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# Use of diesel-biodiesel-bioethanol blends in farm tractors: first results obtained with a mixed experimental-numerical approach

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**Abstract**

The fuelling of internal combustion engines with biofuels has certainly many environmental and energetic advantages. These advantages are particularly effective in the agricultural sector, where an integrated biofuel supply-chain would further benefit the overall carbon balance. Unfortunately, there are also some drawbacks, mainly concerning the engine performances (lowering of the torque curve), but also environmental (possible raising of the NOx emissions). However, by appropriately mixing two biofuels with known opposite effects on the combustion process, it is theoretically possible to compensate the aforementioned disadvantages. In this work, some experiments were carried out in this direction by fuelling a farm tractor with four different fuel mixes; the collected data were processed through the Response Surface Methodology to obtain multi-parameter regression equations useful to identify the optimal fuel mixtures composition. Thanks to this approach, it was found that biodiesel has a positive effect on the torque, while the addition of bioethanol has a much bigger detrimental effect; on the contrary, bioethanol should be added to a mixture with a minimum of 8-12 % of biodiesel to get advantages in terms of NOx concentration reduction.



*Keywords:* Farm Tractor, Biodiesel, Bioethanol, Response Surface Method, Modelling, Optimization.

## 1. Introduction

The constantly-increasing energy-demand represents a challenge for researchers and technicians involved in the study of clean alternative fuels and in the development of energy-conversion technologies, aimed at reducing polluting emissions. Liquid fossil fuels are the main and most frequently-used fuels for internal combustion engines

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(ICEs) in mobile machinery (for transportation, construction, industry and agriculture) [1]. Considering the actual diffusion of ICEs, the substitution of current energy-conversion systems with new ones will not likely come in the short run. Positive developments could instead come from adapting and reforming the actual technologies using new fuels able to meet the requests and characteristics of current machines. This is the core direction of several scientific studies and the base criteria of the fossil-fuels replacement approach. The use of alternative fuels or biofuel mixtures can have significant but complex impacts on the ICEs performances. Indeed, there are direct and indirect effects on the combustion process, due to the different chemical, physical and fluid-dynamic characteristics (mainly, density and viscosity, influent on the fuel-spray formation). During the last two decades, biodiesel, namely fatty-acid methyl-ester, has become the most common renewable liquid fuel, due to its physical characteristics that make its use easy as petro-diesel substitute in compression-ignition ICEs [1,2], even if older engines need a replacement of seals and fuel injection hoses [3]. biodiesel can be produced from a great variety of feedstocks [4]: very common vegetable oils (e.g., from: soybean, cottonseed, palm, peanut, rapeseed/canola, sunflower, safflower, coconut), animal fats (usually tallow) and also waste oils (e.g., used frying oils). The feedstocks are chosen largely on geography and local economy and production [4]. Many studies report that biodiesel has positive effects on exhaust emissions of compression-ignition ICEs: carbon monoxide (CO) is lowered up to 30-50 % depending on the share of biodiesel in the blend [5], as well as hydrocarbons (HC) and particulate matter (PM). The higher oxygen content and the lower hydrogen and carbon content, with respect to petro-diesel, are the main responsible for these positive effects [4,5]. On the other hand, the mentioned fuel characteristics bring in negative effects on nitrogen oxides (NOx) emissions, whose sensible relative increase represents one of the main cons of using biodiesel as petro-diesel substitute [6]. Improvements in terms of NOx emissions can be obtained varying the biodiesel substitution-rate in binary diesel oil-biodiesel blends, as well as introducing small percentages of a third alcohol-based fuel (ethanol or methanol), to realize ternary diesel-blends. When using ternary blends, fuels substitution in the mixture should respect a trade-off between the derating of performance and the reduction of polluting emissions. For example, in [7] the best results have been obtained with 5%-ethanol blends. The use of these ternary blends has positive effects on the brake specific fuel consumption and, at the same time, brings sensible reductions of PM, HC, CO and $CO_2$ emissions [7]. The effects on NOx emission are still not clear: some works register positive effects [8], other works report an increase of concentration [7,9]. These controversial results are probably due to the different fuel-injection systems and controls, thus highlighting the need for further investigations in terms of emissions and performances.

