Chapter 7
Effects of Biodiesel Usage on Engine Performance, Economy, Tribology, and Ecology

Biodiesel usage influences directly the injection and combustion processes and consequently also the *engine performance*, *ecology*, and *economy characteristics*. This influence is determined by the chemical and physical properties of biodiesel and depends on many parameters related to the engine, operating conditions, and so on.

According to most investigations, engine power and torque, particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC) in general decrease when mineral diesel is replaced by biodiesel. On the other hand, nitrogen oxides (NO_x) typically increase. Of special interest is the variation of PM and NO_x emissions which is attributed both to the difference in chemical characters of mineral diesel and biodiesel (which affects combustion kinetics) and to different physical properties, which affect fuel spray characteristics (Kousoulidou et al. 2012; Giakoumis 2012; Kegl 2008).

Biodiesel fuels have lower energy content than mineral diesel. Thus, if the efficiency is kept constant, the engine fuel consumption will be higher when mineral diesel is replaced by biodiesel. Furthermore, biodiesel usage can contribute to the formation of deposits, the degradation of materials, or the plugging of filters. This depends mainly on their degradability, their glycerol content, their cold flow properties, and other fuel quality specifications (Lapuerta et al. 2008a).

In spite of all potential problems related to biodiesel usage, biodiesel fuels exhibit an interesting potential to improve engine characteristics and reduce harmful emissions. In order to get as much insight as possible, these topics need to be addressed with regard to *biodiesel properties*, *engine type*, and *engine operating conditions* (including *ambient conditions*). In this context it may be worth noting that most modern engines have electronically controlled high pressure direct fuel injection systems, which are more sensitive to fuel quality than mechanically controlled injection systems. Since modern engines are optimized for mineral diesel, it is reasonable to compare all engine characteristics, obtained by usage of biodiesel fuels, to those obtained with mineral diesel (Canakci 2007).

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7.1 Engine Performance, Economy, and Tribology Characteristics

In general, investigation results show that the *engine power* and *torque* will decline when biodiesel replaces mineral diesel. This is especially evident for neat biodiesel fuels, because biodiesels have lower energy content than diesel. It is interesting to note, however, that the results reported are not completely uniform. For example, some investigations reveal that because of power recovery the observed power loss is actually lower than expected due to lower heating value of biodiesel (Xue et al. 2011). Anyhow, most of researches agree that lower energy content of biodiesels has evident consequences, which are also reflected in higher *fuel consumption*.

The influence of biodiesel fuels on the engine tribology characteristics depends to a great extent on the raw material used for biodiesel production and consequently its properties. Compared to mineral diesel, biodiesels typically exhibit higher viscosity and lower volatility, which can lead to injector coking and trumpet formation on the injectors. Furthermore, one can observe various influences on carbon deposits, oil ring sticking, and thickening and gelling of the engine lubricant oil, after the engine has been operated on biodiesel for a longer time period. Therefore, many biodiesel investigations are related to wear of engine components like piston, piston ring, cylinder liner, bearing, crankshaft, cam tappet, valves, and injectors (Dorado et al. 2003; Demirbas 2006; Giannelos et al. 2005). On the other hand, biodiesels typically exhibit better lubrication properties than mineral diesel. Therefore, biodiesels and their blends with mineral diesel may reduce long-term engine wear. In some tests, the engine wear was reduced to less than half of what was observed in the engine running on current low sulfur diesel fuel (Demirbas 2009).

7.1.1 Influence of Biodiesel Properties

Biodiesel chemical and physical properties influence significantly the injection process, fuel spray development, and combustion. Especially in a mechanically controlled injection system a replacement of mineral diesel by biodiesel results in higher injection pressure, the injection timing and start of combustion are advanced, the ignition delay is shorter, and the in-cylinder pressure and temperature rise earlier. Furthermore, the maximum firing temperature, the exhaust gas temperature, and heat release rate are smaller than to those obtained with mineral diesel. Shorter ignition delay of biodiesel results in an advanced combustion, longer expansion period, and lower exhaust gas temperature. Clearly, according to all this, biodiesel properties indirectly influence all engine characteristics. But apart from this, they also have a direct influence on engine performance, economy, and tribology characteristics (Kegl 2008, 2011; Ozsezen et al. 2008; Sayin and Gumus 2011;

Xue et al. 2011). In this context, the following properties are perhaps the most exposed:

- *Energy content*: biodiesels typically exhibit lower energy content than mineral diesel. Thus, biodiesel usage typically results in lower effective engine power and higher fuel consumption. Of course, this effect is the most exposed for neat biodiesel and declines by blending biodiesel with mineral diesel. Furthermore, it should be noted that the energy content varies in dependence on biodiesel source, its production processes, and quality.
- *Density*: higher density of biodiesel means that if the injected fuel volume is kept constant, the mass of injected fuel and consequently the fuel consumption are also higher.
- *Lubricity and solvent action*: in general, biodiesels exhibit good lubricity properties and good solvent action. Therefore, compared to mineral diesel, biodiesel usage may result in lower carbon deposits and wear of the key engine parts. The durability of the engine may further be improved due to the lower soot formation when using biodiesel. Good lubricity properties also positively affect the engine effective power.

In Kegl (2006) a *DI diesel bus* MAN 2566 MUM engine (Table 7.1) was tested in order to investigate the influence of *rapeseed biodiesel* (RaBIO) usage on engine performance. The results were compared to those obtained with mineral diesel (D100).

The histories of *heat release rate*, *in-cylinder pressure*, and *in-cylinder temperature* are shown in Figs. 7.1 and 7.2, along with the corresponding injection pressure and needle lift histories. It is evident that the maximums of the in-cylinder pressure, in-cylinder temperature, and heat release rate appear earlier when using RaBIO. The lower in-cylinder temperature of RaBIO can be attributed to the fact that, compared to D100, RaBIO exhibits higher latent heat of vaporization and lower heating value. Thus, more heat is needed for RaBIO vaporization, while the energy released by RaBIO is lower than that from the same mass of D100. As a result, the in-cylinder gas temperature can be lower for RaBIO. The start of injection and the start of combustion at peak torque and at rated conditions are also shown in Figs. 7.1 and 7.2. The start of injection is indicated by the point of needle lifting. The start of combustion is marked by a rapid increase of in-cylinder gas pressure and by the point of heat release start.

In Pehan et al. (2009) the same engine (Table 7.1) was used in order to get some insight into the influence of RaBIO on *tribology characteristics* of the engine. Firstly, the most important pump plunger surfaces were analyzed before and after biodiesel usage. Then, biodiesel deposits at the injectors and in the combustion chambers were examined. The deposits in the injector nozzle holes were investigated by considering the measured discharge coefficients. Before using RaBIO, the engine was run with mineral diesel.

The influence of RaBIO usage on *pump plunger surface* is illustrated in Fig. 7.3. The surface area shown in the figure is positioned close to the top of the pump plunger. This area has been selected for examination since it has a very important

Table 7.1 Engine specifications (Kegl 2006)

Engine model	MAN 2566 MUM
Engine type	4 stroke, 6 cylinders in line, water cooled
Displacement	11,413 cm^3
Bore and stroke	125 mm × 155 mm
Compression rate	17.5:1
Maximal power at engine speed	162 kW at 2,200 rpm
Maximal torque at engine speed	158 Nm at 1,600 rpm
Injection model	Mechanically controlled M direct injection system
Injector opening pressure	175 bar
Injection pump timing	23°CA BTC

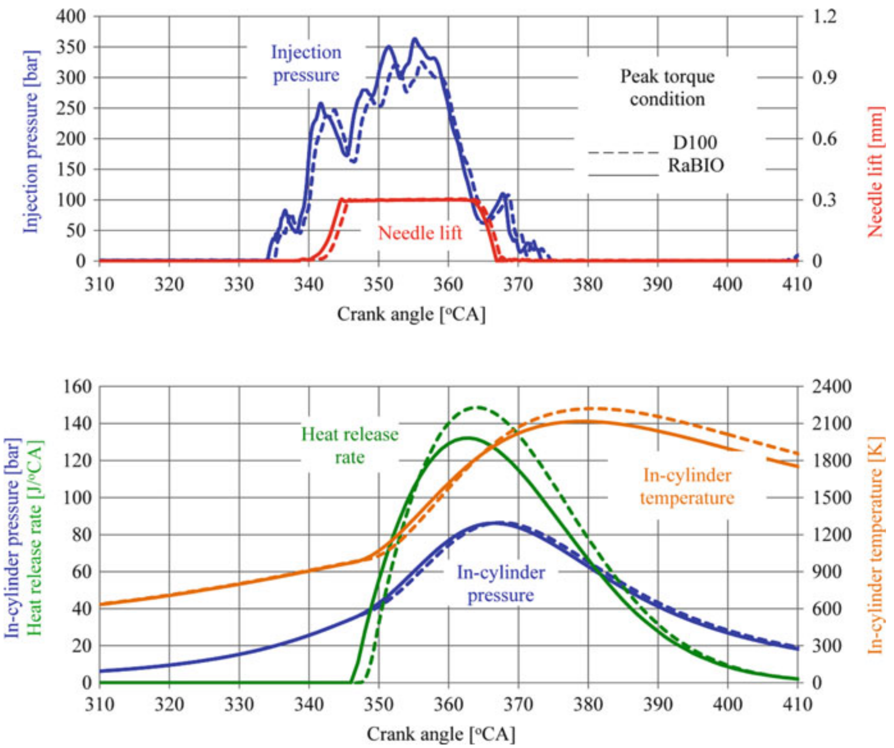

Fig. 7.1 Combustion characteristics for RaBIO (*solid*) and D100 (*dashed*) fuels at peak torque condition

influence on the injection pressure. It turned out that under the microscope the surface looked always pretty the same, regardless of the fuel used.

In order to obtain the *surface roughness* parameters, five measurements were performed on both plunger skirt and head for each parameter. It turned out that the influence of RaBIO usage is rather minor for the *plunger skirt* (Fig. 7.4). On the contrary, the roughness parameters of the *plunger head* exhibited significant changes after RaBIO usage (Fig. 7.5).

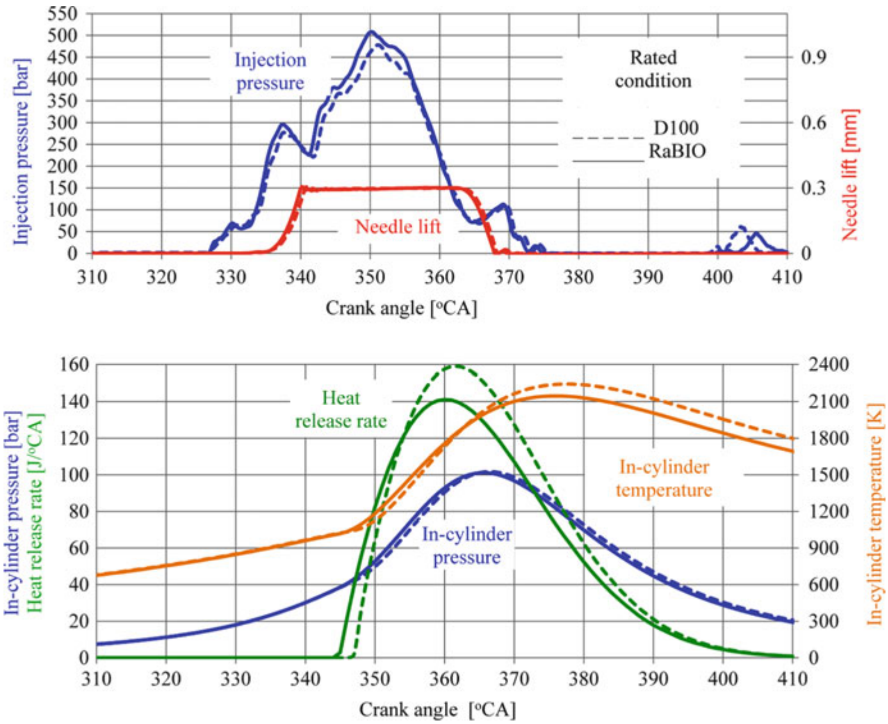

Fig. 7.2 Combustion characteristics for RaBIO (*solid*) and D100 (*dashed*) fuels at rated condition

