Utilisation of the internal engine potential of biodiesel (FAME) with consideration for specific fuel characteristics in the common rail diesel engine

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List of abbreviations

ASP	Operating cycle
b_e	Specific, gravimetric fuel consumption
B7	Diesel fuel with up to 7 % v/v FAME proportion
B30	Diesel fuel with up to 30 % v/v FAME proportion
B100	Pure FAME fuel
BMEP	Brake Effective mean pressure
CO	Carbon monoxide
DOE	Duration of Energising
FAME	Fatty acid methyl ester
HC	Hydrocarbons
M	(Turning) moment
n	Speed
NO_x	Nitrogen oxides
P	Performance, Power
PM	Particulate matter
SCR	Selective catalytic reduction
SUE	Specific use of energy
SOE	Start of Energising
TDC	Top dead centre

US EPA	United States Environmental Protection Agency
°CA	Degrees crank angle
λ	Combustion air ratio

Summary

With consideration for the specific fuel characteristics of fatty acid methyl ester (biodiesel), the goal of this project is to work out the internal engine potential of this fuel. A single-cylinder diesel engine with common rail injection system will be used for this purpose. Three measurement series (each with four measurement points) will be conducted, in each case one with diesel B7 (in accordance with DIN EN590), one with biodiesel B100 (in accordance with DIN EN14214) and one with a blended fuel B30 (30 % v/v biodiesel proportion, 70 % v/v diesel). In the next step, a performance adjustment to the reference values of the B7 measurement series will be carried out by increasing the injection duration. Furthermore, variation of injector activation commencement (and hence the start of the injection process) will be carried out for one operating point. In this way, in particular for the fuel B100, a target area for commencement of activation can be found at which comparable nitric oxide emissions and at the same time a clear reduction in particulate emissions in comparison with diesel B7 is possible.

With the knowledge and results, optimisation for B30 and B100 will be carried out wherein a sharp reduction in particulate emissions can be attained with a tendency towards lower specific use of energy and only a moderate increase in nitric oxide emissions (B30) or comparable nitric oxide emissions (B100).

1. Introduction and task specification

Hitherto, predominantly so-called “blended fuels” have been used to operate diesel engines in the mobile sector. These are composed of mineral diesel fuel with its bandwidth of different hydrocarbon species, and also fatty acid methyl esters which are frequently based on rape seed oil. With this, the diesel fuel that is currently available at filling stations comprises up to seven per cent regenerative energy carriers (as of September 2012).

However, for certain applications it is fundamentally conceivable and reasonable to use pure fuels (e.g. biodiesel, vegetable oil, etc.) – e.g. in agriculture or other special sectors. Furthermore, it is of interest as to how higher proportions of biodiesel behave in diesel fuel. Developments (including political developments) in recent years have led to development work on pure fuels being comparatively strongly restricted. The majority of research was carried out by (public) research establishments, and although these analysed the specific properties of the respective pure fuels when used in engines in detail, they did not implement an optimisation process that made use of the available advantages of these fuels.

This is the precise point at which this project starts. It contains an examination of biodiesel in accordance with DIN EN14214 (Deutsches Institut für Normung e.V., 2010) in comparison with standard B7 diesel in accordance with DIN EN590 (Deutsches Institut für Normung e.V., 2010), carried out on a regineering research engine. Here, a second measurement series compares a blended fuel comprising 30 % v/v biodiesel and 70 % v/v diesel (hereinafter designated as B30). In doing this, particular attention will be placed on emissions (both regulated gaseous emissions and particulate matter).

The goal is to investigate and demonstrate the internal engine potential of biodiesel and B30 by considering the specific fuel characteristics in the common rail diesel engine with open engine control unit (development control unit).

Commencing with a literary overview in the next section, the test bed, the utilised measurement technique and applied methodology will be described in Chapter 3. The results of the reference measurements (Chapter 4) will then serve as a basis for the optimisation process, the results of which will be presented in Section 5. To conclude, the knowledge and conclusions gained from the project will then be summarised.

2. Literary references

The following section contains information and literary recommendations that, under some aspects, relate to biodiesel fuel. Only essential points are raised here; a description of the detailed results of the individual activities does not form part of this report.

Fundamentally, the subject of “biodiesel” can largely be viewed as researched. For example, Giebel (Giebel, 2007) describes the use of biodiesel based on rape seed oil in Deutz engines, wherein no serious anomalies could be found up to 15,000 operating hours. However, for long-term operation it is noted that fuel-carrying components made from rubber and membrane fuel pumps are to be replaced annually and that oil change intervals were halved during the tests. Two years later, test bed runs and field tests were carried out in Knuth & Winkler, 2009 on EURO IV common rail engines. Here, as in other tests, reference is made to the attainable maximum performance in comparison with diesel (approx. 9% in Knuth & Winkler, 2009) and higher specific fuel consumption (about 12 % w/w in Knuth & Winkler, 2009) with unchanged engine settings. The reason for this is primarily that the higher density of biodiesel cannot compensate for the lower heating value and hence the energy yield through the injection system is not identical to that of diesel operation with unchanged engine settings.

Furthermore, with the emerging use of exhaust gas aftertreatment systems with diesel engines, the effects of biodiesel operation were examined both as a pure fuel (see e.g. Knuth & Winkler, 2009, Tschöke et al., 2002) and also as a blended fuel (e.g. in Tatur et al., 2009, Richter et al., 2012). Retrofittable exhaust gas aftertreatment systems were also used in Blassnegger, 2005. Here, the loading and self-cleaning behaviour in cases where a particulate filter is used is different from that with comparable diesel operation and must therefore be taken into account.

A further important viewpoint is engine wear behaviour. The company Robert Bosch GmbH, among others, has examined this subject in detail (with the focus on the injection system) and e.g. presented it in Ullmann & Stutzenberger, 2007. Other tests on the subject of wear behaviour and long-term operation can also be found in e.g. Knuth & Winkler, 2009, and Okamoto, 2011. In summary, it can be seen that the fuel quality is of decisive importance and that this must definitely be maintained in order to guarantee reliable operation. Hence current engine generations (e.g. EU Stage IIIB or US Tier 4 interim) can also be operated with biodiesel, see e.g. Knuth et al., 2012.