Therefore, this work aims at investigating the performance and environmental effects of binary and ternary blends on a commercial farm tractor. Specifically, the engine torque and NOx emissions are experimentally inquired; moreover, proper numerical models, evidencing the effect of the mix components and the engine speed, are developed by using a powerful numerical tool, the Response Surface Modelling. Hence, the final aim is to present a mixed experimental-numerical approach that can be useful to optimize the fuel mix composition by balancing the contrasting effects of the different components of the fuel mix.

## 2. Materials and methods

Tests have been performed on a "*New Holland T4020V*" farm tractor, equipped with a 3200-$cm^3$ diesel engine with direct injection (Table 1). Other than pure diesel oil, two binary and two ternary blends of diesel oil (D), biodiesel (B; Table 2) and bioethanol (E) have been used to fuel the tractor by using an external tank: B15 (85% D, 15% B in volume), B25 (75% D, 25% B), B15E3 (82% D, 15% B, 3% E) and B25E3 (72% D, 25% B, 3% E).

Table 1 – Main properties of the New Holland T4020V farm tractor.

| Description | Specification |
|---|---|
| Engine (manufacturer; type; building year; total displacement) | New Holland; F5A E9484A*A001; 2009; 3200 $cm^3$ |
| Cylinders (number; configuration) | 4; straight |
| Fuel-system type | With direct injection, rotary fuel pump, turbocharger, intercooler, mechanical speed-regulator |
| Nominal gross power at the engine (value, engine speed) | 47.7 kW (according to ISO/TR 14396:1996) @ 2300 rpm |
| Maximum torque (value; engine speed) | 290 Nm @ 1250 rpm |

Table 2 – Main properties of the biodiesel used in the tests.

| Properties | Value | Test method | Properties | Value | Test method |
|---|---|---|---|---|---|
| Ester content [% m m$^{-1}$] | 98.5 | EN 14103 | Flash point [°C] | >160° | EN ISO 3679 |
| Density at 15°C [kg m$^{-3}$] | 883.1 | EN ISO 3675 | Cetane number | >51 | EN ISO 5165 |
| Viscosity at 40° [mm$^2$ s$^{-1}$] | 4.1 – 4.7 | EN ISO 3104 | Water content [mg kg$^{-1}$] | 210 | EN ISO 12937 |

A "*SIGMA 50 Mobile*" PTO-dyno (by N. J. Froment & Co Ltd, Easton-on-the-Hill, East Northamptonshire, England, UK) and a "*Vario Plus Industrial*" gas analyser (by MRU Instruments, Houston, TX, USA) were used to measure respectively the engine torque and the NOx concentration in the exhaust gases [10] at full-load and at six different speeds (300-400-500-600-700-800 rpm at the PTO, corresponding to 822-1096-1370-1644-1918-2192 rpm at the engine), controlled by the dyno. The gas samples (360 in total; 12 per each fuel and speed) were taken only after the engine speed was stable at each set value.

