BioEthanol for Sustainable Transport

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Short report from emission test using low blend of ethanol derivative in diesel fuel

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Summary

A vehicle demonstration test using low blend of ten percent ethanol derivatives in diesel fuel has been running in the city of Örnsköldsvik since May 2007. Two Scania Omni city buses have been running the normal city routs. To evaluate the environmental advantages using low blend, emission test was made on an identical 9 litre Scania engine.

The emission test was made by STT Emtec AB at their test cell laboratory in Sundsvall, Sweden.

ED-diesel plus 5 percent RME, the bus fleet test fuel

The test result shows that low blend in diesel with 10 percent of ethanol derivative and 5 percent RME, reduces the NOx emissions with 3.1 percent, CO is reduced with 8 percent and particulates are reduced with 6.2 percent according to the ECS test cycle. This fuel composition has been used in the bus fleet test for more than 150.000 kilometers.

ED-diesel

Low blend in diesel with solely 10 percent of ethanol derivative reduces the NOx emissions with about 1 percent, CO is considerably reduced with 22.7 percent and particulates are reduced with 12.3 percent according to the ECS test cycle. This fuel composition has only been evaluated in bench engine tests.

Reduction of CO2 emission

The result shows that ED-diesel including 5 percent RME reduces the total fossil CO2 emission with 16.9 percent compared to standard diesel Mk1. ED-diesel reduces the total fossil CO2 emission little less, 12.5 percent, which also could be expected since without RME the renewable content in ED-diesel is less.

Background

The diesel engine has taken its position as the leading prime mover for heavy-duty vehicles mainly on the grounds of high fuel efficiency and reliability. In most countries, diesel is in practise the sole fuel for heavy-duty vehicles, buses and trucks. The main drawbacks of the diesel engine are high particle emissions and high emissions of nitrogen oxides.

Fuel modifications, so called low blend, provide an interesting option to emission reductions for the existing vehicle fleets. The main advantages of fuel modifications are that the lead time for implementation is relatively short, and that in the best cases no modifications are needed to the fuel distribution system or the vehicles.

This report is a short summary on emission test using low blend of ethanol derivatives in standard diesel fuel. This type of low blend fuel we call ED-diesel. See under Fuels below.

Preparation and planning of the emission test

By way of introduction we had to decide which engine test laboratory we should consult. We invited tenders from three companies; VTT Technical Research Centre in Helsinki, AVL MTC Motortestcenter AB in Stockholm and STT Emtec AB in Sundsvall. All three test centres are certified in accordance with the ISO 9001 Quality standard.

After studying and comparing the offers we decided to go with STT Emtec, which was the cheapest and closest test laboratory, only 150 kilometres from Örnsköldsvik. In addition, STT Emtec also has been accredited according to the internationally accepted standard for engine laboratories (ISO/IEC 17025:1999).

Discussion with the test lab

Before the test plan was decided, we had a detailed discussion with the test laboratory and the responsible test manager. We agreed on the test methods and what fuels should be tested. Except from the regulated emissions some unregulated emissions also were measured, such as aldehydes. The regulated emissions are nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC) and particulate matters (PM).

Test methods

The tests were made according to the European emission test cycles ESC (European Steady Cycle) and ETC (European Transient Cycle), see figure 1, 2 and 3.

The tests at STT Emtec were made by using a transient test cell for heavy duty diesel engines, with capacity to test engines rated up to 660 kW. The test cell had advanced test equipment with access to measurement of a wide range of engine and exhaust emission related data.

European Steady Cycle

The ESC test cycle (also known as OICA/ACEA cycle) has been introduced, together with the ETC and the ELR (European Load Response) tests, for emission certification of heavy-duty diesel engines in Europe starting in the year 2000 (Directive 1999/96/EC of December 13, 1999). The ESC is a 13-mode, steady-state procedure that replaces the R-49 test.

The engine was tested on an engine dynamometer over a sequence of steady-state modes (Table 1, Figure 1). The engine must be operated for the prescribed time in each mode. Emissions were measured during each mode and averaged over the cycle using a set of weighting factors. Particulate matter emissions were sampled on one filter over the 13 modes. The final emission results are expressed in g/kWh.