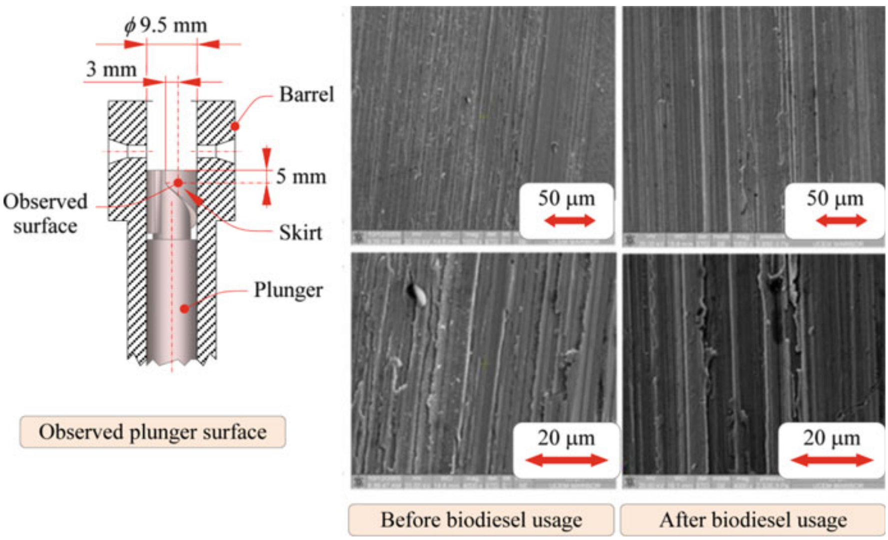

Fig. 7.3 Pump plunger skirt surface before and after RaBIO usage

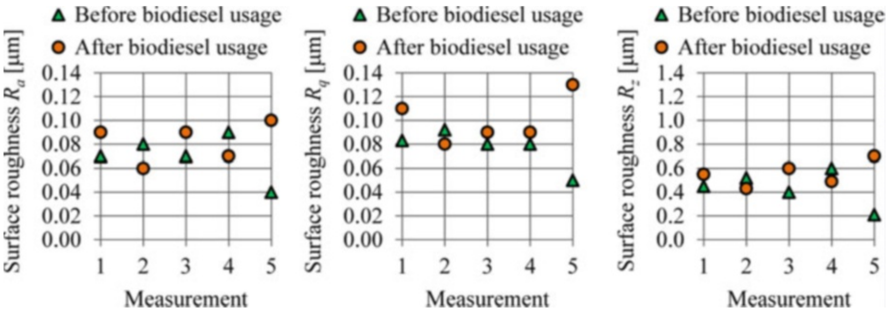

Fig. 7.4 Surface roughness parameters at pump plunger skirt surface

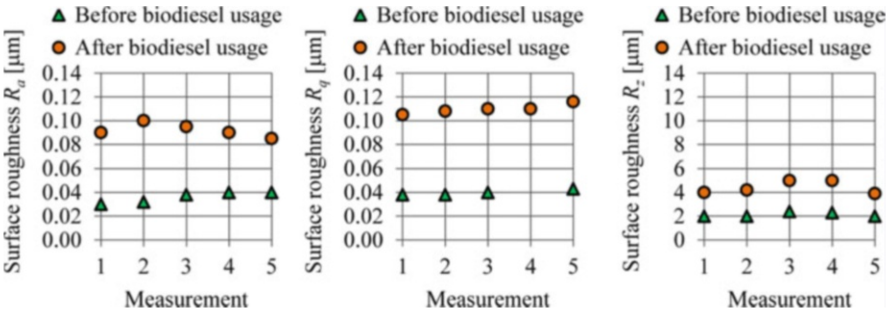

Fig. 7.5 Surface roughness parameters at pump plunger head

One can see that the surface roughness at the pump plunger head increased by a factor of two when biodiesel was used for about 110 h. Luckily, with respect to fuel leakage in the HP pump, the surface roughness at the pump plunger head is not as important as the roughness at the pump plunger skirt. For this reason, the obtained results are not alarming, although some further tribology investigations would be necessary to evaluate the situation more precisely.

It should be noted that greater roughness, obtained after biodiesel usage, would probably not worsen the sliding conditions at the pump plunger skirt. Namely, after biodiesel usage the average value of the root mean square roughness R_q decreased; in fact, it dropped from 0.45a to 0.4a, which might indicate improved lubrication conditions.

The influence of RaBIO usage on *carbon deposits* was also investigated by endoscopic inspection. Figures 7.6 and 7.7 show the carbon deposits on the injectors of cylinders 3 and 5 after D100 usage and after running the engine with RaBIO for 110 h. By simply looking at the photographs, it is evident that after biodiesel usage the injectors became cleaner. Since the injector was not cleaned before biodiesel usage, it can be concluded that the carbon deposits that remained after mineral diesel usage were partially removed by running the engine on biodiesel. This is obviously due to the physical and chemical properties of the

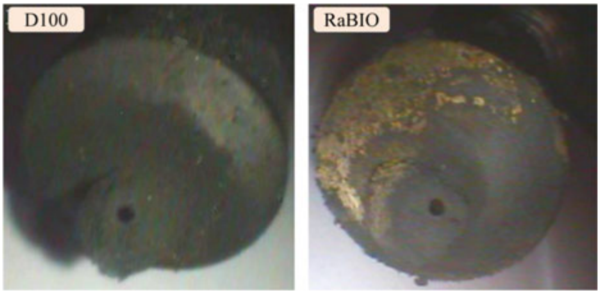

Fig. 7.6 Carbon deposits on the injector of cylinder 3

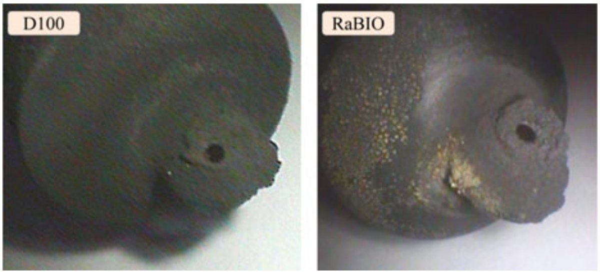

Fig. 7.7 Carbon deposits on the injector of cylinder 5

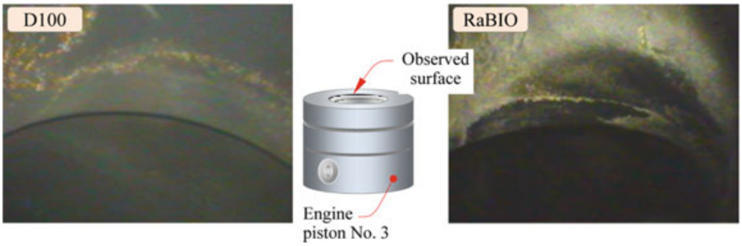

Fig. 7.8 Carbon deposits in the combustion chamber of cylinder 3

tested biodiesel, which is known to have excellent solvent action and can also loosen old deposits.

Furthermore, the combustion chambers were observed by using videoscopy. It was found out that at some places of the combustion chamber the carbon deposits increased, while at some other places they decreased. Figure 7.8 shows the carbon deposits on one side of the combustion chamber of the third cylinder. The situation in chamber 5 (at two positions) is shown in Fig. 7.9. One can say that the carbon deposits in the combustion chambers vary in dependence on the fuel used.

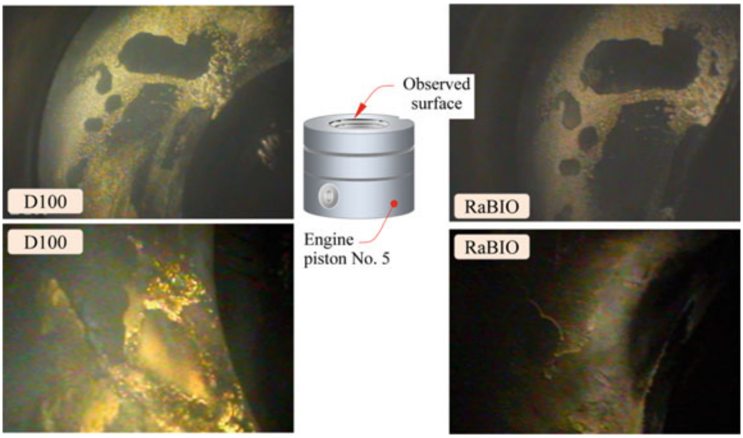

Fig. 7.9 Carbon deposits in the combustion chamber of cylinder 5

Examination and comparison of all six combustion chambers (in all cylinders) revealed that the situation is pretty much the same in all six chambers. However, the deposits look differently distributed—depending on whether D100 or RaBIO was used. High viscosity and high molecular weight of biodiesel result in injection characteristics (injection pressure, injection timing, etc.) that may be quite different to those of D100. This may lead to different distribution of the deposits. However, although biodiesel is known to exhibit poor atomization and low volatility, it seems that the total amount of the deposits did not increase by using RaBIO.

In order to investigate the influence of biodiesel usage on the discharge coefficient of the injector, three injectors from the engine (that has been run about 500,000 km on mineral diesel) have been investigated. At first, the discharge coefficients of all three injectors were measured by using a calibration fluid. The first injector (that served only for comparison purposes) was mounted on an injection system and "run" for 110 h with mineral diesel. The second injector was also mounted on the injection system and "run" for 110 h with biodiesel. The third injector was mounted into the engine and run under normal engine operation for 110 h by using biodiesel. After that the nozzle discharge coefficients of all three injectors were measured again by using the calibration fluid.

The analysis of the obtained results showed that the influence of biodiesel usage on the nozzle discharge coefficient is rather minor (Fig. 7.10). There were minor differences between the measured discharge coefficients, but these differences practically vanished at higher needle lifts. The results show that after biodiesel usage the coefficients in the injection system are lower than before usage of biodiesel for the most of the needle lifts. This was a somewhat surprising result. Namely, since biodiesel has a good solvent action, it was expected that the old deposits in the injector nozzle would be reduced, resulting in an increase of the discharge coefficient. Therefore, the same experiment was repeated with a new (clean) injector and the result was as expected: the discharge coefficient was not decreased after biodiesel usage. As it looks, the only reasonable explanation seems

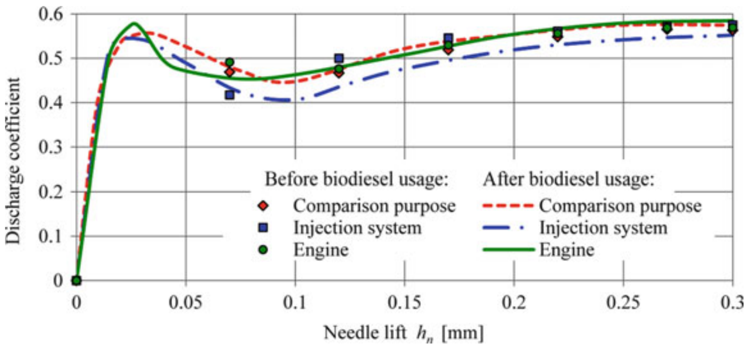

Fig. 7.10 Influence of biodiesel usage on nozzle discharge coefficient

to be that biodiesel caused the old deposits in the nozzle to swell up. It is possible that after a longer period of biodiesel usage the old deposits would begin to decay (at least partially). In any case, the experimental time period (110 h) is obviously not enough to reduce the deposits. Finally, it may be worth noting that even if the coefficient variations are not so dramatic, one must recognize that many investigations are done primarily on the basis of numerical simulation of the fuel injection processes. Therefore, taking into account the influence of small nozzle discharge coefficient variations on the numerically obtained injection characteristics might prove to be of benefit when high accuracy results are needed.

Most investigations confirm that biodiesel usage reduces engine effective power due to lower *energy content* of biodiesel (Buyukkaya 2010; Carraretto et al. 2004; Choi and Oh 2006; Hazar 2009; Kaplan et al. 2006; Karabektas 2009; Xue et al. 2011). However, the results reported show some fluctuations. Some investigators report that the actually observed power loss is lower than expected and that this is a consequence of power recovery (Murillo et al. 2007; Ozsezen et al. 2009; Oğuz et al. 2007). For example, a power loss of about 7 % was observed on a 3-cylinder, naturally aspirated, submarine diesel engine at full load, when mineral diesel was replaced by biodiesel; the energy content of used biodiesel fuels was about 13.5 % lower than that of mineral diesel. Furthermore, by testing RaBIO, *soybean biodiesel* (SoBIO), and *palm biodiesel* (PaBIO) on a 4-stroke, 30 kW TUMOSAN diesel engine (without any engine modification), it was shown that, compared to D100, there were no significant differences in engine power (Oğuz et al. 2007).

In Ozsezen et al. (2009) a naturally aspirated DI diesel engine (Table 7.2) was tested under full load. The tested fuels were D100, PaBIO, and *canola biodiesel* (CaBIO). As one can see from Fig. 7.11, D100 always delivered the highest engine *effective power*, but the differences were rather minor. Furthermore, the maximum brake power values obtained with either PaBIO or CaBIO were quite similar. Larger differences were observed in the *specific fuel consumption* (Fig. 7.12). The differences between mineral diesel and both biodiesels agreed approximately with the differences in fuel heating values.