### *2.1. The response surface methodology*

One of the key-points of this experimentation is running the power unit with alternative fuels but without any modification, hence no re-calibration of the fuel system and exhaust after-treatment systems were performed. Therefore, modelling the emissions and the engine output could become particularly complex and not necessarily solely correlated to the components percentages in the fuel blends (the system responses are not proportional to the fuel components). Therefore, having simple relations at the users' disposal to assess the machine's outputs in case of use of alternative fuels can be very interesting from a practical point of view. Thus, a very effective methodology, based on a statistical analysis, was adopted to process the experimental data and to infer the trends and the influence of the single independent factors. Specifically, an interpolating function was derived to estimate the value of each independent variables (here: *the engine torque T, the NOx concentration in the exhaust gases*) by using the dependent variables values. Formally, the relations among the quantities are completely independent from the physics of the represented process, being mainly oriented to obtain numerically-acceptable results within the validity domain and, therefore, a reliable prediction-capability. All the collected data, concerning the mechanical and environmental performances of the engine, have been elaborated statistically by using Design-Expert 7.0.0 software (Stat-Ease, Minneapolis, MN, USA). After a first analysis of variance (ANOVA), aimed at evidencing the parameters of influence (*factors*) on each of the above-indicated quantity (*response*), a subsequent application of the Response Surface Methodology (RSM) allowed to calculate the regression function coefficients that describe the effects of the statistically-significant independent variables on the response [11]. Differently from other mathematical tools such as artificial neural networks [12], the RSM is a very effective numerical tool that allows calculating, from a set of input data, an explicit polynomial regression-function that is the best approximation, in a limited validity domain, of the real function governing the phenomenon under study [13–17]. In particular, the effect of the three following numerical factors on the two above-mentioned responses has been inquired (Figure 1):

- the gross volumetric composition of the fuel mix, in term of percentage parts of the fuel-components added to the diesel oil ($B$, $E$: numerical factors controllable by the experimenters when preparing the fuel mixes);
- the engine speed $n$ (numerical factor controllable by the experimenters through the PTO-dyno).

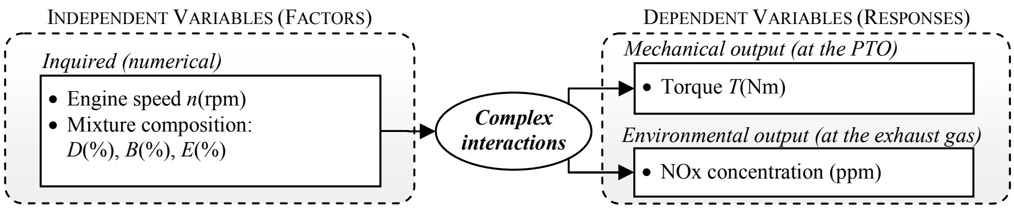


Figure 1 – Variables considered in the assessment of the indicated mechanical and environmental performances of the tested tractor.

## 3. Results and discussions

The following equation, able to predict the engine torque value, has been obtained by applying the RSM on the experimental measurements; it is based on a quadratic model, properly reduced to the statistically significant terms on the basis of a backward algorithm making use of the results of the ANOVA on the model coefficients:

$$\begin{aligned} T[Nm] = &+7.5174 \cdot 10^{-2} + 7.7198 \cdot 10^{-1} \cdot B[\%] - 5.6397 \cdot 10^{0} \cdot E[\%] + \\ &+ 9.5585 \cdot 10^{-3} \cdot n[rpm] - 6.2426 \cdot 10^{-5} \cdot \{n[rpm]\}^2 \end{aligned} \tag{1}$$

The predictive capability of this model is very high: $R^2$ is 0.9930 and the adjusted $R^2$ is 0.9918. Similarly, another equation based on a reduced quadratic model and able to predict the NOx concentration, is proposed:

$$\begin{aligned} NOx[ppm] = &+4.8875 \cdot 10^{+2} - 3.7219 \cdot 10^{-1} \cdot B[\%] + 2.5651 \cdot 10^{+1} \cdot E[\%] + 1.44445 \cdot 10^{-1} \cdot n[rpm] + \\ &- 1.8199 \cdot 10^{0} \cdot B[\%] \cdot E[\%] - 5.8949 \cdot 10^{-4} \cdot B[\%] \cdot n[rpm] - 4.6797 \cdot 10^{-3} \cdot E[\%] \cdot n[rpm] + \\ &+ 2.2224 \cdot 10^{-1} \cdot \{B[\%]\}^2 - 1.2930 \cdot 10^{-4} \cdot \{n[rpm]\}^2 \end{aligned} \tag{2}$$

Also in this last case, the predictive capability is high: the $R^2$ is 0.9820 while the adjusted $R^2$ is equal to 0.9816.