The ESC test is characterized by high average load factors and very high exhaust gas temperatures.

ESC Test Modes				
Mode	**Engine speed**	**Load, %**	**Weight factor, %**	**Duration**
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

Table 1 Sequence over steady-state modes.

This picture is taken at the transient test cell at STT Emtec laboratory in Sundsvall.

The AVL test system is equipped with following measurement and control modules:

- Dynamometer for heavy duty engines.
- Data sampling equipment.
- Emission measurement equipment.

Ref. http://www.sttemtec.com/1/1.0.1.0/73/Engine_laboratory.pdf

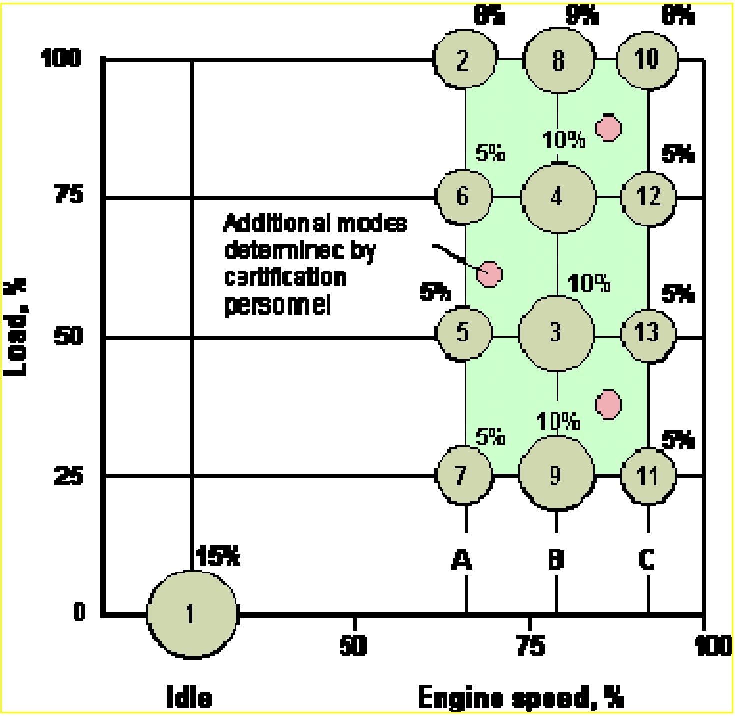

Figure 1 European Stationary Cycle (ESC)

European Transient Cycle

The ETC test cycle (also known as FIGE transient cycle) has been introduced, together with the ESC, for emission certification of heavy-duty diesel engines in Europe.

The ETC cycle has been developed by the FIGE Institute, Aachen, Germany, based on real road cycle measurements of heavy duty vehicles (FIGE Report 104 05 316, January 1994). The final ETC cycle is a shortened and slightly modified version of the original FIGE proposal.

Different driving conditions are represented by three parts of the ETC cycle, including urban, rural and motorway driving. The duration of the entire cycle is 1800 seconds. The duration of each part is 600 seconds.

- Part one represents city driving with a maximum speed of 50 km/h, frequent starts, stops, and idling.

- Part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h
- Part three is motorway driving with average speed of about 88 km/h.

Vehicle speed versus time over the duration of the cycle is shown in Figure 2. For the purpose of engine certification, the ETC cycle is performed on an engine dynamometer. The pertinent engine speed and torque curves are shown in Figure 3 and Figure 4.