An important key technology with the diesel engine is the injection system. For this reason, for example, in various works the spray behaviour of biodiesel (and other biofuels) was and is examined in comparison with diesel fuel, see e.g. Heilig et al., 2011, Backofen et al., 2010, Kuti et al., 2010, Wloka et al., 2010 or Battistoni, 2012.

Here, the results found by Backofen et al., 2010 are to be particularly emphasised, which among other things reached the result that with increasing injection pressures substantially above 2000 bar, the fuel spray volumes of biodiesel become closer and closer to those of diesel.

Not least, combustion engine emissions also with biodiesel operation were and are primarily in focus. For example, an insight can be found in Chien et al., 2009, Knothe et al., 2009, Blassnegger et al., 2009. Hitherto non-regulated exhaust gas components of diesel and biodiesel have also been examined (Munack et al., 2011).

The effects of biodiesel operation of combustion engines on emissions cannot be answered in an across-the-board manner, as the results depend on interlinked factors such as specific engine components and the type of injection system, the selected operating points or exhaust gas cycles, the manner of sampling and the applied measurement techniques, etc. But fundamentally, without concretely going into the respective measurement, almost all reports mention a reduction in hydrocarbons, carbon monoxide and particulate emissions in comparison with diesel operation. A (small) increase in nitric oxide emissions is also usually reported. The known "PM-NO_x trade-off" falls into line with this connection, although it has a different course for different fuels. On the other hand, until now diesel has been replaced with biodiesel and no alterations have been carried out to the engine (or its management system) that would take the specific characteristics of biodiesel (or its boiling point) in a modern common rail diesel engine.

Here, the knowledge gained opens up a further field for optimisation potential. These viewpoints can also be found in literature: Krahl, 2002, also mentions principally possible (in part, massive) constructional alterations that can be carried out on the internal combustion engine, wherein it should be noted that these do not appear to be expedient for economic reasons. Instead, it is optimum adjustment of the engine management system that, in combination with a fuel identification system, represents an economic solution and hence makes use of the specific characteristics of the fuel biodiesel. In doing this, Krahl also formulates the advantage of the aforementioned, more favourable "PM-NO_x trade-off". Here, a single-cylinder MWM diesel engine with cam-controlled injection system was used for the tests. Hence alterations to injection timing can only be represented manually by varying the time that the fuel supply commences.

Investigations were also carried out on engines with cam-controlled injection systems (Hatz industrial diesel engines) in Spessert & Schleicher, 2007. Here, the authors compared running performance, noise development and emissions when operating the test bed with biodiesel and vegetable oil. They come to the knowledge that without optimisation measures, engine operation that is comparable with diesel fuel is only conditionally possible. Hence an amendment of the injection pump cam profile is discussed. However, an improvement can only be attained in a limited characteristic curve area of the engine with this.

Cam-independent injection of fuel is necessary in order to obtain positive effects over the entire characteristic curve area of an engine when operating with biodiesel. This functionality is offered by the common rail injection system. These types of engine are used in Knuth & Winkler, 2009. A “biodiesel sensor” (the function of which is to measure the dielectricity constants) is mentioned here with which one principally has the option of detecting the respective fuel (or a blended fuel) and hence to make the optimum adjustment with regard to fuel quantity and injection point. An example of the mentioned engine management adaptation is not described in the cited report (Knuth & Winkler, 2009).

By way of example, a thermodynamic analysis of biodiesel combustion can be found in Wichmann et al., 2011). Here, Wichmann et al. describe three biofuels (FAME, hydrated vegetable oil and refined rape seed oil) with the same engine settings in each case. Here, different points in the characteristic curve of the test bed (2.0 litre 4-cylinder diesel car engine, controller parameter set “diesel standard”, common rail injection system) were measured. Somewhat later, results were also presented from tests with different blended fuels (Richter et al., 2012). In this way, e.g. the fuel influence on the ignition delay or NO_x conversion when using an SCR catalytic converter was tested. However, fuel-specific optimisation of the engine management did not take place here either.

Overall, it can be summarised that the author was not aware of any source on the date this report was created that was devoted to the goal of the current undertaking. Here, the action mechanisms that lead to different emissions behaviour with the use of biodiesel are largely known (e.g. influence of the boiling point, oxygen content, heating value, etc.). However, tests have hitherto not been conducted on the development of optimum settings on a test bed with common rail injection system when using biodiesel in accordance with DIN EN14214 (or a blended fuel B30) compared to diesel in accordance with DIN EN590. Hence this represented the goal of the undertaking.

3. Test bed and methodology

The test bed and the applied measurement techniques are described in the following text. Following this, the utilised fuels and the methodology of the procedure on the test bed are described.

3.1 Test bed and measurement technology

The regineering test bed “MP2” is used for this undertaking. It is based on a Senertec single-cylinder diesel engine (normally-aspirated, 579 cm^3 cylinder capacity) and is designed as a research engine. The MP2 is modular in design but the utilised configuration does not correspond with any specific series production engine. Depending on requirements, various sub-systems (such as boosting, exhaust gas recirculation, piston crown geometry, etc.) or special measurement technology (indexing, exhaust gas measurement technology, special measurement technology) can be attached. The MP2 is equipped with a Bosch common rail injection system (max. common rail pressure 1800 bar, up to 5 injections per operating cycle) and has an open engine control unit for free selection of the injection strategy. In normally-aspirated configuration, and depending on application, engine output is up to 7 kW at 2,500 rpm. The key technical data can be found in Table 1.

regineering MP2 Single-cylinder-DI-Dieselengine	
V_h	579cm³
ε	22,5
Piston crown bowl	Standard MP2
Valve train	Senertec, Serienzustand
Injection system	Bosch Common-Rail, 5-hole-nozzle Bosch-regineering
Charging	none
EGR (external)	none
Exhaust aftertreatment	none

Tab. 1: MP2 technical data

For this project, the test bed is set up as a reference (with diesel fuel "B7" in accordance with DIN EN 590) so that with four operating points that are to be reached (see Section 3.3), the arithmetic mean of emissions is orientated on the strictest exhaust emissions standard (US EPA Tier 4 < 8 kW (VDMA, 2011)) for this engine category.