Figure 2 shows the shape of the surfaces representing the engine torque and the NOx concentration for a bioethanol content of 0 % (Figures 2.a and 2.c) and 3 % (Figures 2.b and 2.d), modelled by eq. 1 and 2, as well as the experimental measurements (little spheres positioned within the inquired hyperspace; notice that many points are superimposed each other or positioned under the represented surface and, hence, are not visible in the pictures).

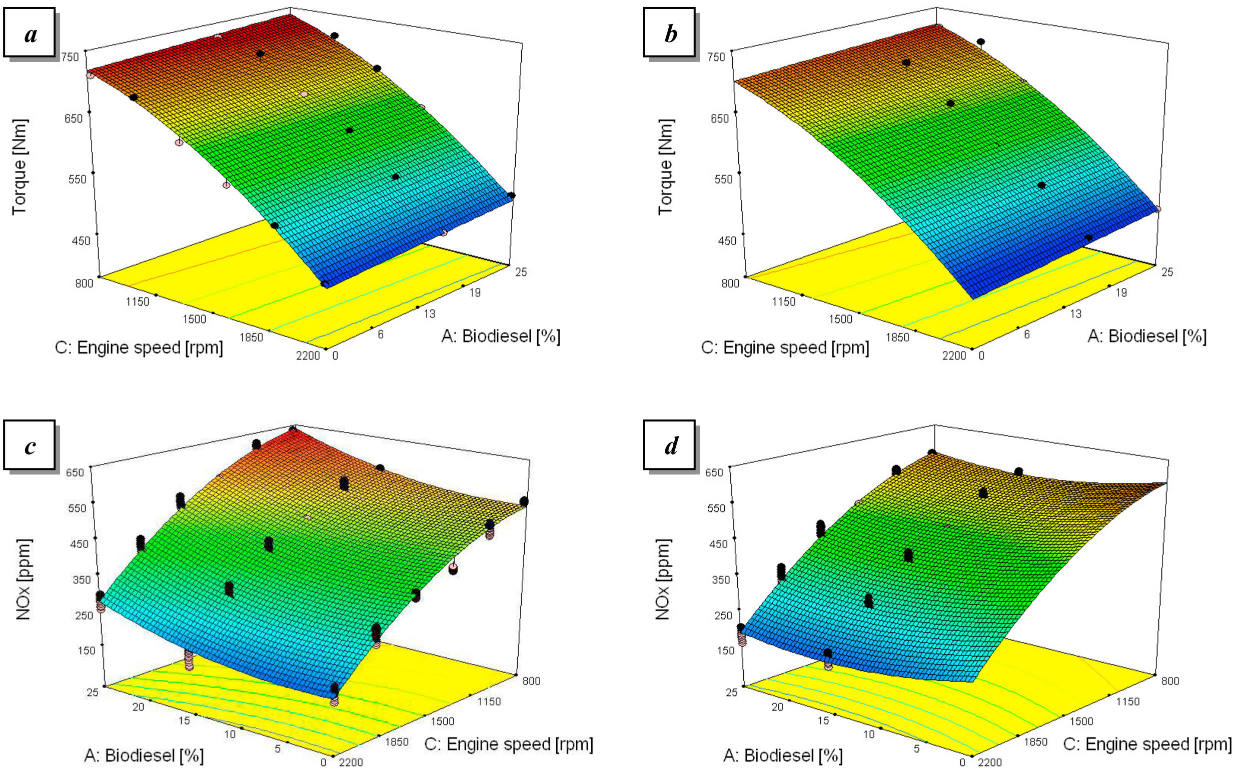


Figure 2 – Surface plot of the engine torque (*a* and *b*) and the NOx concentration in the exhaust gases (*c* and *d*) as a function of the biodiesel percentage and of the engine speed, with the 0 % (*a* and *c*) and the 3 % (*b* and *d*) of bioethanol in the blend.