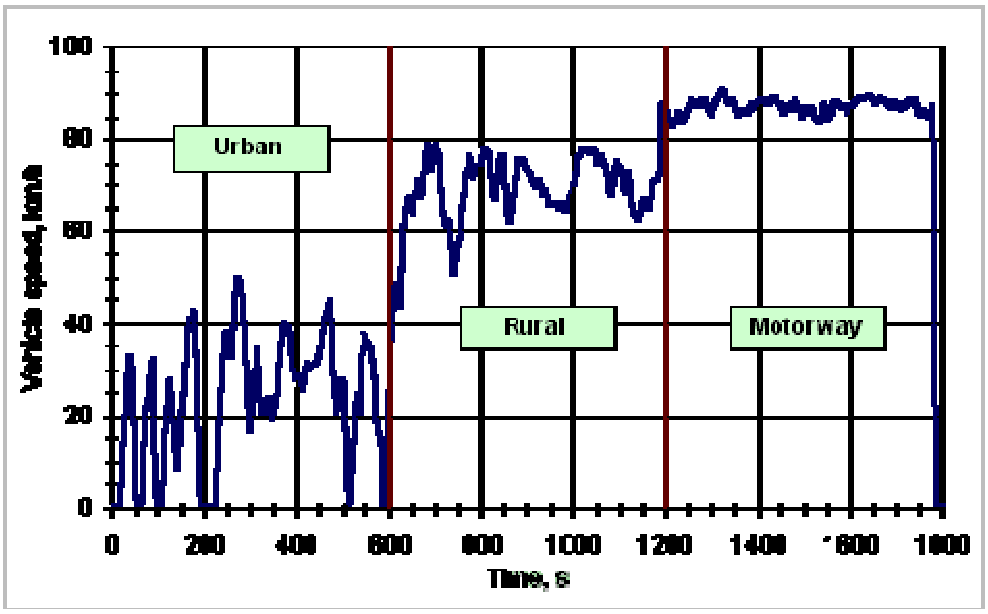

Figure 2 European Transient Cycle (ETC) – vehicle speed.

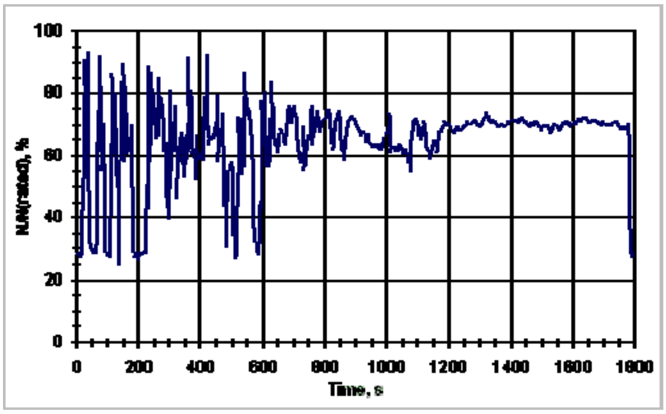

Figure 3 European Transient Cycle (ETC) – engine speed.

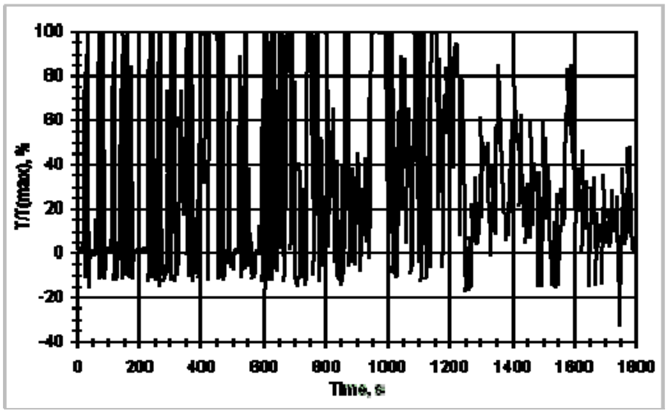

Figure 4 European Transient Cycle (ETC) – Engine Torque

The test engine

The test engine was an identical 9 litre Scania engine, which is running in the two test buses.

The Scania engine specification

- Manufacturer: Scania
- Type(model): DC905 emission class Euro3
- Rated power: 180 kW
- Rated speed: 2000 rpm
- Serial number: 5131804

The catalyst and particulate filter specification

- Catalyst manufacturer: Johnson Matthey
- Type (model): Oxidation catalyst
- Particulate filter manufacturer: Johnson Matthey
- Type (model): CCRT (Catalytic Coating Reduction Technology)

Fuels

For the emissions tests, two different ED-diesel fuel blends were evaluated. Fuel number one was a blend of diesel Mk1, 5 percent RME (rape methyl ester) and 10 percent ethanol derivative. That fuel composition was also used in the bus fleet test.

Fuel number two was a blend of diesel Mk1 and 10 percent ethanol derivative. Fuel number three was diesel fuel Mk1 with 5 percent RME and fuel number four was diesel Mk1, which was used as reference fuel. See table 2.