As standard, the MP2 is equipped with a number of pressure and temperature measurement points. These measurement points are not described further in the following text, and are only used where they are relevant to this test.

The combustion air ratio is continuously recorded, as is the fuel consumption (gravimetric determination).

Furthermore, the following emissions measurement technology is used:

- Horiba Mexa exhaust gas analysis 9230 (recording of gaseous emissions: nitrogen oxides (NO_x), hydrocarbons (HC) and carbon monoxide (CO))
- Pierburg CVS tunnel and particulate measurement system (hereinafter referred to as PM), measurement process following the principle of EU Guideline 2004/26 EC (European Parliament and Council, 2004)).

The engine-out emissions of the test bed are measured. Each measurement series is carried out with conditioned test beds, i.e. the engine is at operating temperature and the measurement technology is within the framework of the usual measurement tolerance, tested with a reference run at the start of every day of measurements and a subsequent comparison against comparison data.

3.2 Utilised fuels

Three fuels are used for the project:

I. Diesel, hereinafter designated as B7, in accordance with DIN EN590 (Deutsches Institut für Normung e.V., 2010)
II. Blended fuel (B30) of 70 % v/v diesel fuel and 30 % v/v rape seed methyl ester
III. Biodiesel, rape seed methyl ester, hereinafter designated as B100, in accordance with DIN EN14214 (Deutsches Institut für Normung e.V., 2010)

B30 is produced from I. and II. in accordance with the volumetric mixture ratio.

An analysis sheet is provided for B100 (see Annex).

The following numerical values are used for the parameter "heating value" (for the subsequent calculations with respect to the specific energy utilisation, hereinafter also referred to as "SUE"):

I. B7: 41.80 MJ/kg
II. B30: 40.36 MJ/kg
III. B100: 37.00 MJ/kg

3.3 Procedure / methodology

At the beginning, B7 is measured as a reference fuel at the following operating points:

Operation point	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
Injected fuel mass for Diesel operation[mg]	17	25.3	15.6	26.1
Start of energising ("SOE") [°CA before TDC]	4	1	6	4
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	500	1000	900	1000
bmep [bar] für B7	3.03	5.58	3.06	5.31
M [Nm] für B7	14.0	25.69	14.1	24.45
P [kW] für B7	2.27	4.04	3.25	5.63

Tab. 2: Overview of operating points

With this engine setting, on average the test bed attains the exhaust gas threshold values in accordance with US EPA Tier 4 (VDMA, 2011). It should be noted that a defined test cycle (ISO 8187) is specified for formally correct determination. Here, orientation merely takes place to the threshold value of the specified exhaust emissions standard for the respective emissions. The threshold values (numerical values) are listed in Section 4. Calculation of the specific emissions in [g/kWh] is carried out in accordance with EU Guideline 2004/26 EC (European Parliament and Council, 2004). The overall result is calculated via arithmetic averaging of all four partial results.

In the second step, fuels B30 and B100 are utilised at identical B7 engine settings. A reduction in effective output (or torque, brake mean effective pressure) is expected (less so with B30), because with identical injection duration (hereinafter referred to as DOE: “duration of energising”), less energy enters the combustion chamber via the injection process primarily due to the lower heating value of fatty acid methyl esters.

In order to compensate for this, in the third step output equilibration takes place in the form of an extension of the DOE and a renewed measurement series for B30 and B100.

In order to obtain knowledge about the emissions behaviour dependent on the commencement of injection (hereinafter referred to as SOE: “start of energising” and the utilised fuel, in the next step a variation of the SOE is implemented at one of the four operating points (2200_3) with otherwise constant conditions.

Implementation of the optimisation process commences with the knowledge gained. In principle, this is carried out in accordance with the following schema:

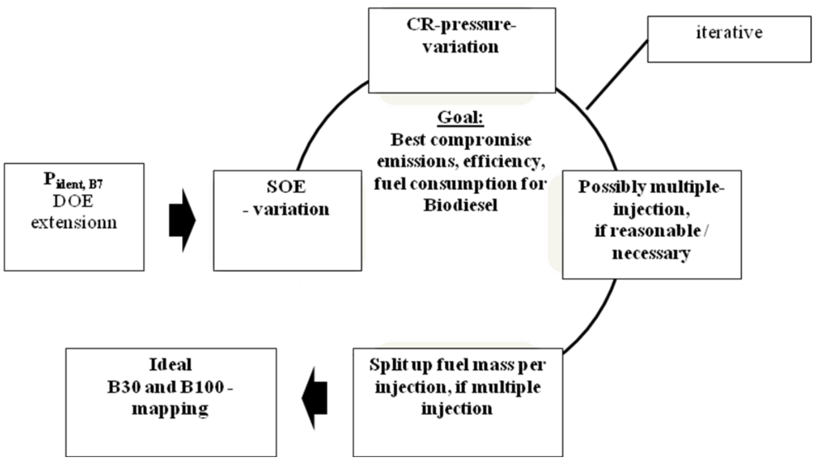

Fig. 1: principal optimisation process

As a matter of priority, variation of the SOE and the common rail pressure takes place (with corresponding adaptation of the DOE).

Here, the goal is to at least attain the result of the diesel measurement and at the same time to find the best possible setting with regard to fuel consumption and degree of efficiency (in each case for B30 and B100).

4. Results of the reference measurements

4.1 Measurement series B7

The results of the B7 reference measurements are shown in Table 3:

B7-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.62	1.05	0.91	1.55
Spec. Fuel consumption b_e [g/kWh]	273.13	260.72	281.40	275.92
SUE[MJ/kWh]	11.42	10.90	11.76	11.53
Eff. Power P [kW]	2.27	4.04	3.25	5.63
λ [-]	2.77	1.58	2.93	1.71
NO_x [g/kWh]	5.99	5.88	8.12	5.08
CO [g/kWh]	6.09	4.92	1.34	4.11
HC [g/kWh]	0.31	0.05	0.08	0.06
PM[mg/kWh]	23.35	108.72	31.86	225.95

Tab. 3: B7 measurement results, individual operating points

If one takes an average of the four individual results and compares them to the threshold values of US EPA Tier 4 (< 8kW) for orientation, the following result is received:

Measurement	US EPA Tier 4 <8kW	B7
Spec. Fuel consumption b_e ⊘ [g/kWh]	-	272.79
SUE. ⊘ [MJ/kWh]	-	11.40
P. ⊘ [kW]	-	3.80
NO_x + HC ⊘ [g/kWh]	7.50	6.39
CO. ⊘ [g/kWh]	8.00	4.11
PM. ⊘ [mg/kWh]	400.00	97.50

Tab. 4: B7 overall result

With the engine settings mentioned in Table 2, the averaged result of the selected operating points lies under the threshold values of US EPA Tier 4.