Table 7.2 Engine specifications (Ozsezen et al. 2009)

Engine model	6.0 L Ford Cargo
Engine type	Naturally aspirated, four stroke, water cooled
Displacement	5,947 cm^3
Compression rate	15.9:1
Bore and stroke	104.8 mm × 114.9 mm
Maximal power at engine speed	81 kW at 2,600 rpm
Maximal torque at engine speed	335 Nm at 1,500 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	197 bar
Injection pump timing	16.35°CA BTC

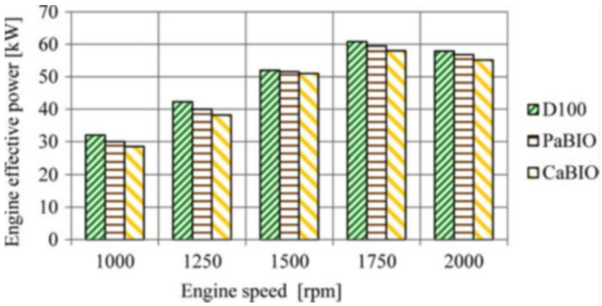

Fig. 7.11 Engine effective power obtained with various fuels

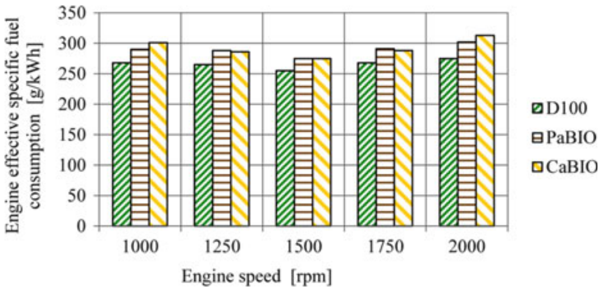

Fig. 7.12 Engine effective specific fuel consumption obtained with various fuels

The *effective specific fuel consumption* may vary significantly in dependence on biodiesel source (Ozsezen et al. 2009; Reyes and Sepúlveda 2006; Lin et al. 2009; Sahoo et al. 2009), which determines the *energy content*, *density*, and *viscosity* of biodiesel. A comparison of biodiesels from various sources, performed at constant conditions, revealed that the highest value of the effective specific fuel consumption was obtained with PaBIO, which has particularly low energy content and shorter *carbon chains*, compared to other biodiesels (Lin et al. 2009). It may be worth noting that the explanations for the increased fuel consumption of biodiesel are not very uniform among the authors. In some investigations, the most exposed reason is the higher density of biodiesel, which causes the higher mass injection for the same volume at the same injection pressure (Buyukkaya 2010; Qi et al. 2009;

Godiganur et al. 2009, 2010; Puhan et al. 2005a). Some other authors interpret the increase in fuel consumption to be a consequence of combination of biodiesel properties. For example, the following reasons are often highlighted: lower energy content and higher density (Utlu and Koçak 2008; Carraretto et al. 2004; Tsolakis et al. 2007), combined effect of higher viscosity and lower energy content of biodiesel (Aydin and Bayindir 2010; Ramadhas et al. 2005; Qi et al. 2010), and interaction of higher density, higher viscosity, and lower energy content of biodiesel (Lin et al. 2009; Song and Zhang 2008).

7.1.2 Influence of Engine Type

The influence of biodiesel usage on engine characteristics may depend significantly on various parameters related to engine design, control, and so on (Hazar 2009; Karabektas 2009; Pandey et al. 2012; Sayin and Gumus 2011). Of those parameters, the following ones might be the most important:

- *Compression ratio*: specific fuel consumption and thermal efficiency are considerably improved by increasing the compression ratio; higher compression ratio raises the density of air charge in the cylinder; higher air density leads to higher spray angles which results in an increase of the amount of air entrainment in the spray; this contributes to more complete combustion.
- *Injection timing*: in order to get minimal specific fuel consumption and maximal thermal efficiency, the injection timing has to be set optimally for each individual biodiesel fuel.
- *Naturally aspirated and turbocharged operation*: effective engine power and torque obtained with mineral diesel are higher than those obtained with biodiesel; this holds true for both naturally aspirated and turbocharged operation; by applying a turbocharger, the benefit of increased effective power and torque is more evident in biodiesel usage; because of higher fuel density and lower energy content, biodiesel shows slightly higher specific fuel consumption for both operations in comparison with mineral diesel; for both fuel types the specific fuel consumption decreases in the turbocharged operation, compared to naturally aspirated operation.
- *Coated and uncoated engine*: for biodiesel and diesel, the effective power of a coated engine is typically higher than that of the uncoated engine; this may be explained by an increase in the temperature of the combustion chamber elements, due to a thermal barrier effect caused by the ceramic coating; higher temperatures improve combustion.

In Sayin and Gumus (2011) the influence of *compression ratio* and *injection pump timing* on the brake specific fuel consumption and brake thermal efficiency was investigated experimentally on a *naturally aspirated DI diesel* engine (Table 7.3). The used fuel was biodiesel from a commercial supplier. Here and in the following, the term *relative variation* will be used to denote the relative difference Δp of a parameter p, calculated as

Table 7.3 Engine specifications (Sayin and Gumus 2011)

Engine model	Lombardini 6 LD 400
Engine type	Naturally aspirated, four stroke, one cylinder
Displacement	395 cm^3
Compression rate	18:1
Bore and stroke	86 × 68 mm
Maximal power at engine speed	7.5 kW at 3,600 rpm
Maximal torque at engine speed	21 Nm at 2,200 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	200 bar
Injection pump timing	20°CA BTC

$$\Delta p[\%] = \frac{p_{\mathrm{BIO}} - p_{\mathrm{D100}}}{p_{\mathrm{D100}}} \times 100, \tag{7.1}$$

where p_{BIO} is the parameter obtained with biodiesel and p_{D100} is the same parameter obtained with mineral diesel usage.

Among other quantities, the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE) were measured and compared to the same quantities obtained with mineral diesel. By increasing the *compression ratio* from 17:1 to 19:1 the relative differences in BSFC and BTE both tend to decrease (Fig. 7.13). It is evident that with higher compression ratios the difference between biodiesel and mineral diesel declines.

By increasing the *pump injection timing* from 15 to 25°CA BTC the relative difference in BSFC also showed some variation (Fig. 7.14). This variation, however, was not monotonic. On the other hand, the relative BTE difference was practically unaffected by various injection pump timings.

In Kegl (2006) a *DI diesel bus* MAN 2566 MUM engine (Table 7.1) was tested in order to investigate the influence of *pump injection timing* on injection and in-cylinder pressures. The fuels investigated were RaBIO and D100.

The injection pressure obtained with RaBIO was higher than that obtained with D100. The opposite was observed for the peak in cylinder pressure (Fig. 7.15). By reducing the pump injection timing, the peak injection pressure location of RaBIO was shifted towards the top dead center while the peak in-cylinder pressures decreased. This indicates that retarded pump injection timing considerably influences the air–fuel mixing, start of combustion, and consequently all engine performances.

The influence of *pump injection timing* on engine performance is shown in Fig. 7.16, which presents the relative differences of several parameters. The compared quantities are the effective power, effective specific fuel consumption, thermal efficiency, and temperature of exhaust emissions. The presented results show that for RaBIO the minimal specific fuel consumption g_e is obtained with pump injection timing of $\alpha_i = 19$°CA TDC at peak torque condition and $\alpha_i = 20$°CA TDC at rated condition (Fig. 7.16). This can be explained with the nature of fuel injection of the employed engine. The M injection system with its single-hole injection

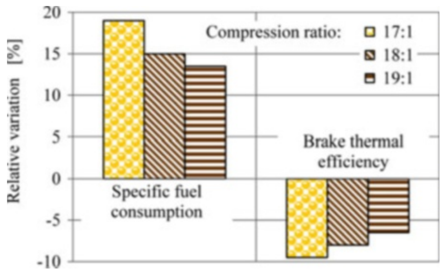

Fig. 7.13 Relative variations of BSFC and BTE for various compression ratios

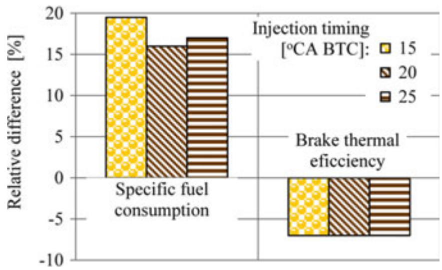

Fig. 7.14 Relative variations of BSFC and BTE for various injection timings

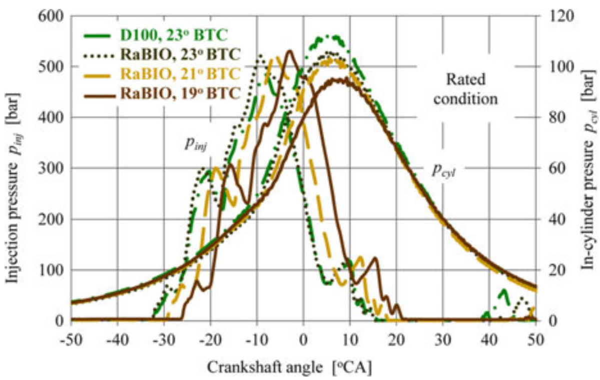

Fig. 7.15 Injection and in-cylinder pressures for various pump injection timings

nozzle is oriented so that most of the fuel is deposited on the piston bowl walls. The use of a bowl-in-piston combustion chamber results in a substantial swirl amplification at the end of the compression process. The air swirl increases as the piston approaches the top center, influencing significantly the fuel–air mixing rate. It is known, however, that optimum (and not maximum) swirl level gives minimum specific fuel consumption. Obviously, the optimum swirl for RaBIO fuel was obtained at $\alpha_i = 19°$CA TDC. At this setting the maximum cylinder pressure is lower by about 15 bar compared to D100 with standard $\alpha_i = 23°$CA TDC (Fig. 7.15). The temperatures of exhaust gases are at the lowest levels at $\alpha_i = 20°$CA TDC and the thermal efficiency is optimal at $\alpha_i = 20$ °CA TDC for rated condition and at $\alpha_i = 19°$CA TDC for peak torque condition.

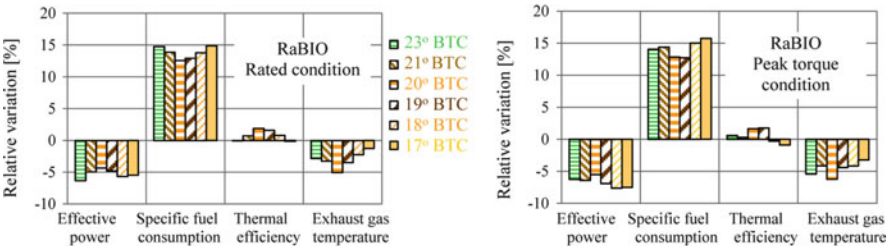

Fig. 7.16 Influence of pump injection timing on engine performance

Table 7.4 Engine specifications (Karabektas 2009)

Engine model	Steyr
Engine type	Naturally aspirated, water cooled, 4 stroke, 4 cylinders
Displacement	3,142 cm^3
Compression rate	16.8:1
Bore and stroke	100 mm × 100 mm
Maximal power at engine speed	51 kW at 2,400 rpm
Maximal torque at engine speed	215 Nm at 1,400 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	215 bar
Injection pump timing	12°CA BTC

In Karabektas (2009) the effects of a *turbocharger system* installation into a *naturally aspirated diesel engine* (Table 7.4) were studied. The fuel used was RaBIO and the tests were performed at the same load and at various *engine speeds*. The experimentally obtained results show that *specific fuel consumption* of RaBIO in *turbocharged* operation is averagely 15–17 % lower than that of *naturally aspirated* operation (Fig. 7.17). This reduction is mainly caused by the improvement in fuel atomization, air–fuel mixing, and combustion characteristics of the fuel and due to the high air temperature and increased air charge in the cylinder of the turbocharged engine. Furthermore, the effective power reached its peak value at the speed of about 2,400 rpm for all fuels and engine operations. The effective power obtained with D100 is higher than that obtained with RaBIO for both naturally aspirated and turbocharged operations. In naturally aspirated operation, the mean reduction in the effective power is about 5 % when RaBIO replaces D100. Due to the fact that the energy content of RaBIO is about 12 % lower than that of D100, both the effective torque and power decline. However, the differences are relatively small in most cases. Figure 7.18 also shows that the difference in the effective power between D100 and RaBIO reduces in turbocharged operation. The effective power obtained with RaBIO is on average 3 % lower than that of D100 in turbocharged operation, due to better combustion, resulting from increased air supply.

In Hazar (2009) the influence of low heat rejection engine on engine characteristics was investigated. The investigated fuel was CaBIO. Two versions

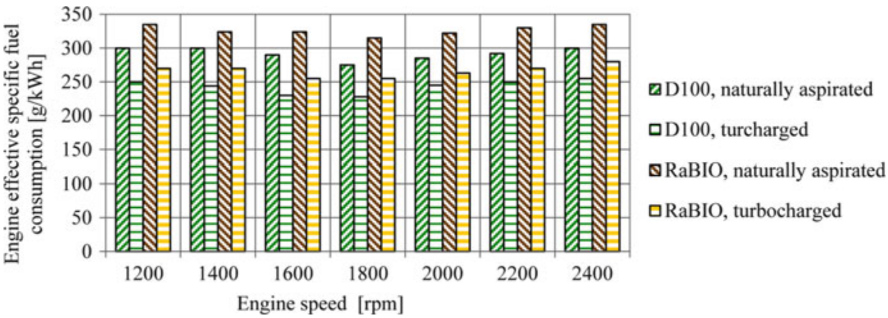

Fig. 7.17 Effective specific fuel consumption of the naturally aspirated and turbocharged engine

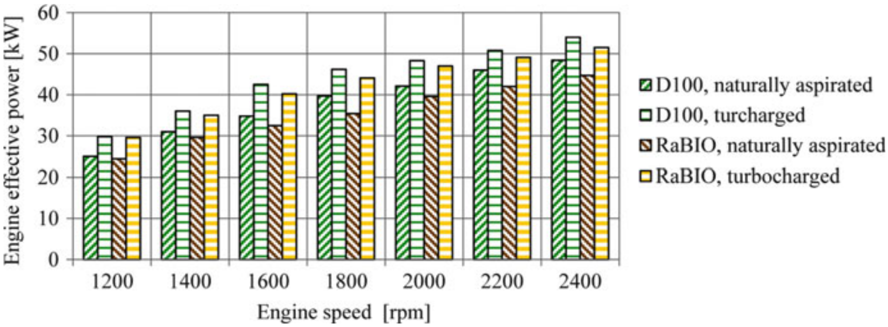

Fig. 7.18 Effective power of the naturally aspirated and turbocharged engine

of the tested engine (Table 7.5) were utilized. The first one was the regular, *uncoated*, version. The second, *coated*, version was modified as follows: the cylinder head, exhaust, and inlet valves were coated with the ceramic material $MgO–ZrO_2$ by the plasma spray method; the piston surface was coated with ZrO_2.