	Diesel Mk1 (vol-%)	**Ethanol derivative (ED) (vol-%)**	**RME (vol-%)**
ED-diesel, Fuel no.1 (The bus fleet test fuel)	85	10	5
ED-diesel. Fuel no.2	90	10	-
Diesel Mk1 5% RME. Fuel no.3	95	-	5
Diesel Mk1. Fuel no.4	100	-	-

Table 2 Fuels

Test plan

Together with STT Emtec the testing matrix was drawn. All tests are listed in table 3 below. Each fuel was tested by ESC and ETC test cycle, with and without catalyst and particulate filter. In this short emission report, the ED-diesel fuels are only evaluated with respect to diesel Mk1, fuel no.4. In the test program, we also did run Diesel Mk1 5 % RME, fuel no.3 to obtain a complete testing matrix and be able to evaluate this fuel later on.

Testing Matrix					
		Fuel			
	Test ID	Diesel Mk1	5 % RME	10 % Ethanol derivative	Catalyst and particulate filter
Emission test ESC 1	7121	X			
Emission test ESC 2	7139	X		X	
Emission test ESC 3	7127	X			X
Emission test ESC 4	7149	X		X	X
Emission test ESC 5	7136		X		
Emission test ESC 6	7154		X	X	
Emission test ESC 7	7135		X		X
Emission test ESC 8	7150		X	X	X
Emission test ETC 11	7123	X			
Emission test ETC 12	7140	X		X	
Emission test ETC 13	7130	X			X
Emission test ETC 14	7148	X		X	X
Emission test ETC 15	7138		X		
Emission test ETC 16	7153		X	X	
Emission test ETC 17	7134		X		X
Emission test ETC 18	7151		X	X	X

Table 3 All fuels were tested with and without catalyst and particulate filter.

Test result

All tests were performed in engine test cell 3 of STT Emtec Engine Test Centre in Sundsvall, Sweden. The engine was mounted on an asynchronous dynamometer with a maximum braking capability of 660 kW. A full flow CVS tunnel with secondary dilution was used for PM sampling and diluted gaseous emissions measurements. Raw, undiluted exhaust was sampled for stationary measurements and FTIR (Fourier Transform Infrared Spectroscopy).

Emissions

Regulated emissions

The test results show a significant reduction in regulated emissions for the test fuels no.1 and no.2 compared to standard diesel Mk1. All emission data results are shown in appendix 1, table A and B. In the text below, results only from tests without catalyst and particulate filter are discussed. The reason is that the filter equipment is so efficient and reduced HC emissions up to 98 percent and particulates reduction up to 73 percent. To elucidate the differences between the fuels, only the untreated emissions are discussed.

Diesel with ethanol derivative and RME

Fuel no.1 was a low blend of ethanol derivative and RME, which also has been used in the bus fleet test. This fuel reduces the NOx emissions with 3.1 percent, CO was reduced with 8 percent and particulates were reduced with 6.2 percent according to the ECS test cycle.

The result from the ESC test cycle is shown in figure 5. All figures from the ESC test cycle are shown in Appendix 1, table A.

The ETC test cycle show no changes in NOx. Carbon monoxide emission increased with 3.4 percent. The pronounced difference compared to ESC was the reduction in HC and PM. The hydrocarbons were reduced with 14 percent and the particulates with 21.5 percent. All figures from the ETC test cycle are shown in Appendix 1, table B.

