-Valmet	0- -20%	+ 8-30 %	same	same - 40 %	-48- 94 %			4
Stage II									
Stage IIIA									
Stage IIIB									
LD vehicles									
Euro 1									
Euro 2									
Euro 3	Car A	- 40 %	-50 %	same	-40 %				2
	Car B	-	-30 %	-5 %	low levels				2
	Car A	-14 %	same	-5 %	-21 %	same	-50 % mut	-27% benzene	3
Euro 4									
Euro 5									
Euro 6									
other	Car A, Euro 3 without catalyst	-12 %	-10 %	-5 %	-14 %	-70 %	-63 % mut	-31 % benzene	3
HD engines									
Pre Euro									
Euro I									
Euro II									
Euro III	several references*	+/-10-20 %	+10-30 %	-10 %	-20-30 %	-40- 90 %	same TCDD -20 - 45% mut	PN -18 % PN + 3 %	4
	Scania		+ 15 %	- 10 %	0 – -15 %	-40 %		+15 % aldehydes higher PN, more small particles	5
Euro IV	several references *	0- +18 %(ESC) -50 % - +19 % (ETC)	-10 % - + 30 %	- 4-25 %-	- 5-30 %	-70 %		Lower PN	4
Euro V	Euro5	+8 % (ESC) + 30 % (ETC)	Low levels	- 25 %	Same (ESC) -30 % (ETC)				2,4*
Euro VI									

Bio= bioreactivity, Mut =mutagenicity, *In reference 4 there are tests that also is in reference 2

6. Conclusions and Discussions

There are only a few studies on comparing emissions from MK1 and EN590:2009. For older vehicles and for the latest engine technology there are no studies. There have been some studies. These studies cover engines of the following categories:

- Off road engines Stage I
- Light vehicles, Euro 3
- Heavy Duty engines, Euro III, Euro IV, Euro V

For many of these engine categories there is little information of unregulated emissions. For light duty vehicles there are only two measurements on PAH and bioreactivity. Only one Euro V engine is tested and only for regulated emissions.

There is a gap in knowledge regarding emissions when using these fuels in the following categories of older vehicles as well as in the latest engine technology:

- Off road engines Stage II, Stage III A or Stage III B
- Light vehicles, Euro 1, 2, 4, 5, 6
- Heavy Duty engines, Pre Euro, Euro I, Euro II, Euro VI

When using MK1 comparing to EN590 the studied reports show that MK1 have some emission benefits.

CO and HC

Generally CO- and HC-levels are low and well under emission limits in all studies. MK1 reduces CO and HC for light vehicles. For heavy duty engines the emissions are increased in most tests and reduced in some tests. For Euro IV and V the levels are so low that differences are of less importance.

NO_x

NO_x have generally levels closer to emission limits so differences between fuels can be important. MK1 gives a moderate reduce of NO_x in almost all tests.

Particles

PM is generally lower with MK1. In some tests there are no or low difference but in most tests reduction is in the order of 20-40 %. The impact from fuel on the particle number (PN) is more unclear. Studies showed both higher and lower PN with MK1. As reference 1 has few numeric data and no indication of Euro classes it does not fit in table 2. However it shows the relation between the content of sulphur and aromatic and the formation of particles and strengthens the findings that MK1 gives lower PM.

PAH

MK1 gave a substantial reduction of PAH in most tests.

Bioreactivity

MK1 gave a substantial reduction of AMES mutagenicity in all of the three tests. There was only one TCDD evaluation and it showed no difference between the fuels.

7. References

1. Fridell 2006. En kunskapssammanställning av partikelutsläpp från dieselfordon. IVL-rapport. För Svenska Statoil.
2. Thomson et al 2004. Fuel Effects on Regulated Emissions From Advanced Diesel Engines and Vehicles. SAE paper.
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5. Lindberg, D, 2007. Jämförelse mellan svavelfri Europadiesel och MK1. Emissioner från en tung motor utan avgasrening. Lunchseminarium 2007-04-24. Svenska Statoil.