Increased engine power and decreased specific fuel consumption were observed for either CaBIO or D100 fuelled coated engine, compared to the uncoated version. The average increase of power in the coated engine was about 8.4 % for D100 and 3.5 % for CaBIO (Fig. 7.19). This increase in power value may be explained by the increase in the temperature of the combustion chamber elements due to a thermal barrier effect, caused by the ceramic coating. Higher temperatures improve the combustion.

In Haşimoğlu et al. (2008) the effects of *sunflower biodiesel* (SuBIO) usage on engine performance of an *uncoated* and *coated* engine (Table 7.6) were investigated. In the coated version the cylinder head and valves were coated with plasma-sprayed yttria-stabilized zirconia ($Y_2O_3ZrO_2$) with a thickness of 0.35 mm over a 0.15 mm thickness of NiCrAl bond coat.

Table 7.5 Engine specifications (Hazar 2009)

Engine model	Lombardini 6LD 400
Engine type	Naturally aspirated, air cooled, 4 stroke, 1 cylinder
Displacement	395 cm^3
Compression rate	18:1
Bore and stroke	86 mm $\times$ 68 mm
Maximal power at engine speed	6.25 kW at 3,600 rpm
Maximal torque at engine speed	16.6 Nm at 2,400 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	200 bar
Injection pump timing	20°CA BTC

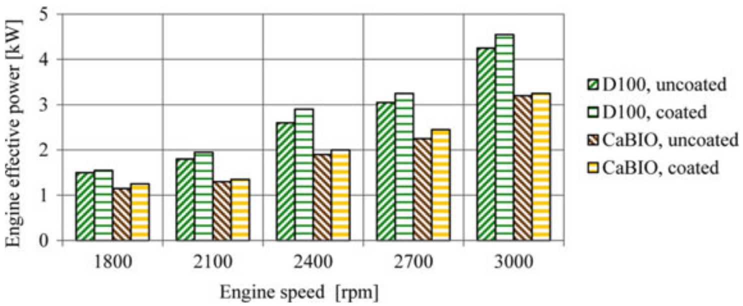

Fig. 7.19 Effective power of the uncoated and coated engine

Table 7.6 Engine specifications (Haşimoğlu et al. 2008)

Engine model	Mercedes-Benz/OM364A
Engine type	Turbocharged diesel engine, four cylinders
Displacement	3,972 cm^3
Compression rate	17.25:1
Bore and stroke	97.5 mm $\times$ 133 mm
Maximal power at engine speed	66 kW at 2,800 rpm
Maximal torque at engine speed	266 Nm at 1,400 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	200 bar
Injection pump timing	18°CA BTC

The variations of engine torque in dependence on engine speed are shown in Fig. 7.20. By using D100, the coated engine torque was higher by about 7 % at all engine speeds. By using SuBIO, however, the coated engine torque at low and at high engine speeds was up to 10 % lower than that of the uncoated engine. At medium engine speeds, the coated engine torque was higher up to 6 %. The reason for increased torque of the coated engine, compared to the uncoated version, was the increase of exhaust gas energy. This leads to improved volumetric efficiency, because of the increased turbocharger outlet pressure. Furthermore, it was observed

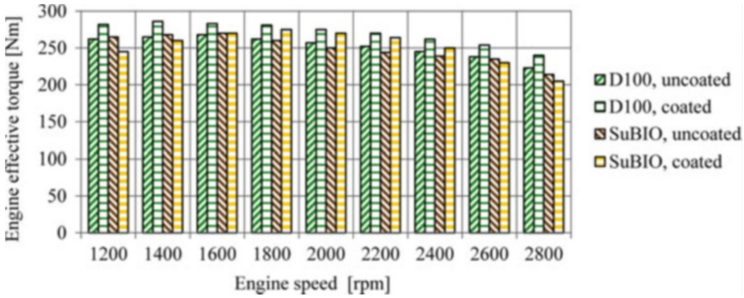

Fig. 7.20 Effective torque of the uncoated and coated engine

that the specific fuel consumption of the coated engine, when using SuBIO, was lower by approximately 4 %, compared to the uncoated version.

7.1.3 Influence of Engine Operating Regime

The influence of biodiesel fuels on engine performance may depend to some extent on the engine operating regime (Kegl 2008, 2011; Meng et al. 2008; Raheman and Phadatare 2004; Ramadhas et al. 2005; Qi et al. 2010; Zhu et al. 2010; Xue et al. 2011):

- *Engine load*: with increased load, the effective specific fuel consumption of biodiesel decreases since the brake power increases faster than the fuel consumption; full engine load delivers the maximal difference in engine power between biodiesel and mineral diesel; by reducing the engine load, the power delivered by biodiesel becomes similar to the one delivered by mineral diesel; engine load has a variable (non-monotonic) effect on exhaust gas temperature.
- *Engine speed*: the basic trends of engine power and specific fuel consumption in dependence on engine speed are similar for biodiesel and diesel, but there is of course some offset between the biodiesel and diesel curves.

In Kegl (2006) the influence of *engine speeds* on engine parameters was investigated on a bus engine (Table 7.1). The engine was run at partial (PL) and full (FL) loads and the injection pump timing used was the one that is prescribed for D100. The engine speeds were varied from 1,000 up to 2,500 rpm. As one can see from Fig. 7.21, the effective torque M_e and power P_e decreased by about 5 % when D100 was replaced by RaBIO. Furthermore, the effective specific fuel consumption g_e (for the actual fuel mass) increased by about 10–15 % in the whole engine speed range. On the other hand, the temperatures of exhaust gases $T_{g,e}$ declined by about 30 °C, which is probably mostly due to the lower calorific value of RaBIO.

The effective engine power varied practically negligible at lower loads at practically all engine speeds (Fig. 7.22).

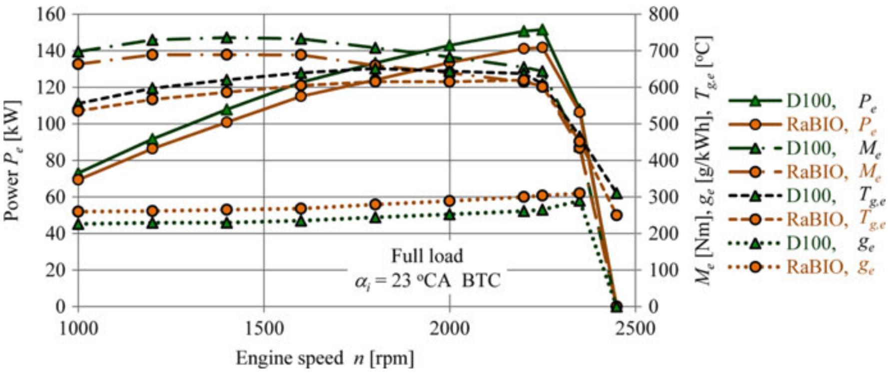

Fig. 7.21 Engine parameters at full load

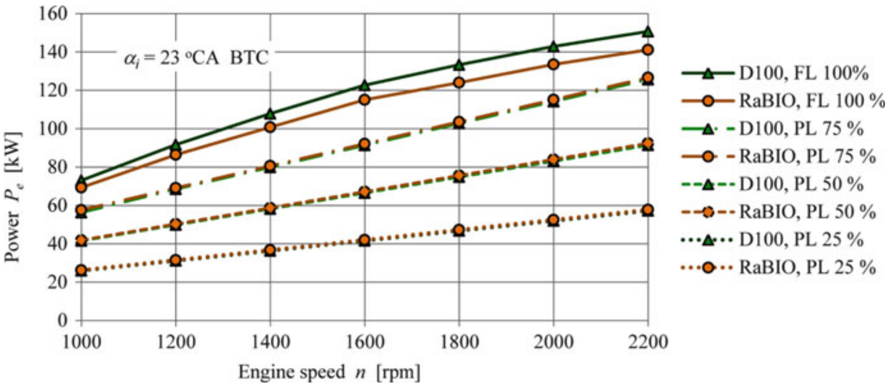

Fig. 7.22 Engine power at various engine regimes

The comparison of temperature $T_{g,e}$ of exhaust gases at FL and PL shows that $T_{g,e}$ at 25 %, 50 %, and 75 % load is higher for RaBIO than for D100 at almost all engine speeds (Fig. 7.23). The difference, however, became fairly small at 50 % partial load.

A comparison of specific fuel consumption g_e at FL and PL at various engine pump speeds shows that, compared to D100, g_e for RaBIO was higher by about 10–15 % at all engine speeds and loads (Fig. 7.24). The highest specific fuel consumptions were delivered by RaBIO at low loads and high engine speeds.

In Gumus and Kasifoglu (2010) a single-cylinder, four-stroke, air-cooled, direct injection diesel engine was tested by running it with *apricot seed kernel biodiesel*. It turned out that the effective specific fuel consumption initially decreased with increasing engine load until it reached a minimum value and then increased slightly with further increase of engine load.

In Usta et al. (2005) a four-cylinder, four-stroke, water-cooled, turbocharged, indirect injection diesel engine, Ford XLD 418 T, was tested with SuBIO and

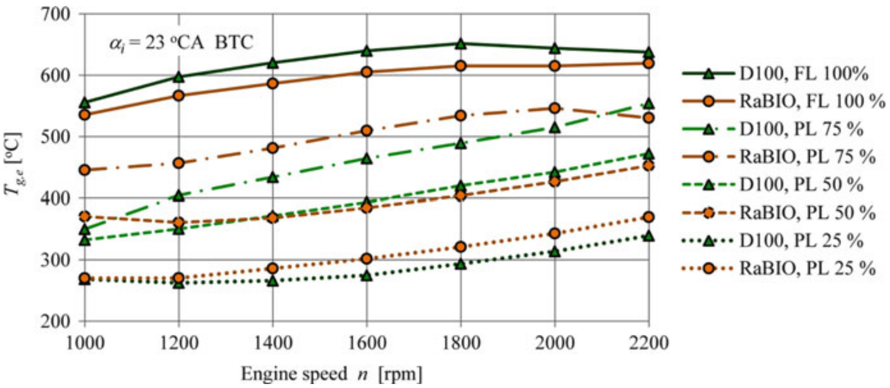

Fig. 7.23 Exhaust gas temperature at various engine regimes

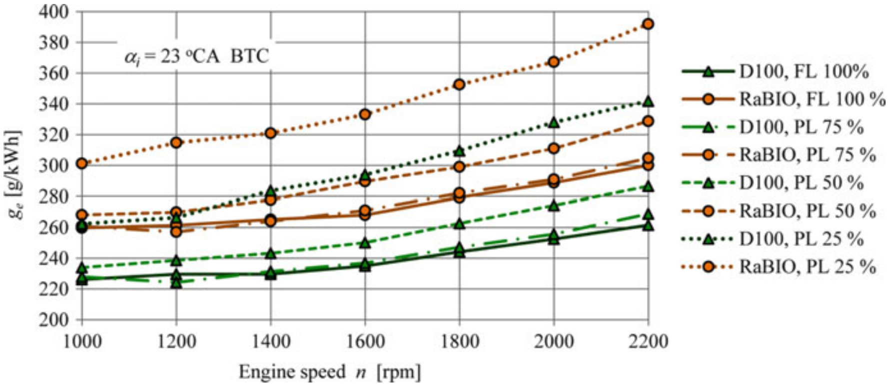

Fig. 7.24 Specific fuel consumption at various engine regimes

hazelnut biodiesel (HaBIO). The results show that a replacement of D100 by these biodiesels leads to an increase in effective specific fuel consumption. The increase at full load is higher than at partial load.

7.2 Engine Harmful Emissions

The most important diesel engine harmful emissions are NO_x, PM/smoke, CO, and unburned HC. A replacement of mineral diesel by biodiesel influences the quantities of these emissions (Xue et al. 2011). A general trend of this influence is illustrated in Fig. 7.25, showing the emission relative variations, with respect to mineral diesel (Giakoumis 2012). One can see that, in general, the situation is quite favorable for biodiesel, except for the NO_x emission.