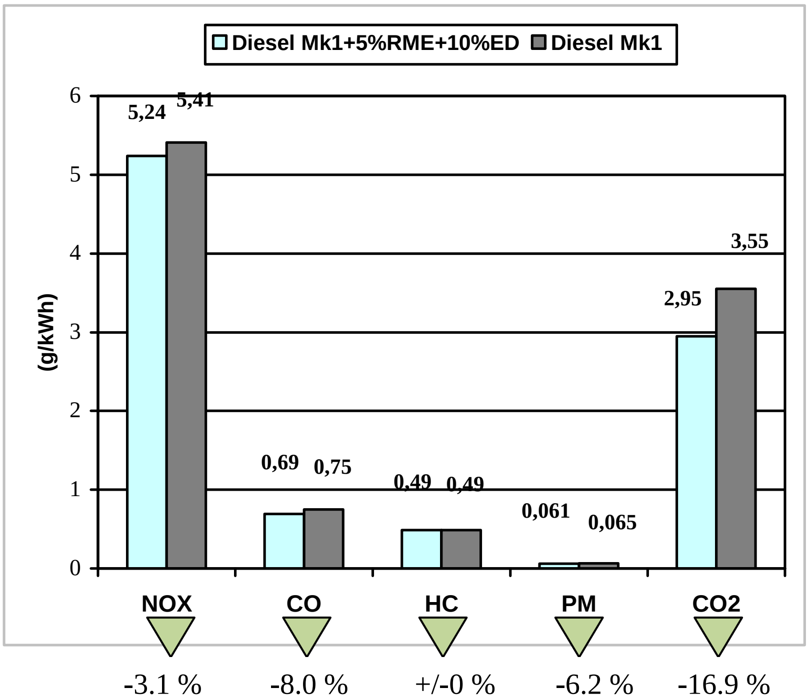

Figure 5 Regulated emissions for low blend in diesel, fuel no.1, versus standard diesel Mk1. Emissions from ESC test cycle. This result was achieved without catalyst and particulate filter.

Diesel with ethanol derivative

Fuel no.2 was a low blend of only 10 percent ethanol derivative. This fuel reduces the NOx emissions with about 1 percent, CO was considerably reduced with 22.7 percent and particulates were reduced with 12.3 percent according to the ECS test cycle. Fuel no.2 has only been evaluated in bench engine tests.

The result from the ESC test cycle is shown in figure 6. All figures from the ESC test cycle are shown in Appendix 1, table A.

The ETC test cycle show a little increase in NOx, about 1 percent. Carbon monoxide emission decreased with 1.7 percent. The pronounced difference compared to ESC was, even with this fuel, the reduction in HC and PM. The hydrocarbon emission increased with 16.1 percent and the particulates decreased with 16.2 percent. All figures from the ETC test cycle are shown in Appendix 1, table B.

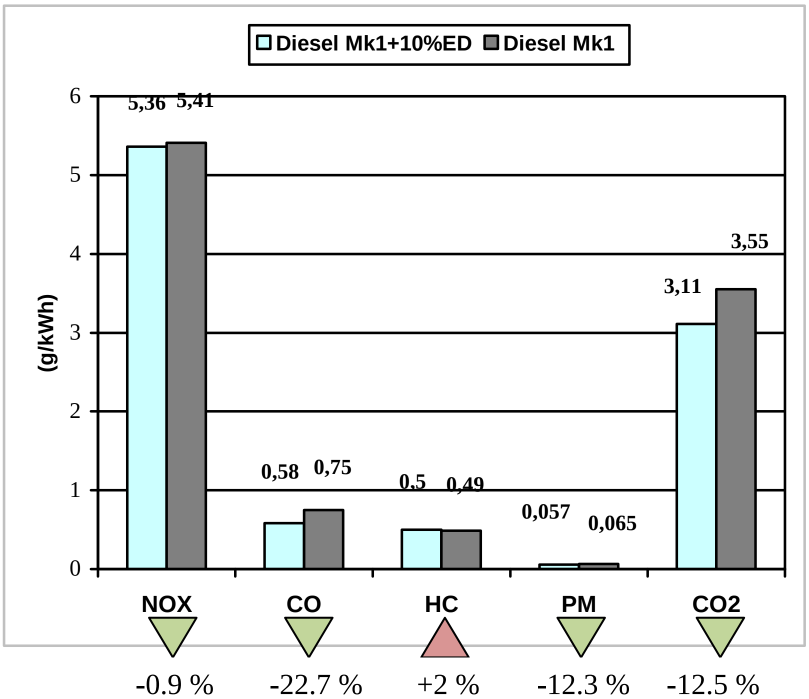

Figure 6 Regulated emissions for low blend in diesel, fuel no.2, versus standard diesel Mk1. Emissions from ESC test cycle. This result was achieved without catalyst and particulate filter.