Eq. 1 shows that increasing percentages of biodiesel in the mix lead to a slight increase of the engine torque with respect to the pure diesel oil test results (about 0.77 Nm per percentage point of biodiesel, limiting the considerations to a maximum of 25 % of biodiesel). Instead, the bioethanol has always a negative effect (up to 3 %), and the magnitude of its effect is more than 7 times higher than the effect of the biodiesel addiction at equal volumes. Indeed, for example, the predicted torque at 1600 rpm is 607.2±6.8 Nm (95 % confidence interval) with pure diesel oil, and the same value can be obtained with the 7.31 % of biodiesel and the 1 % of bioethanol (i.e., B7.31E1). This is also evidenced by the (constant) values of the first (partial) derivatives of the eq. 1 with respect to the biodiesel or bioethanol content.

$$\begin{aligned} &(a)\quad \frac{\partial}{\partial B[\%]}\{T[Nm]\} = +7.7198\cdot 10^{-1} > 0 \rightarrow \textit{always in the validity domain} \\ &(b)\quad \frac{\partial}{\partial E[\%]}\{T[Nm]\} = -5.6397\cdot 10^{0} > 0 \rightarrow \textit{never in the validity domain} \end{aligned} \tag{3}$$

To assess the contribution of biodiesel and bioethanol on NOx concentration, it is necessary to study, also in this case, the first (partial) derivatives of Eq. 2 with respect to the “Biodiesel [%]” or to the “Bioethanol [%]” content:

$$\begin{aligned} &(a)\quad \frac{\partial}{\partial B[\%]}\{NOx[ppm]\} = -3.7219\cdot 10^{-1} - 1.8199\cdot 10^{0}\cdot E[\%] - 5.8949\cdot 10^{-4}\cdot n[rpm] + 4.4448\cdot 10^{-1}\cdot B[\%] \\ &(b)\quad \frac{\partial}{\partial E[\%]}\{NOx[ppm]\} = +2.5651\cdot 10^{+1} - 1.8199\cdot 10^{0}\cdot B[\%] - 4.6797\cdot 10^{-3}\cdot n[rpm] \end{aligned} \tag{4}$$

These first derivatives are both bilinear functions, so it is difficult to highlight a single trend involving one single factor, as presented above for the torque model. However, it is possible to simplify both equations by acting on the “Engine speed” term: as the engine speed ranges between 822 and 2192 rpm (domain validity of the model), the related term in the partial derivatives has an absolute value of $4.8456\cdot10^{-1}$-$1.2922\cdot10^{0}$ (in eq. 4.a) or $3.8467\cdot10^{0}$-$1.0258\cdot10^{1}$ (in eq. 4.b) and, hence, the two partial derivatives of Eq. 4 become:

$$\begin{aligned} &(a)\quad \frac{\partial}{\partial B[\%]}\{NOx[ppm]\} = \begin{cases} -8.5675\cdot 10^{-1} - 1.8199\cdot 10^{0}\cdot E[\%] + 4.4448\cdot 10^{-1}\cdot B[\%] & \textit{for } n = 822 \textit{ rpm} \\ -1.6644\cdot 10^{0} - 1.8199\cdot 10^{0}\cdot E[\%] + 4.4448\cdot 10^{-1}\cdot B[\%] & \textit{for } n = 2192 \textit{ rpm} \end{cases} \\ &(b)\quad \frac{\partial}{\partial E[\%]}\{NOx[ppm]\} = \begin{cases} +2.1804\cdot 10^{+1} - 1.8199\cdot 10^{0}\cdot B[\%] > 0 \Leftrightarrow B[\%] < 11.9810 & \textit{for } n = 822 \textit{ rpm} \\ +1.5393\cdot 10^{+1} - 1.8199\cdot 10^{0}\cdot B[\%] > 0 \Leftrightarrow B[\%] < 8.4582 & \textit{for } n = 2192 \textit{ rpm} \end{cases} \end{aligned} \tag{5}$$