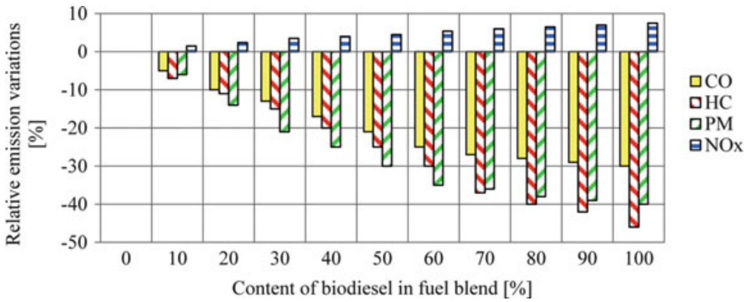

Fig. 7.25 A general trend of harmful emission variations due to biodiesel usage

Apart from the harmful emissions listed above, it may also be worth to mention the CO_2 emission that is not detrimental for human health, but has a negative effect on the world climate. Namely, nowadays the traffic contributes about 23 % of total CO_2 emissions and biodiesel usage has a potential to influence positively this situation (Xue et al. 2011). Firstly, biodiesels exhibit lower elemental carbon to hydrogen ratio, which might be reflected in lower CO_2 emission (Lin and Lin 2007; Ozsezen et al. 2009; Utlu and Koçak 2008). Unfortunately, experiments also show that this might not always be the case. For example, by using the soy biodiesel in a diesel engine, it was experimentally obtained that CO_2 emissions rise or remain similar, compared to mineral diesel usage (Canakci 2005; Puhan et al. 2005a; Usta et al. 2005). Secondly, there is a strong argument to favor biodiesel over mineral diesel with regard to CO_2 emission. Namely, biodiesel is mainly produced from crops that use CO_2 for their growth. If biodiesel CO_2 emission is evaluated through the whole life cycle of CO_2, one gets a respectable 50–80 % reduction in CO_2 emission, compared to mineral diesel (Carraretto et al. 2004).

7.2.1 *Influence of Biodiesel Properties*

All engine emissions depend significantly on biodiesel properties, which may vary significantly in dependence on biodiesel source (Aydin and Bayindir 2010; Buyukkaya 2010; Giakoumis et al. 2012; Kalligeros et al. 2003; Karabektas 2009; Karavalakis et al. 2009; Kegl 2008, Keskin et al. 2008; Kidoguchi et al. 2000; Koçak et al. 2007; Qi et al. 2009; Labeckas and Slavinskas 2006; Lapuerta et al. 2008b; Puhan et al. 2005b; Sayin and Gumus 2011; Usta 2005; Wu et al. 2009). The most influential properties, however, seem to be:

- *Sulfur content*: biodiesel fuels have practically zero sulfur content; note, however, that this advantage against mineral diesel gradually fades out owing to the increasingly better desulfurization of mineral diesel; lack of sulfur and aromatic compounds in biodiesels contributes to a reduction of PM emissions.

- *Oxygen content*: the relatively high oxygen concentration in biodiesel fuels, which improves the soot oxidation process, has been identified as the key contributor for the benefits related to PM emissions; high oxygen content also promotes complete combustion and thus leads to a reduction of CO emissions; since the formation of NO_x emission strongly depends on oxygen concentration and burned gas temperature, high oxygen content of biodiesel is the main reason for higher NO_x emissions; namely, due to its higher concentration, oxygen can react more easily with nitrogen during the combustion, thus causing an increase of NO_x emissions.
- *Density*, *bulk modulus*, *cetane number*, *iodine number*: the iodine number is closely related to density, bulk modulus, and cetane number and suggests that the observed increase in NO_x is also caused by the effects related to either injection or combustion timing; biodiesel has a higher cetane number than mineral diesel, which is reflected in a shorter ignition delay period and better autoignition capability; shorter ignition delay periods, associated with higher oxygen content of biodiesels, can also contribute significantly to lower CO emission.
- *Carbon* and *hydrogen content*: the carbon/hydrogen ratio of biodiesels is slightly lower than that of mineral diesel; this is reflected in lower CO emissions of biodiesel, compared to mineral diesel.

In Koçak et al. (2007) the effects of various biodiesel fuels on harmful emissions were tested on a Land Rover TDI 110 diesel engine (Table 7.7). The experiments were performed without engine modifications at full load and at various engine speeds. The tested fuels were CaBIO, HaBIO, *waste cooking biodiesel* (WcBIO), and D100.

In the range of engine speeds between maximal torque and maximal power, the increase of NO_x emission coincides with the increase of temperature and rise of volumetric efficiencies for all four tested fuels. Figure 7.26 shows the relative variations of NO_x emission (biodiesel, compared to mineral diesel). It can be seen that at some engine speeds the relative NO_x emission increased up to 2 %; meanwhile at some speeds it was lower up to 5 %. The reason for the decrease of relative NO_x emission for biodiesels is that the temperature at the end of combustion is somewhat lower, because the cetane numbers of biodiesel fuels are higher than those of mineral diesel (Koçak et al. 2007). Among all tested fuels, the lowest NO_x emissions were mostly obtained with CaBIO. CaBIO also delivered the lowest smoke emission at full load conditions.

In Cecrle et al. (2012) a Yammar L100V DI diesel engine with a mechanically controlled fuel injection system (Table 7.8) was used to test biodiesels at various engine loads at constant engine speed of 3,600 rpm. The tested fuels were RaBIO, PaBIO, SoBIO, WcBIO, CaBIO, *olive biodiesel* (OlBIO), and *coconut biodiesel* (CoBIO).

Figure 7.27 shows the relative NO_x emission variations for individual biodiesels with respect to D100. The results reveal that PaBIO consistently yielded the lowest

Table 7.7 Engine specifications (Koçak et al. 2007)

Engine model	Land Rover TDI 110
Engine type	Turbocharger, four stroke, four cylinders
Displacement	2,495 cm^3
Compression rate	19.5:1
Bore and stroke	90.5 mm × 97 mm
Maximal power at engine speed	82 kW at 3,850 rpm
Maximal torque at engine speed	235 Nm at 2,100 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	200 bar
Injection pump timing	15°CA BTC

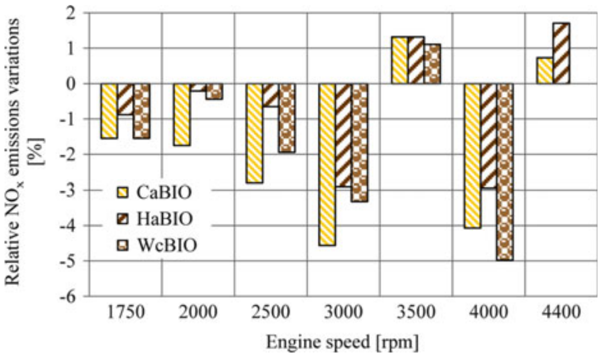

Fig. 7.26 Influence of biodiesel source on NO_x emissions at full load

Table 7.8 Engine specifications (Cecrle et al. 2012)

Engine model	Yanmar L100V
Engine type	Naturally aspirated, air cooled, four stroke, one cylinder
Displacement	435 cm^3
Compression rate	21.2:1
Bore and stroke	86 mm × 75 mm
Maximal power at engine speed	6.2 kW at 3,600 rpm
Maximal torque at engine speed	98.4 Nm at 1,440 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	196 bar
Injection pump timing	15.5°CA BTC

relative NO_x levels at all engine loads, while WcBIO mostly delivered the highest relative NO_x emission.

Figure 7.28 shows the relative particulate matter (PM) emission variations for various biodiesels, compared to mineral diesel. The results were obtained by running the Yanmar L100V DI diesel engine (Table 7.8) at 25 % load and at 3,600 rpm for 1 h (Cecrle et al. 2012). As expected, the PM emissions of all biodiesels were lower than those of D100. The total WcBIO emissions, which were the highest among all tested biodiesels, were approximately 20 % lower

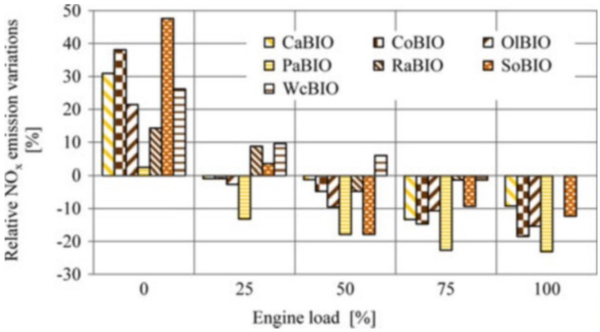

Fig. 7.27 Influence of biodiesel source on NO_x emissions at constant engine speed

than that of D100. The best result, obtained with CoBIO, produced 60 % lower emissions than D100.

In mechanically controlled injection systems, the start of injection of biodiesel fuels usually occurs earlier than that of mineral diesel due to higher density and viscosity and lower compressibility (Kegl 2006, 2007, 2008; Lapuerta et al. 2008b; Ozsezen et al. 2009).

In Banapurmath et al. (2008, 2009), Tsolakis et al. (2007) the effect of injection timing on engine performance and emissions was studied by using RaBIO and *honge biodiesel*. It turned out that the smoke emission generally increased when the injection timing was retarded. This is somewhat in contrast with the results obtained for mineral diesel. Namely, with D100 the smoke level decreases when the injection timing is advanced slightly but then increases when the injection timing is advanced further.

Biodiesel usage typically results in advance of combustion, as a result of a higher cetane number, and in advance of start of injection, due to the higher density and viscosity and lower compressibility. A high cetane number leads to a shorter ignition delay, which results in a smaller amount of heat, released at the initial combustion phase, and long combustion duration. This means that the injection timing may be somewhat retarded, which, in turn, may lead to increased PM but lower NO_x emission (Kidoguchi et al. 2000).

In Lin et al. (2009) SoBIO, SuBIO, RaBIO, PaBIO, WcBIO, and *corn biodiesel* (CrBIO) fuels were tested in a DI Yanmar TF110-F diesel engine (Table 7.9). PaBIO has the shortest carbon-chain lengths and the most saturated bonds and consequently exhibits superior ignition quality. The superior ignition quality and the higher oxygen content of this fuel allow for better combustion at lower temperatures. This is confirmed by the results, where significant reductions in exhaust gas temperature, smoke, and unburned HC emissions were observed. A lower combustion temperature also suppresses the formation of NO_x emissions. The values of the NO_x and HC emission, averaged from seven various load (12, 15, 20, 25, 30, 35, and 40 Nm) and three various engine speed (1,200, 1,800, and 2,400 rpm) regimes, are shown in Fig. 7.29.

In Wu et al. (2009) SoBIO, RaBIO, PaBIO, WcBIO, and *cottonseed biodiesel* (CtBIO) were tested in a Cummins Euro III diesel engine (Table 7.10) and compared with D100. The harmful emissions were measured at the same speed and various mean effective pressures (BMEP).

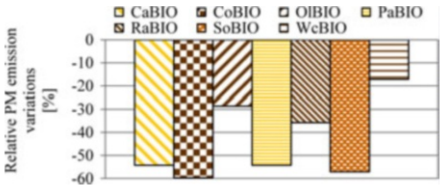

Fig. 7.28 Influence of biodiesel source on PM emissions at constant operating regime

Table 7.9 Engine specification (Lin et al. 2009)

Engine model	Yanmar TF110-F
Engine type	Water cooled, four stroke, single cylinder
Displacement	585 cm^3
Compression rate	17.9:1
Bore and stroke	88 mm × 96 mm
Maximal power at engine speed	8.1 kW at 3,600 rpm
Maximal torque at engine speed	16.7 Nm at 2,500 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	196 bar
Injection pump timing	17°CA BTC

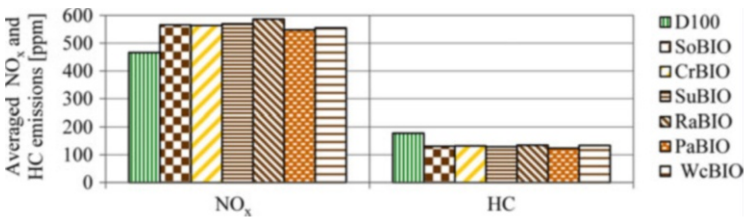

Fig. 7.29 Influence of biodiesel source on averaged NO_x and HC emissions

A comparison of NO_x emissions is shown in Fig. 7.30. All biodiesels exhibit higher NO_x emissions than D100, but the extent of the increase varies, ranging from 10 to 23 % with respect to D100. The biodiesels that result in the least NO_x, in descending order, are CtBIO, PaBIO, SoBIO, WcBIO, and RaBIO. Although PaBIO and WcBIO have almost the same oxygen content, PaBIO produces less NO_x than WcBIO. The most likely reason is the high cetane number of PaBIO. A higher cetane number reduces the ignition delay and the fuel consumed in the premixed phase and may therefore result in lower in-cylinder temperature.

A comparison of HC emissions is shown in Fig. 7.31. Compared with D100, the tested biodiesel usage reduced the average HC emission by 45–67 %. The biodiesels that reduce HC the most, in descending order, are PaBIO, WcBIO, RaBIO, CtBIO, and SoBIO. Theoretically, HC is mainly caused by misfire in a locally rich or locally lean region. The difference in HC emission of various biodiesels is likely to be a combined effect of oxygen content and cetane number.