4.2 Measurement series B30

The results of the B30 measurements are shown in Table 5 and 6:

B30-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.63	1.04	0.97	1.63
Spec. Fuel consumption b_e [g/kWh]	279.77	271.52	301.12	290.41
SUE[MJ/kWh]	11.29	10.90	12.15	11.72
Eff. Power P [kW]	2.23	3.85	3.22	5.60
λ [-]	2.78	1.68	2.90	1.67
NO_x [g/kWh]	6.29	6.19	8.66	5.20
CO [g/kWh]	7.99	4.74	1.38	4.41
HC [g/kWh]	0.40	0.04	0.06	0.05
PM [mg/kWh]	93.49	76.19	31.85	234.45

Tab. 5: B30 measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B30	Δ B30 vs. B7
Spec. Fuel consumption b_e ⊘ [g/kWh]	-	272.79	285.70	+4.73%
SUE. ⊘ [MJ/kWh]	-	11.40	11.53	+1.12%
P. ⊘ [kW]	-	3.80	3.72	-1.90%
NO_x + HC ⊘ [g/kWh]	7.50	6.39	6.72	+5.21%
CO. ⊘ [g/kWh]	8.00	4.11	4.63	+12.55%
PM. ⊘ [mg/kWh]	400.00	97.50	109.00	+11.82%

Tab. 6: B30 overall results, in comparison

With the engine settings mentioned in Table 2, the averaged result (measurement series “B30”) of the selected operating points also lies under the threshold values of US EPA Tier 4.

Due to the B7 engine settings, the effective output is reduced by 1.9 %, the specific energy utilisation tends to increase (+1.12 %). On average, specific nitrogen oxide emissions increase slightly (+5.21 %).

At first glance it seems surprising that the average CO and PM emissions also increase. Amongst other things, this is due to the specific representation of the emission values. If one continues to observe the individual operating points, a significant increase in CO and PM emissions in comparison to B7 can be observed at the operating point “1500_3”, namely at lower load and engine speed. A comparatively low pressure and temperature level is found here, both at the point “inlet closes” and also during the injection, mixture formation and combustion process. Commencement of the combustion process moves towards retarded, primarily due to the altered boiling curve of B30 in comparison to B7. After falling below a specific (combustion) temperature level in the expansion phase, the CO oxidation freezes up. This explains the increased CO emissions.

It should be noted with regard to the simultaneously increased PM emissions: due to the complex processes in the particulate formation process (both engine-internal and also with the dilution process in the PM measurement apparatus), we refer to literature at this point, e.g. (Turns, 2000), (Kirchen, 2008), (Frenklach, 2001). Fundamentally, in many cases the CO emissions can be seen as an indicator for increased particulates emissions, as is the case here. At the other operating points, the emissions values are at a comparable (B7) level with consideration for the lower output (-1.9 %).

4.3 Measurement series B100

The results of the B100 measurements are shown in Table 7 and 8:

B100-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.62	1.04	0.94	1.59
Spec. Fuel consumption b_e [g/kWh]	326.09	291.86	349.26	304.67
SUE[MJ/kWh]	12.07	10.80	12.92	11.27
Eff. Power P [kW]	1.89	3.58	2.70	5.21
λ [-]	3.2	1.88	3.19	1.86
NO_x [g/kWh]	6.30	7.98	9.74	6.47
CO [g/kWh]	11.36	2.18	2.12	2.32
HC [g/kWh]	0.54	0.03	0.06	0.04
PM [mg/kWh]	110.74	30.03	28.70	79.37

Tab. 7: B100 measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B30	B100	Δ B100 zu B7
Spec. Fuel consumption b_e ⌀ [g/kWh]	-	272.79	285.70	317.97	+16.56%
SUE. ⌀ [MJ/kWh]	-	11.40	11.53	11.76	+3.18%
P. ⌀ [kW]	-	3.80	3.72	3.34	-11.94%
NO_x + HC ⌀ [g/kWh]	7.50	6.39	6.72	7.79	+21.86%
CO. ⌀ [g/kWh]	8.00	4.11	4.63	4.49	+9.21%
PM. ⌀ [mg/kWh]	400.00	97.50	109.00	62.20	-36.17%

Tab. 8: B100 overall results, in comparison

With respect to the “NO_x+HC” emissions, the “B100” measurement series with the selected operating points does not attain the US EPA Tier 4 threshold value of 7.5 g/kWh. Among other reasons, this is due to the reduced effective output of -11.76 % in comparison with B7. At this point it would be necessary to adapt the control unit parameters for B100 to meet the threshold values in these operating points.

The phenomenon of increased CO and PM emissions applies even more strongly in the case of operating point “1500_3” than with the “B30” measurement series. At this operating point, the CO emissions are almost doubled in comparison with the B7 result, and the PM emissions also increase sharply. This issue must be taken into account in the optimisation process.

The other operating points, in particular the two higher-load points (1500_5.5 and 2200_5.5) lie within the expectation framework of various results in the available literature: The NO_x emissions increase (slightly) with a significant reduction in HC, CO and PM emissions.