Carbon dioxide emissions

The *total* carbon dioxide (CO2) emission and the fuel consumption (fc) were monitored from each fuel. Both CO2 and fc were measured in gram per kWh. By using this information the total amount of CO2 emitted per unit of fuel was calculated and could be expressed as gram CO2 per gram of fuel, (g CO2/ g fuel).

To calculate the total *fossil* CO2 reduction, the renewable amount of CO2 was estimated by calculations for each fuel. The calculations are showed in appendix 3. In figure 5 and 6 above the amount of fossil CO2 per gram fuel is shown for each fuel according to the ESC test cycle. The result shows that fuel no.1 reduces the total fossil CO2 emission with 16.9 percent compared to standard diesel Mk1. Fuel no.2 reduces the total fossil CO2 emission little less, 12.5 percent, which also could be expected since the renewable content in fuel no.2 is less than fuel no.1.

The result according to the ETC test cycle shows that fuel no.1 reduces the total fossil CO2 emission with 9.4 percent compared to standard diesel Mk1. Fuel no.2 reduces the total fossil CO2 emission with 7.8 percent.

Power and fuel consumption

The energy content in the ED-diesel fuels is lower than for regular standard diesel. The ethanol derivative and RME has both lower heating value, see table 4, which results in 3.2 percent less energy content totally for test fuel no.1. See table 5.

	HEATING VALUE		**DENSITY**
	(MJ/kg)	**(MJ/litre)**	**(g/litre)**
Diesel Mk1 (Preem)	43,3	35,3	815,0
RME	38	33,6	883,0
Ethanol derivative (ED)	30	24,9	830,0
Fuel no.1 (Diesel Mk1 + 5 % RME + 10 % ED)	41,7	34,2	820,0
Fuel no.2 (Diesel Mk1 + 10 % ED)	41,8	34,1	816,5

Table 4 Energy content for the test fuels and fuel components

To compensate for the less energy content, the fuel consumption increased with about 4.9 percent, which also could be expected.

The reduction in output engine power was about 4.4 percent, which is comparable to the less fuel energy content.

Changes compared to Diesel Mk1					
Fuel	Power	Fuel consumption		Heating value	
	(kW)	(g/kWh)	(l/kWh)	(MJ/kg)	(MJ/litre)
Fuel no.1 (Diesel Mk1 + 5 % RME + 10 % ED)	-4,4 %	4,9 %	4,2 %	-3,8 %	-3,2 %
Fuel no.2 (Diesel Mk1 + 10 % ED)	-3,7 %	3,1 %	2,9 %	-3,6 %	-3,4 %

Table 5 Changes in power, fuel consumption and heating value for the two ED-diesel fuels compared to standard diesel Mk1.

The loss in power and the increase in fuel consumption for test fuel no.2 were little less. This could probably only be described by the slightly higher heating value.

Discussion

Diesel engines combine a very high thermal efficiency with low emissions, and their good fuel efficiency results in relatively low carbon dioxide emissions. The main problem for diesel engines is emissions of NOx and particulates, and these two pollutants are traded against each other in many aspects of engine design.

High temperatures in the combustion chamber help reduce the emission of soot and particulates, but produce higher levels of NOx. Lowering the peak temperatures in the combustion chamber reduces the amount of NOx produced but increases the likelihood of particulate formation.

To establish a better mixing of the air and fuel and increase the supply of oxygen in the combustion chamber is the key to lower emissions.

By adding some kind of oxygenated additives to diesel improves the emissions. Using low blend of an ethanol derivative, which contains lots of oxygen, explains the emission test result and why NOx and above all particulate emissions are reduced.

The ethanol derivative lowers the combustion temperature slightly and therefore leads to somewhat lower NOx formation. This effect will not explain the reduction in particulates. But since the ethanol derivative contains more oxygen than diesel and RME, the lower particulate emissions may be caused by the higher supply of oxygen, which improves the combustion and reduce both soot and particulates.

CO formation in the combustion chamber is a result of insufficient local air supply (low air/fuel mixture) and low local temperatures. A high supply of oxygen probably compensates for the slight lower combustion temperature and as a result, the total effect is a quite high CO reduction for both fuel no.1 and no.2.