Table 7.10 Engine specifications (Wu et al. 2009)

Engine model	Cummins ISBe6
Engine type	Turbocharged engine, 4 stroke, 6 cylinders
Displacement	5,900 cm^3
Compression rate	17.5:1
Bore and stroke	102 mm × 120 mm
Maximal power at engine speed	136 kW at 2,500 rpm
Maximal torque at engine speed	670 Nm at 1,500 rpm
Injection model	Electronically controlled direct injection system
Injection type	Common rail

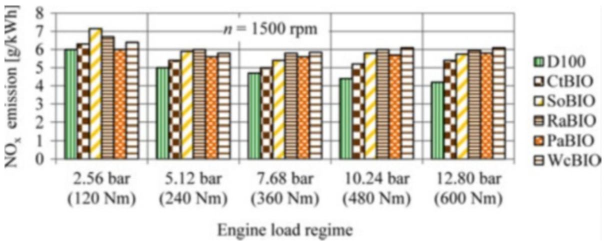

Fig. 7.30 Influence of biodiesel type on NO_x emission

From Fig. 7.31 one may also conclude that, as the cetane number increases, the HC emissions decrease consistently for biodiesel fuels. It was observed that an increase in chain length or saturation level of various biodiesels leads to a higher reduction of HC emissions. Finally, it may be worth noting that the lower HC emissions of all biofuels, compared to D100, are partly due to the oxygen presence in biodiesel molecules.

In Canakci and Van Gerpen (2003) a turbocharged DI diesel engine was tested. It was shown that there are no significant differences in HC emissions between the WCBIO and SoBIO. In Sahoo et al. (2009) a significant difference in HC emission reduction (compared to mineral diesel) was observed between the *jatropha* and *karanja biodiesels* (20.7 % and 20.6 %) and *polanga biodiesel* (6.8 %). The tests were performed on a water-cooled three-cylinder tractor diesel engine.

7.2.2 *Influence of Engine Type*

The influence of biodiesel usage on engine characteristics varies in dependence on engine type (Hazar 2009; Karabektas 2009; Kousoulidou et al. 2012, McCormick et al. 2005, Pandey et al. 2012; Sayin and Gumus 2011). The most influential parameters seem to be the following ones:

- *Compression ratio*: in general, for all compression ratios the emissions of HC, smoke, and CO, obtained with biodiesel fuels, are lower than those obtained with mineral diesel; by increasing the compression ratio, the temperature also

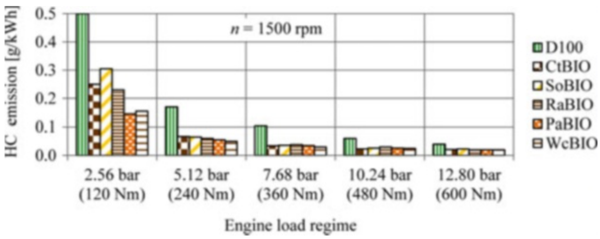

Fig. 7.31 Influence of biodiesel type on HC emission

increases which results in less smoke, CO, and HC emissions, but more NO_x emission.

- *Injection timing*: fuel injection timing is mainly influenced by the physical properties of the fuel, especially density, bulk modulus, and kinematic viscosity; higher density, bulk modulus, and kinematic viscosity of a fuel lead to faster needle lift and advanced injection timing; the advanced injection timing results in higher maximum pressure and temperature in the combustion chamber, faster combustion, and higher NO_x emissions.
- *Injection type*: by comparing harmful emissions from the two different engine technologies, like common rail and unit injector injection system, one can observe that the common rail technology seems to be more compatible with biodiesels since it leads to lower NO_x and PM emissions, compared to the unit injector or to mechanically controlled fuel injection system.
- *Naturally aspirated and turbocharged operation*: a noticeable increase in the NO_x emissions can be observed in turbocharged operation for mineral diesel and biodiesel fuels when compared to the naturally aspirated operation; CO emission, on the other hand, decreases if naturally aspirated operation is replaced by turbocharged operation. In general, the performance and exhaust variations related to turbocharged operation are more significant for biodiesels than for mineral diesel.
- *Coated* and *uncoated engines*: in the coated engine the after-combustion temperature is higher as in the uncoated engine as a result of lower heat losses. This may influence positively CO and HC, but worsen NO_x emissions. This can be observed for biodiesel and mineral diesel.
- *EGR*: it seems that the use of EGR is more effective for biodiesel fuels than for mineral diesel; EGR can reduce NO_x efficiently and the accompanied smoke increase of biodiesels is lower than that observed for mineral diesel.

The experiments, performed on the *naturally aspirated DI diesel engine* (Table 7.3), show the influence of the compression ratio on harmful emissions, when using biodiesel from a commercial supplier (Sayin and Gumus 2011). By increasing the compression ratio from 17:1 to 19:1, the relative NO_x emission increased, while the relative smoke, unburned HC, and CO emissions decreased with respect to mineral diesel (Fig. 7.32). It is evident that with higher compression ratio, the difference between biodiesel and mineral diesel increases.

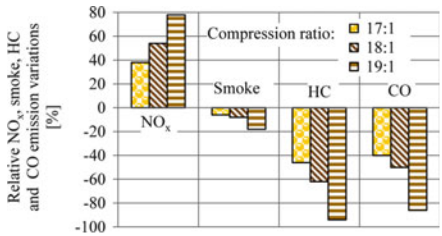

Fig. 7.32 Influence of compression ratio on relative NO_x, smoke, HC, and CO emissions

Increased compression ratio raises the density of air charge in the combustion chamber, which results in an increase of air entrainment in the spray. More air in the spray contributes to more complete combustion. From Fig. 7.32 it is evident that for all compression ratios the emissions of smoke, unburned HC, and CO of biodiesel are lower than those of mineral diesel. On the other hand, the increased compression ratio increases the in-cylinder temperature, which is one of the factors for higher NO_x emission.

In Sayin and Gumus (2011) the influence of injection timing on harmful emissions was also investigated experimentally on the engine, specified in Table 7.3. By increasing the injection timing from 15 to 25°CA BTC, the time available for carbon oxidation increases, which leads to higher in-cylinder temperatures during the expansion phase. Consequently, the relative smoke, unburned HC, and CO emissions were reduced while the relative NOx emission increased, compared to mineral diesel (Fig. 7.33). It is evident that with advanced injection timing the difference between the tested biodiesel and mineral diesel increases.

In Kegl (2006) RaBIO was tested in a *DI diesel bus* engine with *M injection system* (Table 7.1) in order to evaluate the influence of *pump injection timing* on engine emissions. For this purpose, RaBIO emissions, obtained at several pump injection timings, are compared to D100 emissions, obtained with the prescribed pump injection timing; Fig. 7.34 shows the corresponding relative emission variations. By taking into account all harmful emissions, one can say that for the tested conditions the optimal pump injection timing for RaBIO usage is $\alpha_i = 19$ °CA TDC.

It is known that the *advance* in *injection* and *combustion* for biodiesel fuels has an impact on NO_x emissions. In Carraretto et al. (2004) it was observed that NO_x emissions increase by advanced injection timing. In Tsolakis et al. (2007) the retarded injection timing resulted in reduced NO_x emissions and increased smoke, CO, and HC emissions. Furthermore, it was also found out that the variation of NO_x is a function of injection pressure and that there is a significant effect of injection pressure on NO_x emissions (Sharma et al. 2009).

In Karabektas (2009) a *naturally aspirated diesel engine* with or without installed *turbocharger system* (Table 7.4) was used to investigate the influence of RaBIO usage on CO and NO_x emissions at constant load and various *engine speeds*.

The variation of CO emission as a function of engine speed is shown in Fig. 7.35. During naturally aspirated operation, the CO emissions of RaBIO were on average about 17 % lower than those of D100. During the turbocharged operation the CO

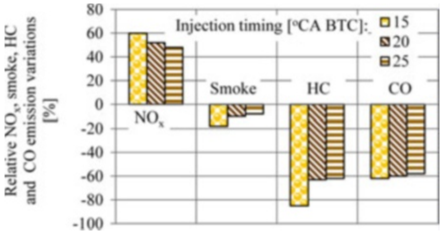

Fig. 7.33 Influence of injection timing on relative NO_x, smoke, HC, and CO emissions

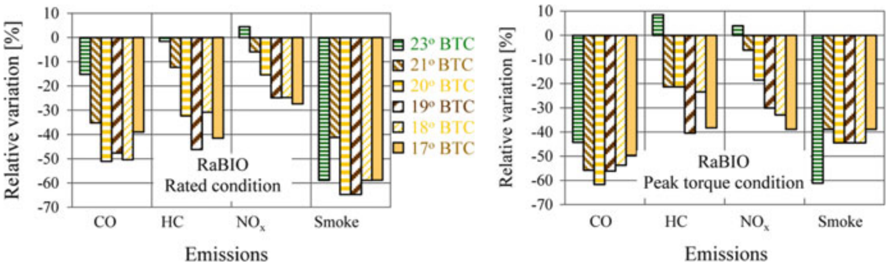

Fig. 7.34 Influence of pump injection timing on engine emissions

emissions of D100 and RaBIO were on average 47 and 52 % lower than those obtained during naturally aspirated operation. In turbocharged operation the CO emissions of RaBIO were on average 26 % lower than those of D100. The application of a turbocharger provides more air to the engine and better fuel–air mixing, thereby causing better combustion and lower CO emission values.

The variation of NO_x emission as a function of engine speed is shown in Fig. 7.36. The NO_x emissions of RaBIO were higher than those of D100 during both naturally aspirated and turbocharged operation. During naturally aspirated operation, an average NO_x emission increase of 10 % was obtained as RaBIO replaced D100. The application of a turbocharger provides more air to the engine and causes higher combustion temperatures, which yields an increase of NO_x emission. It was found out that under turbocharged operation, the NO_x emissions of D100 and RaBIO are higher on average by 27 and 21 %, respectively, compared to the naturally aspirated operation.

In Haşimoğlu et al. (2008) the influence of low heat rejection engine on engine emissions was investigated. By using SuBIO, the NO_x emission increased when the *low heat rejection engine* was used instead of the original turbocharged DI diesel engine, due to a higher combustion temperature. At the same time, the CO emission dropped when low heat rejection engine was used.

In Hazar (2009) the effects of switching between *coated* and *uncoated* version of the same engine (Table 7.5) on CO and NO_x emissions were investigated. The fuels tested were D100 and CaBIO.

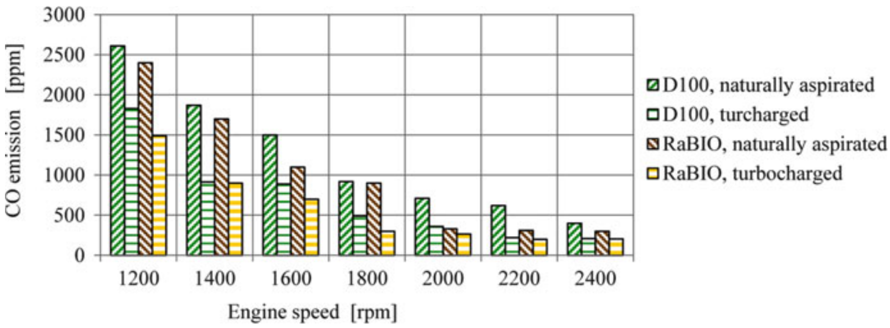

Fig. 7.35 CO emissions of the naturally aspirated and turbocharged engine

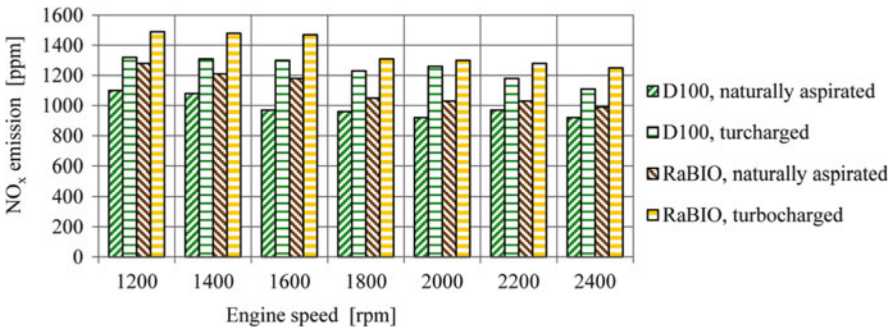

Fig. 7.36 NO_x emissions of the naturally aspirated and turbocharged engine

Figure 7.37 shows the variations of CO emissions in dependence on engine speed. By switching from the uncoated to the coated engine, the CO emission decreased by 25 % for CaBIO and by 22 % for D100.

Figure 7.38 shows the NO_x emissions in dependence on engine speed. In general, the NO_x emission initially increased from low to medium engine speeds and then decreased above medium engine speeds. The NO_x emission is low at low speeds because the combustion chamber temperature is also low. By increasing the engine speed, the temperature and consequently the NO_x emission also rise. Beyond medium speeds, however, the NO_x emission starts to decrease. This is because there is no sufficient time for the NO_x formation, despite the increase in temperature. The increases of NO_x emissions in the coated engine, compared to the uncoated version, are 4.9 % for D100 and 5.3 % for CaBIO. In general, the coated engine practically always yields higher NO_x emission than the uncoated version. This is a result of an increased after-combustion temperature due to the ceramic coating.

Another component that influences the engine emissions is *EGR*. In Agarwal et al. (2006) RaBIO was tested with EGR varying from 0 % up to 20 %. It was found out that although the smoke levels were generally low, the *smoke emission* increased by raising EGR. This is a consequence of reduced availability of oxygen, which results in relatively incomplete combustion and increased formation of *PM*.