4.4 B30 measurement series – adjustment of output to B7

As described in Section 3, adjustment of output to the effective output values of B7 is carried out in the next step by a moderate increase of the DOE:

Operation point adjustment B30-P_{ident}	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
DOE-increasement[%]	1.2	2.4	1.3	0.8%
SOE [°CA before TDC]	4	1	6	4
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	500	1000	900	1000
P [kW]	2.27	4.08	3.26	5.68

Tab. 9: B30 - P_{ident} operating point adjustment

The DOE increase is between 0.8 and 2.4 %. The deviations to B7 are comparatively slight. The results of the measurement series undertaken with these settings are shown in Tables 10 and 11:

B30-P_{ident}-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.63	1.10	0.97	1.62
Spec. Fuel consumption b_e [g/kWh]	277.53	270.43	296.50	284.53
SUE[MJ/kWh]	11.20	10.92	11.97	11.48
Eff. Power P [kW]	2.27	4.08	3.26	5.68
λ [-]	2.77	1.57	3.07	1.55
NO_x [g/kWh]	5.79	5.63	8.16	4.34
CO [g/kWh]	7.25	7.07	1.24	4.23
HC [g/kWh]	0.34	0.03	0.06	0.03
PM [mg/kWh]	76.44	158.77	23.25	274.78

Tab. 10: B30 - P_{ident} measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B30	B30-P_{ident}	Δ B30-P_{ident} zu B7
Spec. Fuel consumption b_e ⊘ [g/kWh]	-	272.79	285.70	282.25	+3.47%
SUE. ⊘ [MJ/kWh]	-	11.40	11.53	11.39	-0.10%
P. ⊘ [kW]	-	3.80	3.72	3.82	+0.62%
NO_x + HC ⊘ [g/kWh]	7.50	6.39	6.72	6.09	-4.68%
CO. ⊘ [g/kWh]	8.00	4.11	4.63	4.95	+20.22%
PM. ⊘ [mg/kWh]	400.00	97.50	109.00	133.30	+36.77%

Tab. 11: B30 - P_{ident} overall results, in comparison

If one orientates oneself again on the threshold values of US EPA Tier 4, these are maintained for the B30-P_{ident} measurement series. The specific energy utilisation is comparable with the B7 measurement series. In comparison with B7, the CO and PM emissions are considerably increased. This issue applies to the specified (comparatively retarded) injection strategy so that the NO_x threshold value is not exceeded. Here, optimisation potential is available via suitable application of the SOE and, under certain circumstances, the common rail pressure. This is also taken into account in the optimisation process.

4.5 B100 measurement series – adjustment of output to B7

As with B30 operation, adaptation of the output of B100 to the B7 values is attained by increasing the DOE:

Operation point adjustment B100-P_{ident}	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
DOE-increasement[%]	9.4	15.0	12.2	9.2
SOE [°CA before TDC]	4	1	6	4
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	500	1000	900	1000
P [kW]	2.25	4.08	3.27	5.65

Tab. 12: B100 - P_{ident} operating point adjustment

For the B100 fuel, the DOE increase is between 9.2 % and 15.0 %. The following result is obtained with this engine setting:

$B100\text{-}P_{ident}$ -operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.64	1.23	1.09	1.74
Spec. Fuel consumption b_e [g/kWh]	284.07	300.91	332.11	307.71
SUE[MJ/kWh]	10.51	11.13	12.29	11.39
Eff. Power P [kW]	2.25	4.08	3.27	5.65
λ [-]	2.73	1.66	2.93	1.75
NO_x [g/kWh]	4.86	6.97	9.26	5.78
CO [g/kWh]	5.91	7.80	1.53	5.41
HC [g/kWh]	0.21	0.03	0.03	0.04
PM [mg/kWh]	29.29	56.55	16.09	116.71

Tab. 13: B100 - P_{ident} measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B100	$B100\text{-}P_{ident}$	$\Delta B100\text{-}P_{ident}$ zu B7
Spec. Fuel consumption b_e ⊘ [g/kWh]	-	272.79	317.97	306.20	+12.24%
SUE. ⊘ [MJ/kWh]	-	11.40	11.76	11.33	-0.64%
P. ⊘ [kW]	-	3.80	3.34	3.81	+0.40%
NO_x + HC ⊘ [g/kWh]	7.50	6.39	7.79	6.79	+6.30
CO. ⊘ [g/kWh]	8.00	4.11	4.49	5.16	+25.53%
PM. ⊘ [mg/kWh]	400.00	97.50	62.20	54.70	-43.92%

Tab. 14: B100 - P_{ident} overall results, in comparison

In contrast to the B100 measurement series without adaptation of the output, the averaged result of the selected operating points lies below the threshold values of US EPA Tier 4.
This is mainly due to the specifically lower NO_x emissions that are, on average, only about 6 % higher than with B7 operation. As with the B30 – P_{ident} measurement series, with the equal-output B100 measurement series, average CO emissions increase by about 25 % in comparison with B7, although with a greater reduction in PM emissions (on average about -44 %). One reason for this may be the oxygen contained in the fatty acid methyl ester (about 11 % by mass) – see also various statements in literature, e.g. (Blassnegger, 2005) and (Blassnegger, et al., 2009).

4.6 Variation of the SOE

In this section, the influence of SOE variation (specified in degrees crank angle, hereinafter designated as °CA) on emissions is examined with

equivalent-output B7, B30 and B100 settings. The results flow into the subsequent optimisation process.
Based on the B7 SOE setting at the 2200_3 operating point, the SOE is adjusted at an interval of 356°CA; 362°CA], with increments of 2°CA. Due to the laborious measurement procedure, particulate emissions are measured using a 4°CA increment. This process is carried out for all three fuels.
The results are clarified with the following figures:

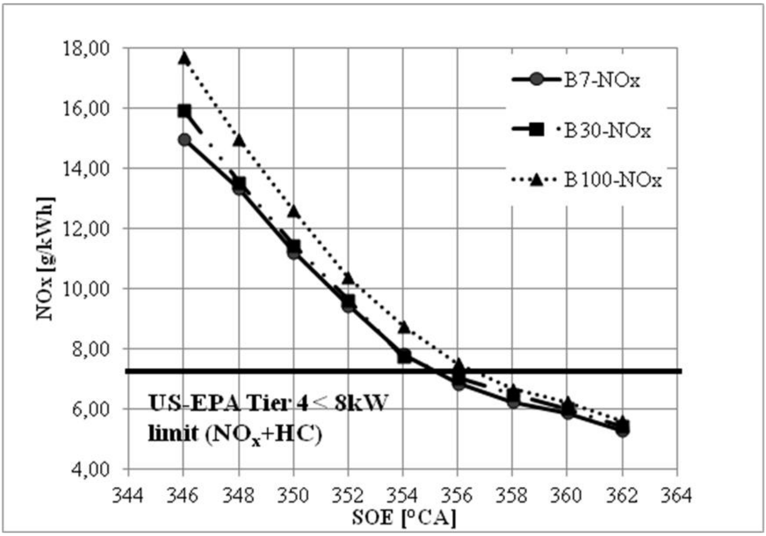

Fig. 2: NO_x trends over SOE, operating point 2200_3

With earlier commencement of injector control, and hence advanced injection, NO_x emissions increase due to the higher peak temperature in the combustion chamber. The earlier the commencement of control, the higher is the difference between B100 and B7 (and to a smaller degree between B30 and B7). If one compares the PM emission trend, figure 3, one can principally recognise the opposing trend. For this operating point, one can clearly see the higher “PM tolerance” of B7 and also B30 with respect to earlier commencement of control, and hence a good degree of effectiveness (figure 4). This greater “tolerance” with respect to PM emissions also applies to very late SOE after top dead centre (as an example, see figure 3: SOE=362°KW and about 420mg/kWh PM emissions for B100, in comparison to B7 PM of about 125mg/kWh).

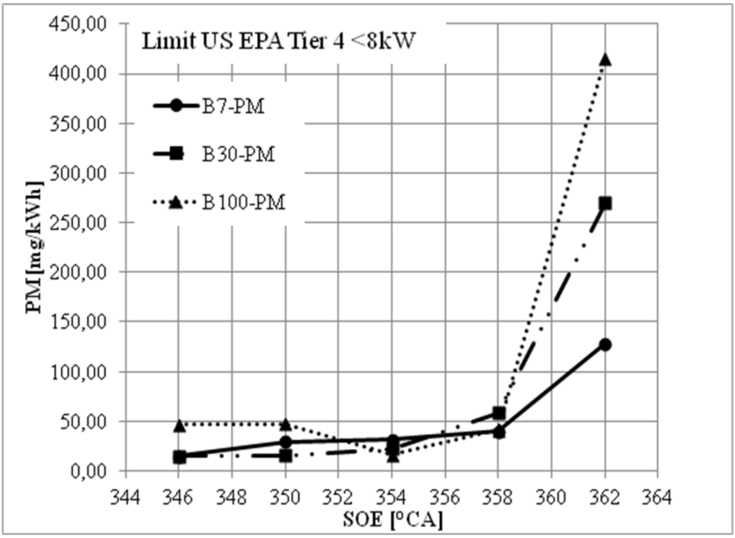

Fig. 3: PM trends over SOE, operating point 2200_3

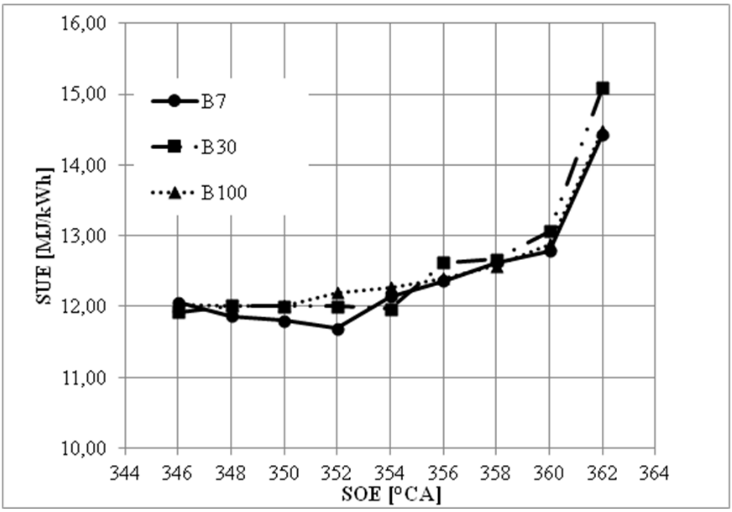

Fig. 4: Specific energy utilisation "SUE" trends over SOE, operating point 2200_3

However, the lowest PM emissions by far are obtained with B100, in a much tighter SOE window in comparison to the other fuels of about 353°CA to 358°CA. This window forms the basis of the optimisation process, since a good compromise for B100 of lower NO_x and PM emissions and fuel consumption (or rather specific energy utilisation, SUE) can be found.

5. Results of the optimisation process

The principal procedure of the optimisation process has been shown in Section 3, figure 1. The knowledge gained from Chapter 4 also flows into the process.

5.1 Optimisation result for B30

Tables 15 and 16 show the amended engine settings in comparison with B7 for each operating point:

Operation point B7	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
Injected fuel mass (target) [mg]	17	25.3	15.6	26.1
SOE [°CA before TDC]	4	1	6	4
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	500	1000	900	1000

Tab. 15: B7 settings, starting point

Operation point B30-OPT.	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
Injected fuel mass (target) [mg]	16.8	25.9	15.7	26.1
DOE-Variation[%]	-1.2	+2.4%	+0.6%	-2.3%
SOE [°CA before TDC]	4	1	5	5
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	550	1000	900	1000

Tab. 16: B30 settings optimised

The following amendments were carried out for the optimised B30 settings:

- Operating point 1500_3: Increase in the common rail pressure for CO and PM reduction (including adjustment of DOE)
- Operating point 1500_5.5: Increase of the DOE to adjust output
- Operating point 2200_3: SOE retarded by 1°KW, corresponding adjustment of DOE
- Operating point 2200_5.5: SOE advanced by 1°KW, corresponding adjustment of DOE

In this way, one reaches the following result (Table 17: individual operating points, Table 18: overall result in comparison with B7):

B30-OPT.-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.61	1.10	0.95	1.61
Spec. Fuel consumption b_e [g/kWh]	272.28	270.43	288.49	283.30
SUE[MJ/kWh]	10.99	10.91	11.64	11.43
Eff. Power P [kW]	2.26	4.08	3.30	5.67
λ [-]	2.9	1.57	3.11	1.72
NO_x [g/kWh]	7.91	5.63	7.64	5.70
CO [g/kWh]	1.63	7.07	1.73	4.17
HC [g/kWh]	0.07	0.03	0.07	0.03
PM [mg/kWh]	17.80	158.77	31.56	160.85