The HC formation in the combustion chamber is the result of incomplete combustion affected by the local air excess, local temperature and uniformity of the air/fuel mixture. Some part of the measured HC is also caused by evaporation of unburned fuel and lubricating oil. This probably explains the poor improvement in HC emission.

Conclusion

By adding 10 percent of ethanol derivative to standard diesel, together with and without RME, the result showed lower regulated emissions and reduced fossil CO2 emission for both fuels compared to standard diesel Mk1.

For fuel no.1, which had a total renewable content of about 15 percent, containing 10 percent ethanol derivative and 5 percent RME, the ESC test cycle showed a NOx reduction about 3 percent, CO reduction 8 percent and a reduction of particulates that reached 6.2 percent. For HC there was no improvement. The ETC test cycle showed less improvement in NOx and CO but even higher reduction in HC and particulates, 14 and 21.5 percent respectively.

The negative part of the test was increased fuel consumption, about 4 percent. This could of course be explained of the lower energy content in the fuel blends.

Appendix 1

Emission test result for the ESC test cycle

Specific test	**results ID**	**NOx (g/kWh)**	**CO (g/kWh)**	**HC (g/kWh)**	**CO2 (g/kWh)**	**Fuel (g/kWh)**	**PM (g/kWh)**	**Fuel Composition**	**Catalyst and filter**
Emissiontest ESC1 Fuel no.4	7121	5,41	0,75	0,49	803,12	226,23	0,065	Diesel Mk1	
Emissiontest ESC2 Fuel no.2	7139	5,36	0,58	0,5	806,81	233,25	0,057	Diesel Mk1 + 10 % ED	
Emissiontest ESC3. Fuel no.4	7127	5,02	0,07	0,01	813,44	228,98	0,024	Diesel Mk1	CAT+PM filter
Emissiontest ESC4. Fuel no.2	7149	5,11	0,14	0,01	823,99	235,78	0,022	Diesel Mk1 + 10 % ED	CAT+PM filter
Emissiontest ESC5 Fuel no.3	7136	5,22	0,76	0,47	804,09	228,38	0,065	Diesel Mk1 + 5 % RME	
Emissiontest ESC6 Fuel no.1	7154	5,24	0,69	0,49	809,92	237,22	0,061	Diesel Mk1 + 5 % RME + 10 % ED	
Emissiontest ESC7. Fuel no.3	7135	5,16	0,09	0,01	819,41	230,25	0,027	Diesel Mk1 + 5 % RME	CAT+PM filter
Emissiontest ESC8. Fuel no.1	7150	5,36	0	0,01	818,6	238,81	0,02	Diesel Mk1 + 5 % RME + 10 % ED	CAT+PM filter

Table A

Emission test result for the ETC test cycle

Specific test	**results ID**	**NOx (g/kWh)**	**CO (g/kWh)**	**HC (g/kWh)**	**CO2 (g/kWh)**	**Fuel (g/kWh)**	**PM (g/kWh)**	**Fuel Composition**	**Catalyst and filter**
Emissiontest ETC1 Fuel no.4	7123	4,97	0,59	0,93	634,54	233,78	0,117	Diesel Mk1	
Emissiontest ETC2 Fuel no.2	7140	5,03	0,58	1,08	656,47	239,7	0,098	Diesel Mk1 + 10 % ED	
Emissiontest ETC3. Fuel no.4	7130	4,76	0,03	0,02	650,76	237,82	0,034	Diesel Mk1	CAT+PM filter
Emissiontest ETC4. Fuel no.2	7148	4,65	0,06	0,07	627,34	240,8	0,024	Diesel Mk1 + 10 % ED	CAT+PM filter
Emissiontest ETC5 Fuel no.3	7138	4,98	0,59	0,97	636,94	236,78	0,108	Diesel Mk1 + 5 % RME	
Emissiontest ETC6 Fuel no.1	7153	4,97	0,61	0,8	667,54	243,34	0,093	Diesel Mk1 + 5 % RME + 10 % ED	
Emissiontest ETC7. Fuel no.3	7134	4,8	0,04	0,03	695,2	235,97	0,032	Diesel Mk1 + 5 % RME	CAT+PM filter
Emissiontest ESC8. Fuel no.1	7151	4,79	0,04	0,06	635,53	244,61	0,021	Diesel Mk1 + 5 % RME + 10 % ED	CAT+PM filter