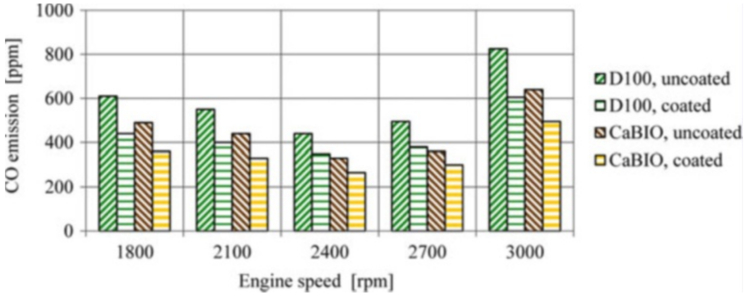

Fig. 7.37 CO emissions of the uncoated and coated engine

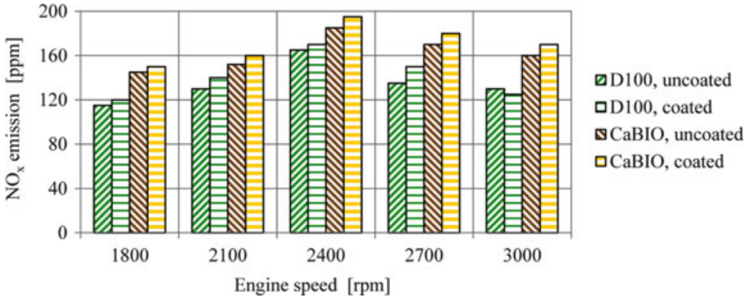

Fig. 7.38 NO_x emissions of the uncoated and coated engine

In Zheng et al. (2008) SoBIO and CaBIO fuels were tested under low temperature combustion in a single-cylinder, 4-stroke, naturally aspirated, DI diesel engine, equipped with EGR. Extensive EGR rates up to 65 % were applied in order to initiate low temperature combustion. From the results one can extract that the *smoke emission* initially increases by raising EGR, but begins to decline after a certain EGR ratio. The *NOx* emissions decreased practically monotonically with increasing EGR.

In Nabi et al. (2006) a blend of 85 % mineral diesel and 15 % *neem biodiesel* was tested in a 4-stroke naturally aspirated DI diesel engine. Compared to mineral diesel, the results showed no significant differences in engine characteristics. It is interesting to note that with neem biodiesel blend, NO_x emission was slightly lower than that of neat mineral diesel for any tested EGR rate.

In Tsolakis et al. (2007) the influence of *EGR* on engine emissions was investigated on a naturally aspirated diesel engine (Table 7.11) by using D100 and RaBIO. Figures 7.39, 7.40, 7.41, and 7.42 show the NO_x, CO, smoke, and HC emissions, obtained with D100 and RaBIO without or with 20 % EGR for two engine operating conditions. It is evident that EGR reduction of NO_x emission is larger for RaBIO than that for D100. Furthermore, EGR increases CO, smoke, and HC emissions. The differences obtained are larger for RaBIO, except for the HC emission where the effect of EGR is similar for D100 and RaBIO.

Table 7.11 Engine specifications (Tsolakis et al. 2007)

Engine model	Lister-Petter TR1 engine
Engine type	Naturally aspirated, air cooled, single cylinder
Displacement	773 cm^3
Compression rate	15.5:1
Bore and stroke	98.4 mm × 101.6 mm
Maximal power at engine speed	8.6 kW at 2,500 rpm
Maximal torque at engine speed	39.2 Nm at 1,800 rpm
Injection model	Mechanically controlled direct injection system
Injector opening pressure	180 bar
Injection pump timing	22°CA BTC

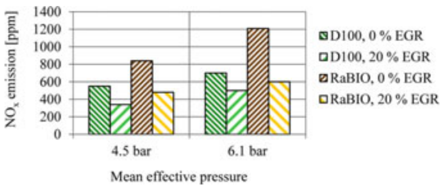

Fig. 7.39 NO_x emissions with and without EGR

7.2.3 Influence of Engine Operating Regime

The influence of biodiesel usage on engine harmful emission varies in dependence on engine operating regime (Baiju et al. 2009; Bhale et al. 2009; Buyukkaya 2010; Cheung et al. 2009; Gumus and Kasifoglu 2010; Kaplan et al. 2006; Kegl 2008, 2011; Koçak et al. 2007; Labeckas and Slavinskas 2006; Liu et al. 2009; Murillo et al. 2007; Nabi et al. 2009; Puhan et al. 2005; Sahoo et al. 2007; Song and Zhang 2008; Usta 2005):

- *Engine load:* engine load influences significantly NO_x emission; higher engine load results in higher combustion temperatures and increased NO_x formation.
- *Engine speed*: it is widely accepted that CO emission of biodiesel decreases with increasing engine speed; this is because increased engine speed results in better air–fuel mixing and/or increased fuel/air equivalence ratio (Keskin et al. 2008; Lin and Li 2009; Qi et al. 2009; Usta 2005); the oxidation converter might also influence significantly CO emission of biodiesels.

Apart from the engine load and speed, other operating conditions, such as the environment temperature, may influence significantly the effects of biodiesel usage on harmful emissions. These topics will also be addressed briefly in this section.

In Kegl (2006) a *DI diesel bus* MAN 2566 MUM engine with *M injection system* (Table 7.1) was tested in order to evaluate the influence of *engine operating conditions* on engine emissions. The pump timing was fixed to the one prescribed

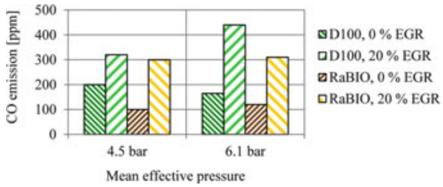

Fig. 7.40 CO emissions with and without EGR

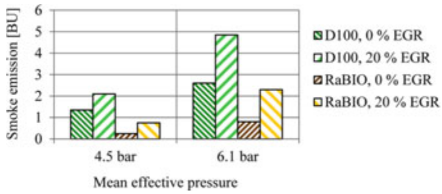

Fig. 7.41 Smoke emissions with and without EGR

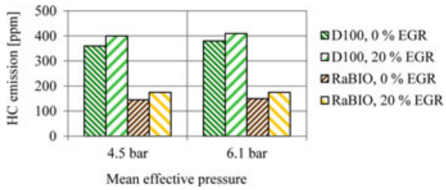

Fig. 7.42 HC emissions with and without EGR

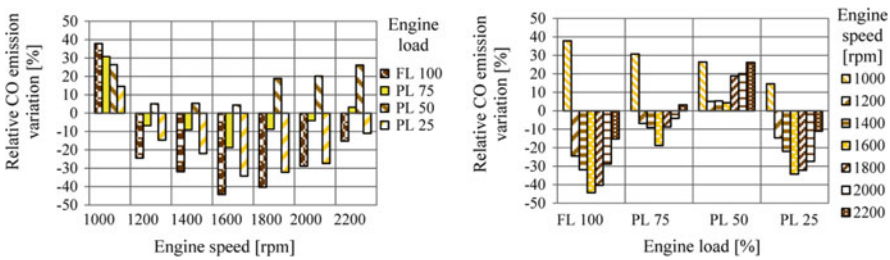

Fig. 7.43 Influence of engine operating conditions on relative CO emission

for mineral diesel. The tested fuels were D100 and RaBIO. The compared quantities are the CO, HC, NO_x, and smoke emissions.

Figure 7.43 presents the relative CO emission variations (RaBIO emission with respect to D100 emission). It is evident that RaBIO emission was higher than that of

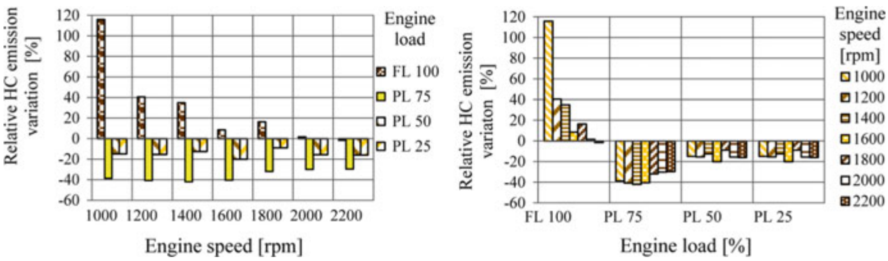

Fig. 7.44 Influence of engine operating conditions on relative HC emission

D100 at engine speed of 1,000 min^{-1} and at partial load PL 50 only. In all other tested conditions RaBIO usage resulted in lower CO emission.

Figure 7.44 presents the relative HC emission variations (RaBIO emission with respect to D100 emission). As can be seen RaBIO delivered higher HC emission at full load at all tested engine speeds. At all other tested conditions, the HC emission obtained with RaBIO was lower than the one obtained with D100.

Figure 7.45 presents the relative NO_x emission variations (RaBIO emission with respect to D100 emission). It is evident that RaBIO usage yielded higher NO_x emissions at practically all engine operating regimes. The only exception is the results obtained at middle engine speeds at partial load PL 50.

Figure 7.46 presents the relative smoke emission variations (RaBIO emission with respect to D100 emission). One can see that RaBIO usage yielded higher smoke emission at partial load PL 25 and low engine speeds only. At all other tested operation conditions, RaBIO usage resulted in lower smoke emission than D100.

In Koçak et al. (2007) TDI diesel engine (Table 7.7) was tested to evaluate the influence of *engine speed* on engine emissions, obtained at *full load* by using CaBIO, HaBIO, and WcBIO fuels.

The experimentally obtained emissions of NO_x and *CO* are shown in Fig. 7.47. For all tested biodiesels, the highest NO_x emissions were obtained within the speed range corresponding to maximum torque and maximum power. These higher NO_x emissions are related to in-cylinder temperatures and rise of volumetric efficiencies. At low engine speeds, the air–fuel mixing process is influenced by the difficulty in atomization of biodiesels due to their high viscosity. The resulting locally rich mixtures of biodiesels caused more CO to be produced during combustion. The turbocharged diesel engine used in the experiments provides more air at higher speeds, which results in an increase of turbulence intensity in the combustion chamber. This affects the air–fuel mixing process, which leads to a more complete combustion. Therefore, the CO emissions decreased at higher speeds (Fig. 7.47). The various fuel properties of tested biodiesels had only a minor effect on the CO emissions due to the dominant premixed lean combustion with a 10–11 % excess of oxygen.

The relative emissions of *smoke* and CO_2 (compared to mineral diesel) are shown in Fig. 7.48. Maximal smoke densities were measured in the range from 3,500 to 4,000 rpm. The relative values, however, mostly decrease as the engine

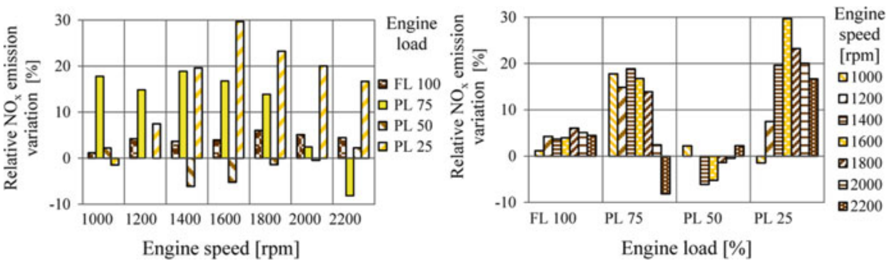

Fig. 7.45 Influence of engine operating conditions on relative NO_x emission

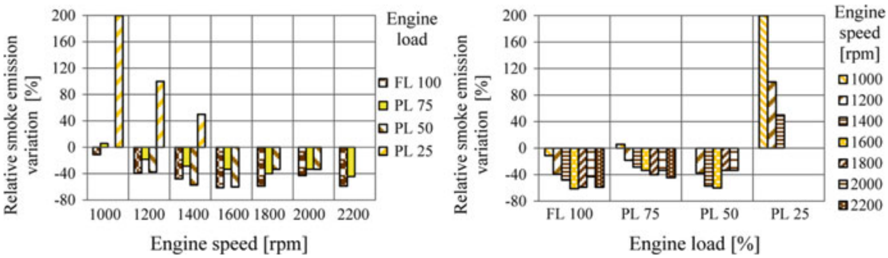

Fig. 7.46 Influence of engine operating conditions on relative smoke emission

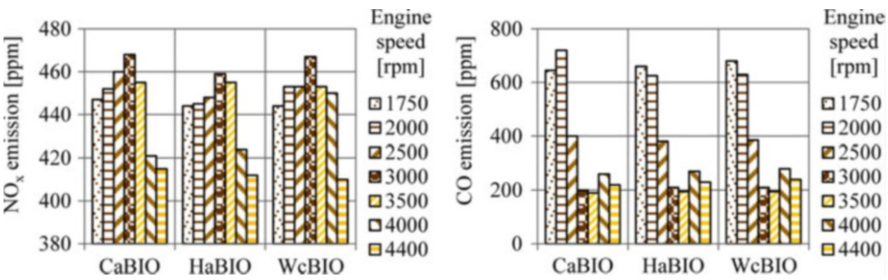

Fig. 7.47 Influence of engine operating conditions on NO_x and CO emissions

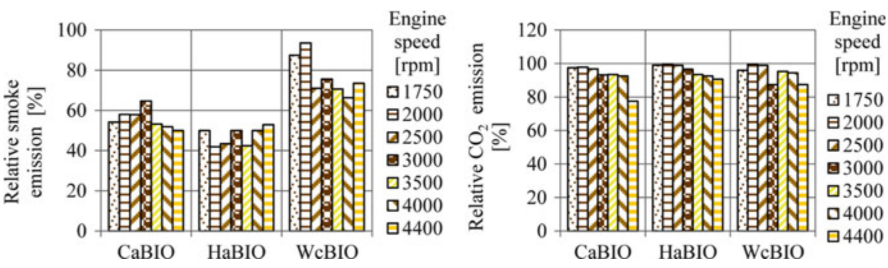

Fig. 7.48 Influence of engine operating conditions on relative smoke and CO_2 emissions

speed increases. This means that biodiesel performance, relative to mineral diesel, mostly improved as the speed increased. The only exception was the smoke emission of HaBIO.