Tab. 17: B30 – optimised – measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B30	B30-OPT.	Δ B30-OPT. zu B7
Spec. Fuel consumption b_e ⊘ [g/kWh]	-	272.79	285.70	278.63	+2.14%
SUE. ⊘ [MJ/kWh]	-	11.40	11.53	11.25	-1.32%
P. ⊘ [kW]	-	3.80	3.72	3.82	+0.53%
NO_x + HC. ⊘ [g/kWh]	7.50	6.39	6.72	6.77	+5.95%
CO. ⊘ [g/kWh]	8.00	4.11	4.63	3.65	-11.19%
PM. ⊘ [mg/kWh]	400.00	97.50	109.00	71.60	-26.56%

Tab. 18: B30 – optimised – overall results, in comparison

Also with optimisation for B30, in accordance with expectations, the averaged result lies below the threshold values of US EPA Tier 4. Since the sum of NO_x + HC already lay clearly below the threshold value, CO and PM emissions reduction could be attained with minor modifications. This is also beneficial to the SUE. This lies below the B7 measurement series (-1.32 %)

5.2 Optimisation result for B100

When using B100 fuel, more extensive modifications are needed in comparison with the alteration requirements for B30.

Table 19 shows the engine settings that were undertaken:

Operation point B100-OPT.	1500_3	1500_5.5	2200_3	2200_5.5
n [1/min]	1500	1500	2200	2200
Injected fuel mass (target) [mg]	17.5	29.1	15.7	26.1
DOE-Variation[%]	+2.94	+15.0	+5.8	+5.0
SOE [°CA before TDC]	3	1	3	6
Number of injections [-]	1	1	1	1
Common-rail-pressure [bar]	600	1000	900	1000

Tab. 19: B100 settings optimised

The following amendments were carried out for the optimised B100 settings:

- Operating point 1500_3: Increase in the common rail pressure and SOE advanced by 1°CA (DOE adjustment) for CO reduction
- Operating point 1500_5.5: Increase of the DOE to adjust power output
- Operating point 2200_3: SOE retarded by 3°CA, corresponding adjustment of DOE
- Operating point 2200_5.5: SOE advanced by 2°CA, corresponding adjustment of DOE

In this way, one reaches the following result (Table 20: individual operating points, Table 21: overall result in comparison with B7):

B100-OPT.-operation point	1500_3	1500_5.5	2200_3	2200_5.5
Fuel consumption [kg/h]	0.62	1.23	1.10	1.70
Spec. Fuel consumption b_e [g/kWh]	278.75	300.91	332.13	301.17
SUE[MJ/kWh]	10.31	10.91	12.29	11.43
Eff. Power P [kW]	2.24	4.08	3.32	5.64
λ [-]	2.80	1.66	3.12	1.73
NO_x [g/kWh]	6.63	6.97	7.32	5.65
CO [g/kWh]	1.87	7.84	1.72	4.56
HC [g/kWh]	0.05	0.03	0.04	0.01
PM [mg/kWh]	29.89	56.55	31.16	105.05

Tab. 20: B100 – optimised – measurement results, individual operating points

Measurement	US EPA Tier 4 <8kW	B7	B100	B100-OPT.	Δ B100-OPT. zu B7
Spec. Fuel consumption b_e ⌀ [g/kWh]	-	272.79	317.97	303.24	+11.16%
SUE. ⌀ [MJ/kWh]	-	11.40	11.76	11.22	-1.60%
P. ⌀ [kW]	-	3.80	3.34	3.82	+0.55%
NO_x + HC ⌀ [g/kWh]	7.50	6.39	7.79	6.48	+1.46%
CO. ⌀ [g/kWh]	8.00	4.11	4.49	3.99	-3.07%
PM. ⌀ [mg/kWh]	400.00	97.50	62.20	55.66	-42.89%

Tab. 21: B100 – optimised – overall results, in comparison

The averaged optimisation result of the selected operating points for B100 also lies below the threshold values of US EPA Tier 4. With a lower SUE in comparison with B7 (-1.6 %) and only slightly increased NO_x+HC emissions, PM in optimised B100 operation drop considerably, on average by about 43 %, due to the more favourable PM – NO_x trade-off.

5.3 Presentation of the overall results in comparison

In summary, figures 5 and 6 represent the optimisation results for B30 and B100 in each case in comparison with the B7 measurement series.

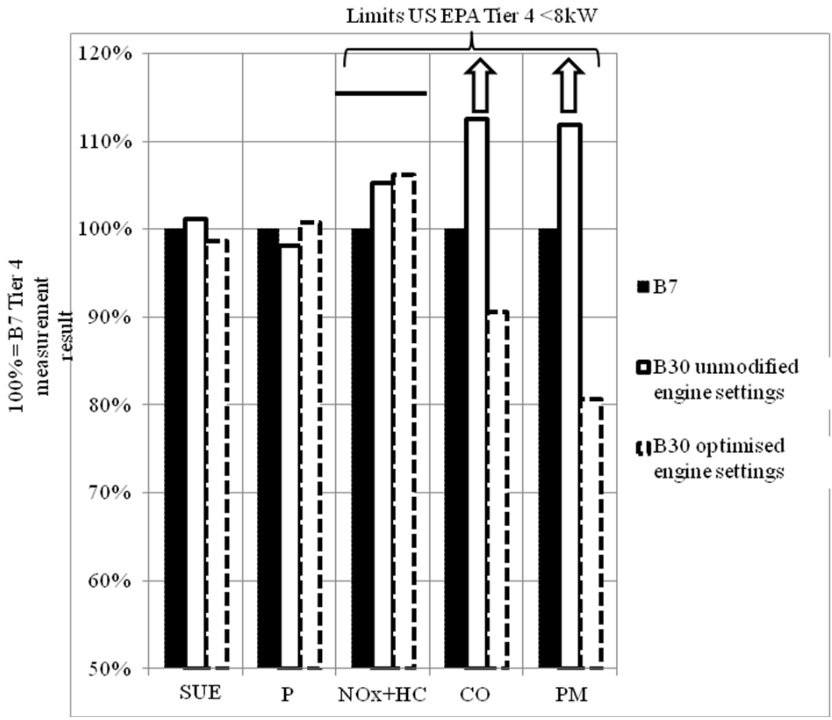

Fig. 5: Comparison of B7, B30 measurement series (unaltered engine settings) and B30 (optimised engine settings)