Table B

Appendix 2

Torque and power for the ESC test cycle

Specific test	results ID	Test cycle Mode	Toque (Nm)	Power (kW)	Fuel Composition	Catalyst and filter
Emissiontest ESC1 Fuel no.4	7121	10	850,6	173,7	Diesel Mk1	
Emissiontest ESC2 Fuel no.2	7139	10	818,9	167,22	Diesel Mk1 + 10 % ED	
Emissiontest ESC3. Fuel no.4	7127	10	855,1	174,61	Diesel Mk1	CAT+PM filter
Emissiontest ESC4. Fuel no.2	7149	10	818,7	167,18	Diesel Mk1 + 10 % ED	CAT+PM filter
Emissiontest ESC5 Fuel no.3	7136	10	853,4	174,27	Diesel Mk1 + 5 % RME	
Emissiontest ESC6 Fuel no.1	7154	10	812,8	165,98	Diesel Mk1 + 5 % RME + 10 % ED	
Emissiontest ESC7. Fuel no.3	7135	10	855,9	174,78	Diesel Mk1 + 5 % RME	CAT+PM filter
Emissiontest ESC8. Fuel no.1	7150	10	811,2	165,65	Diesel Mk1 + 5 % RME + 10 % ED	CAT+PM filter

Appendix 3

Calculation of fossil CO_2 in ED-diesel

Property data

	Density (kg/litre)	Heating value (MJ/kg)	At combustion gram CO_2/ gram fuel
Diesel	0,815	43,3	3,16
RME	0,883	38	3,16*
Ethanol derivative	0,83	30	2,24

Procentage of fossil CO2 from Diesel Mk1 + 10 % ethanol derivative

Specification of 1 litre fuel:

0,9 litre diesel is equivalent to 733,5 gram
0,1 litre ethanol derivative is equivalent to 83 gram

The weight of 1litre is 816,5 gram

Percentage by weight:

Percentage by weight diesel:	733,5/816,5=0,898	89,8%
Percentage by weight ethanol derivative:	83/816,5=0,102	10,2%

The amount of CO2 from 1000 gram of fuel:

898 gram of diesel:	3,16x898=2837,7 gram of CO2	100 % fossile =>	2837,7 g fossil CO2
102 gram of acetal:	2,24x102=228,5 gram of CO2	0 % fossile =>	0 g fossile CO2

Total amount of CO2 from 1000 gram fuel:	3066,2 gram	
Total amount of fossile CO2 from 1000 gram fuel:	2837,7 gram	
Percentage by weight fossil CO2:	**2837,7/3066,2=0,9255 =>**	**92,6 % fossil CO2**

Procentage of fossil CO2 from Diesel Mk1 + 5 % RME + 10 % ethanol derivative

Specification of 1 litre fuel:

0,85 litre diesel is equivalent to 692,8 gram
0,05 litre RME is equivalent to 44,2 gram
0,1 litre ethanol derivative is equivalent to 83 gram

The weight of 1litre is 820 gram

Percentage by weight:

Percentage by weight diesel:	692,8/820=0,845	84,5%
Percentage by weight RME:	44,2/820=0,054	5,4%
Percentage by weight ethanol derivative:	83/820=0,101	10,1%

The amount of CO2 from 1000 gram of fuel:

845 gram of diesel:	3,16x845=2670 gram of CO2	100 % fossile =>	2670 g fossil CO2
54 gram of RME:	3,16x54=170,6 gram of CO2*	35 % fossile** =>	59,7 g fossile CO2
101 gram of acetal:	2,24x101=226,2 gram of CO2	0 % fossile =>	0 g fossile CO2

Total amount of CO2 from 1000 gram fuel:	3067 gram	
Total amount of fossile CO2 from 1000 gram fuel:	2729,9 gram	
Percentage by weight fossil CO2:	**2729,9/3067=0,890 =>**	**89,0 % fossil CO2**

*) Assumed that RME produces equal amount of CO2 for same amount of fuel.
**) According to Svensk Raps AB RME reduce fossil CO2 with 65 % compared to diesel (CO2 equivalent).