The engine operating conditions, such as load, speed, and low temperature, play a significant role in *PM/smoke emission* production when using biodiesels. A PM emission increase, caused by an increase of engine load, was observed on various engines, for example, on a 2.5-L four-cylinder Peugeot XD3p157 engine fuelled by sunflower biodiesel (Kaplan et al. 2006), on a 6-cylinder MAN direct injection turbocharged engine fuelled with rapeseed biodiesel (Buyukkaya 2010), on a 4-stroke naturally aspirated direct injection diesel engine (Puhan et al. 2005), etc. The experiments on a high-speed single-cylinder, 4-stroke, WC Ricardo E6 engine fuelled by mahua biodiesel showed that the smoke level increased sharply with the increase of load due to the decreased air/fuel ratio; in this scenario larger quantities of fuel were injected into the combustion chamber, much of which went unburned into the exhaust (Raheman and Ghadge 2007).

The advantage of biodiesel fuels with respect to PM emissions is weakened or even reversed at *low temperature* tests. By testing SoBIO in a turbocharged direct injection diesel engine of a passenger car VW Golf 1.9 TDi, all emission levels tended to increase significantly over the cold start of the urban part of the new European driving cycle NEDC (Fontaras et al. 2009). The PM emission for biodiesel over the cold phase of the NEDC was approximately 40 times higher than at hot start of the cycle UDC. This is probably due to the fuel's higher kinematic viscosity and lower boiling point which make fuel atomization and evaporation more difficult under cold start conditions. Similar results were also obtained by testing WcBIO and SuBIO in a 4-cylinder, 4-stroke, turbocharged, intercooled, DI diesel engine (Armas et al. 2006).

In Leung et al. (2006) RaBIO was tested in a single-cylinder DI diesel engine with a mechanically controlled fuel injection system at various *load conditions*. It was observed that biodiesel-related decrease of *PM emissions* is higher at high load. SuBIO tests in a 2.5-L four-cylinder Peugeot XD3p157 engine (Kaplan et al. 2006) and in a 4-stroke, 4-cylinder, 55 kW DI diesel engine (Ulusoy et al. 2009) showed that with higher engine speeds the PM emission decreases. Probably, this is mainly because of the improved combustion efficiency that can be attributed to an increase in turbulence effects at higher engine speeds, which promotes complete combustion.

Tests performed on a 3-cylinder, 4-stroke, air-cooled, naturally aspirated DI diesel engine with *fish biodiesel* and on a Cummins 6BTA 5.9 G2-1, 158 HP-rated power, turbocharged, water-cooled DI diesel engine with *mahua biodiesel* revealed that the *NOx* concentration varies linearly with *engine load*. As the load increases, the overall fuel/air ratio also increases which results in an increase in the average in-cylinder temperature. Consequently, the NO_x formation also increases (Deshmukh and Bhuyar 2009; Godiganur et al. 2010; Raheman and Ghadge 2007; Zhu et al. 2010). On the other hand, measurements on a single-cylinder, 4-stroke, naturally aspirated DI diesel outboard engine, performed during the ISO C-3 test cycle, have shown that NO_x emission decreases as the load is increased

(Murillo et al. 2007). Presumably this could be due to the increase in turbulence inside the cylinder, which may contribute to a faster combustion and to lower residence time of reactants in the high temperature zones.

NO_x emissions are also affected by *engine speed*. By testing *fish biodiesel* in a 4-cylinder, 4-stroke, naturally aspirated DI diesel engine, the NO_x emissions decreased with increasing engine speeds (Lin and Li 2009). Probably, this is primarily due to shorter residence time available for NO_x formation, which may be the result of increased volumetric efficiency and flow velocity of the reactant mixture at higher engine speeds. In Utlu and Koçak (2011) waste cooking oil biodiesel was tested in the Land Rower TDI 110, 4-cylinder, turbocharged, inter-cooler DI diesel engine with 235 Nm torque at 2,100 rpm and 82 kW power at 3,850 rpm. It turned out that the NO_x emissions increase between maximum torque and maximum power speeds. In Keskin et al. (2008) the *tall oil biodiesel* was used at full load in a single-cylinder, 4-stroke, air-cooled, DI diesel engine Lombardini 6LD 400, which reaches the maximum power of 6.3 kW and maximum engine speed of 3,600 rpm. It turned out that the NO_x emission increased at low speeds and reached a maximum value at medium speeds. After that it decreased with further increase in engine speed.

Regarding the effects of *engine load* on *HC emissions* of biodiesel, the results are somewhat inconsistent. Some experiments indicate that HC emissions tend to increase with the increased load (Agarwal et al. 2006; Gumus and Kasifoglu 2010).

Increasing the engine load also seems to increase the *CO emission* (Agarwal et al. 2006; Gumus and Kasifoglu 2010; Ulusoy et al. 2009). The main reason for this increase is that the air–fuel ratio decreases with increased load, which is typical for diesel engines. Sometimes, however, the effect of engine load on CO emission is the opposite. In Sharma et al. (2009) and Wu et al. (2009) it was found out that in the low or intermediate load range, the CO emission may also decrease as the load increases. By testing RaBIO in 4-stroke, 4-cylinder, water-cooled, naturally aspirated DI diesel engine, the CO emission was lower at intermediate loads, but became higher in low load, heavy load, and full load (Labeckas and Slavinskas 2006; Mahanta et al. 2006).

7.3 Discussion

The determination of the effects of biodiesel usage on engine performance, economy, tribology, and harmful emissions is a complex topic. Although the use of numerical simulations increases, most of the work still has to be done by experiments. Because there are so many influential factors, experimental work is typically done under circumstances that vary significantly from one experiment to the other. The reasons for this situation are different test engines, different operating conditions or driving cycles, different biodiesels or reference mineral diesel, different measurement techniques, and so on, just to mention the most obvious ones. Consequently, the results obtained often do not show uniform trends of the influence of a particular parameter. In spite of that, some general comments can be given as follows.

- The use of biodiesel leads to the reduced *engine power* due to the lower energy content of biodiesels, compared to mineral diesel. However, high viscosity and high lubricity of biodiesels also have certain effects on engine power. For example, in some investigations the effective engine torque and power drop were less than expected because of biodiesel's higher viscosity, which enhanced fuel spray penetration and improved air–fuel mixing. On the other hand, in some investigations the higher viscosity influenced negatively the effective power, because it decreased combustion efficiency due to bad fuel injection atomization. Biodiesels typically exhibit better lubricity than mineral diesel. This results in reduced friction losses and increased effective power.
- The *effective specific fuel consumption* typically increases when biodiesel replaces mineral diesel. This increase is mainly due to its low heating value, as well as its high density and high viscosity. Various biodiesel raw materials, different production processes, and variable quality also have an impact on engine economy. In any case, the situation may be improved by using a turbocharged or a low heat release engine. Engine operating conditions, such as load and speed, also influence biodiesel engine economy, although this influence is not essential. Additives, used to improve the properties of biodiesel, may potentially improve the combustion performance and promote both engine economy and power.
- It is commonly accepted that *CO emission* decreases when biodiesel replaces mineral diesel. This is due to higher oxygen content and lower carbon to hydrogen ratio of biodiesel, compared to mineral diesel. The CO emissions of biodiesel are affected by its source and other factors such as the cetane number and advance in combustion. Engine load has also been proven to have a significant impact on CO emissions. There is a largely unanimous conclusion that CO emissions of biodiesel decrease with increasing engine speed.
- The *HC emissions* also typically decrease when biodiesel is used instead of mineral diesel. Partially, this depends on biodiesel source and its properties, especially on the chain length or saturation level of biodiesels. For mechanically controlled injection systems, the advance in injection and combustion of biodiesels also favors lower HC emissions. There are, however, inconsistent conclusions related to the effects of engine load on HC emissions.
- Because of the relatively high oxygen content and because of other physical and chemical properties of biodiesels, which lead to higher injection pressure, the *smoke emission* of biodiesel is typically lower than that of mineral diesel. Smoke emission depends on both soot formation and oxidation, which are highly dependent on local burning temperatures and local air/fuel ratios. These seem to be better when biodiesel replaces mineral diesel.
- In general, *PM emission* decreases significantly when biodiesel replaces mineral diesel. Mostly, this reduction is proportional to biodiesel content in a blend with mineral diesel. It should be noted, however, that unexpected variations of PM

emission may appear in case of certain contents of biodiesel in a blend. In any case, it seems that the most important factor, influencing the PM emission, is the higher oxygen content of biodiesel. In general, PM emissions of biodiesel increase with engine load and decrease with engine speed. The use of EGR might deteriorate PM emissions of biodiesel, although the measured levels are still much lower than those obtained with mineral diesel. It should be noted, however, that PM emissions of biodiesel might increase abnormally in the case of low temperature conditions.
- Experimental results mostly confirm that *NO_x emissions* will increase when biodiesel replaces mineral diesel. This increase is partly due to relatively high oxygen content in biodiesel. Furthermore, the higher cetane number of biodiesel, higher content of unsaturated compounds, and variations of injection characteristics also have a notable impact on NO_x emissions. The use of EGR may reduce the NO_x emissions of biodiesel, but the EGR rates must not be the same as for mineral diesel; they have to be optimized for biodiesel usage. By increasing the engine load, the level of biodiesel NO_x emissions will also typically rise. It is interesting to note that by taking into account the calculated maximum heat release rate and maximum firing temperature, the NO_x emission of biodiesel should be lower than actually measured in some experiments. Some combustion analyses indicate that for NO_x formation the maximum in-cylinder temperature and the maximum heat release rate may not be as important as the advance in the start of injection timing, caused by the biodiesel's higher bulk modulus of compressibility in a mechanically controlled injection system. The advanced injection and combustion process lead to higher in-cylinder temperature at the beginning of the combustion process. Earlier peaks prolong the period with conditions favorable for NO_x formation and consequently the total NO_x emissions.
- The measurements of *CO_2 emission* of biodiesel reveal rather inconsistent results. For example, some researches indicated that the CO_2 emission decreases when biodiesel replaces mineral diesel as a result of the low carbon to hydrocarbon ratio. On the other hand, some other researches showed that the CO_2 emission increases or stays similar because of the more effective combustion of biodiesel. Anyhow, one can agree that the CO_2 emission of biodiesel is significantly lower than that of mineral diesel, if one takes into account the whole CO_2 life cycle.
- From the quite limited literature one can conclude that, compared to mineral diesel, biodiesel mostly positively affects *carbon deposits* and *wear* of the key engine parts. At least partially, this can be attributed to good *lubricity* and *solvent action* of biodiesel. However, further studies along with biodiesel engine endurance tests would probably be necessary to clarify fully all the reasons and mechanism of wear.

On the basis of experimental and numerical investigations done so far, it should be clear that significant improvements of biodiesel engine characteristics are possible. To some extent, these improvements can be achieved by performing

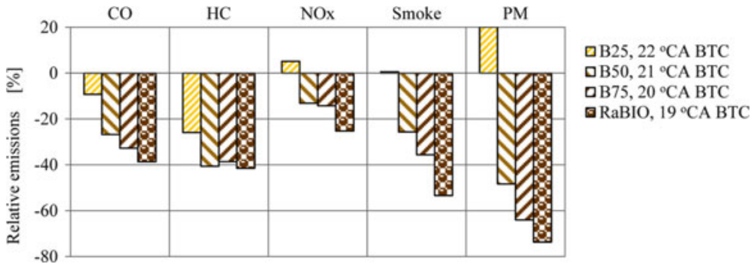

Fig. 7.49 Relative biodiesel and its blends emissions at various pump injection timings

rather inexpensive modifications on existing diesel engines. For example, for an engine equipped with a mechanically controlled fuel injection system, notable improvements can be obtained by setting optimally the pump injection timing.

As an example, it may be worth to take a look at the harmful emissions of a bus MAN diesel engine (Table 7.1) investigated at various pump injection timings (Kegl 2008). According to the ESC test, the individual characteristic points were weighted by corresponding factors that take into account the importance of individual engine regimes. RaBIO and its blends with D100 were tested at various pump injection timings and compared to D100 with the standard pump injection timing. The results clearly showed that it is possible to obtain lower CO, HC, NO_x, smoke, and PM emissions, if the injection timing is set appropriately (Fig. 7.49).

Figure 7.49 illustrates the importance of finding proper pump injection timing for each individual fuel in order to reduce harmful emissions while keeping engine performance and economy at desirable levels. Of course, the pump injection timing is only one of the many parameters which can influence the engine characteristics. In the search for the optimal values of various engine design and control parameters, a lot of experimental and numerical work needs to be done. But besides this, it may also be worth to engage systematic optimization procedures and techniques.

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