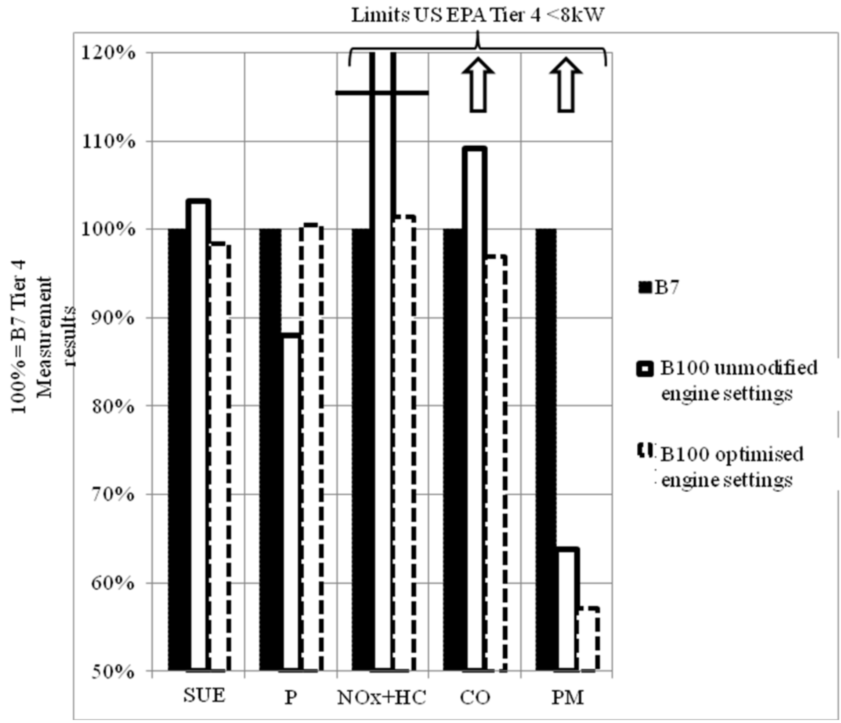

Fig. 6: Comparison of B7, B100 measurement series (unaltered engine settings) and B100 (optimised engine settings)

6. Conclusions

With consideration for the specific fuel characteristics of fatty acid methyl esters (such as the boiling point or the more favourable PM-NO_x trade-off), in comparison with the B7 measurement series it was possible to attain a significant reduction in particulate emissions with comparable nitrogen oxide emissions and specific energy utilisation. This result is valid for the specified test bed and the described methodology within this project.

Whilst the differences in engine behaviour with fuel B30 were smaller than with B100, as anticipated, there are characteristic curve areas (low partial load) in which increased CO and PM emissions can occur. This can be compensated for via suitable injection strategy measures.

For B100 fuel, purely due to the significant output reduction with unaltered B7 engine management parameters, adaptation of the injection strategy should take place. With fuel-specific knowledge, the advantages of particulate matter reduction can be utilised without having to accept an increase in nitrogen oxide emission or increased fuel consumption (energy-equivalent).

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Annex

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Prüfmuster: Pflanzenölmethylester (Biodiesel)
Verladetank
Werkszertifikat gem. DIN EN 14214

Datum: 16.07.2012	aus Tank: A11
Versandnr. :	

Eigenschaft	Methode	Resultat	Einheit	Grenzwerte EN 14214	
				min.	max.
Geruch	Organolep.	Typisch			
Dichte 15°C	EN ISO 12 185	883	kg/m³	860	900
Flammpunkt	DIN EN 2719	>150	°C	101	
Estergehalt	EN 14103	>99	% (m/m)	96,5	
Linolensäureester	EN 14103	9,2	% (m/m)		12
Viskosität	EN ISO 3104	4,461	mm²/s	3,5	5
Schwefel	ISO 20846	<2	mg/kg		10
Koksrückstand	EN ISO 10370	0,1	% (m/m)		0,3
Cetanzahl	EN ISO 5165	51,1		51	
Sulfatasche	ISO 3987	<0,001	% (m/m)		0,02
Wassergehalt	EN ISO 12937	177	mg/kg		500
Oxidationsstabilität	EN 14112	9,9	h	6	
Gesamtverschmutzung	EN 12662	7	mg/kg		24
Kupfer-Korrosion	EN ISO 2160	1a		Klasse 1	
Säurezahl	DIN EN 14104	0,28	mg KOH/g		0,5
Jodzahl	EN 14111	112	g Iod/100g		120
Methanol	EN 14110	<0,05	% (m/m)		0,2
Monoglyceride	EN 14105	0,42	% (m/m)		0,8
Diglyceride	EN 14105	<0,1	% (m/m)		0,2
Triglyceride	EN 14105	<0,1	% (m/m)		0,2
Freies Glycerin	EN 14105	0,007	% (m/m)		0,02
Gesamtglycerin	EN 14105	0,13	% (m/m)		0,25
Alkaligehalt	EN 14538	<2	mg/kg		5
Erdalkaligehalt	EN 14538	<2	mg/kg		5
Phosphorgehalt	EN 14107	<2	mg/kg		4
CFPP	EN 116	-14	°C		a)
Cloud Point	DIN EN 23015	-6	°C		
Pour Point	DIN ISO 3016	-12	°C		

a)

15.04. bis 30.09.	0 °C
01.10. bis 15.11.	-10°C
16.11. bis 28.02.	-20°C
01.03. bis 14.04.	-10°C

Ware enthält BHT - Additiv, Konzentration 200ppm - 500ppm

Das vorliegende Werks-Zertifikat ist zur Kunden-Information bestimmt und bezieht sich ausschließlich auf die ausgelieferte Ware. Seine Weitergabe zur Produktkennzeichnung ist nur zulässig, wenn die Ware in unveränderter Form, d. h. insbesondere ohne Vermischung mit anderen Stoffen und ohne Transport- und Lagerschäden an die nächste Handelsstufe übergeben wird.

14. Mai 2012 Unterschrift:

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Euro payments Kto.-Nr.: 1361 3511 43 | IBAN: DE19 3701 0600 1361 3511 43
US$ payments Kto.-Nr.: 1361 3504 36 | IBAN: DE96 3701 0600 1361 3504 36