As observable from eq. 5.b, both the two limits of biodiesel B resulting from the discussion of the partial derivative sign (about 8.46 % at 2192 rpm and 11.98 % at 822 rpm) have the same magnitude order of the tested percentages (0-25 %), so the contribution of bioethanol E in the reported experiments could be positive or not depending on the presence/quantity of the biodiesel in the mixture. This effect is also graphically visible by observing the trends in Figure 3 of the contour lines connecting the points with the same NOx concentration values for the two different aforementioned engine speeds (822 and 2192 rpm); the same pictures show also the positions of the experimental measurements (little dots positioned within the inquired plan; notice that in each position there are 12 points superimposed). In both the diagrams, the points corresponding to blends generating lower NOx concentration values at the exhaust gases are all placed in a strip crossing the diagram approximately from the bottom-left corner to the upper-right corner, while the higher NOx concentration values can be registered for blends positioned, as concentration of the components, in the upper-left corner and in the lower-right corner. Indeed, the predicted NOx concentration at 1600 rpm is 389±4 ppm (95 %) with D100, 419±5 ppm (95 %) with B15, hence +7.78 % of the predicted mean value, but only 392±5 ppm (95 %) with B15E3, hence +0.74 % of the predicted mean value, due to the positive effect of bioethanol in the mix. The framed part of the contour plots corresponds to blends with a biodiesel percentage greater than the indicated threshold (11.98 % for 822 rpm, 8.46 % for 2192 rpm); within that evidenced sub-domain, the higher is the bioethanol percentage in the blend (in this case, a point representing the blend has the ordinate value that increases, hence the point moves upward), the lower is the NOx concentration in the exhaust gases (observe the labels and the contours trend).

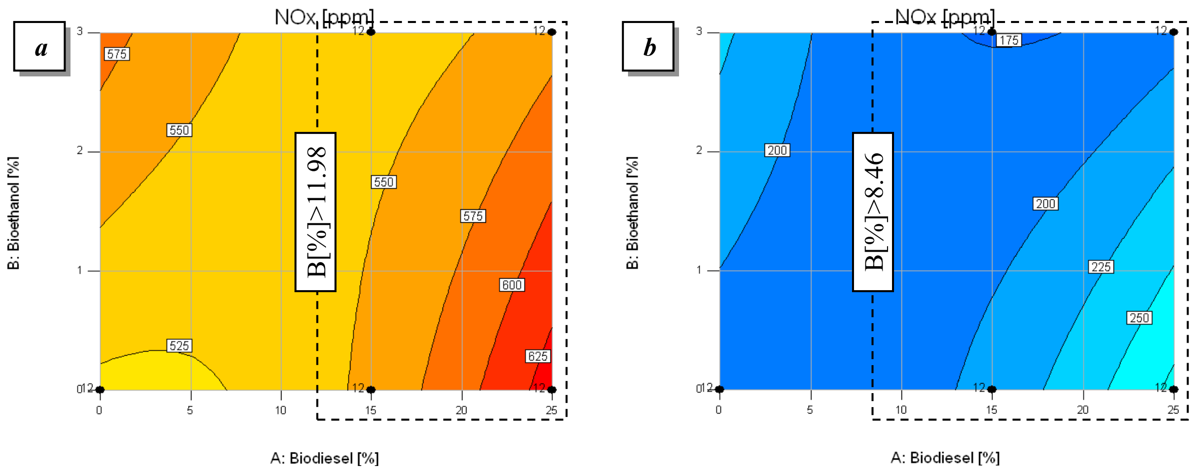


Figure 3 – Contour plots of the NOx concentration as a function of the bioethanol and biodiesel percentages (full ranges of concentration), at 1121 rpm (*a*) and 2991 rpm (*b*); the values of NOx are reported as labels directly on the contours.

## 4. Conclusions

The experimental surveys on a farm tractor and the numerical models allowed discerning the effect, on the engine torque and the NOx concentration, of two biofuels (biodiesel-B, bioethanol-E) added to the diesel oil in several mixes. In the inquired domain (B: 0-25%; E: 0-3%), the bioethanol has a negative and opposite effect on the torque (it lowers the curve) compared to biodiesel, up to 7 times greater, mainly due to the lower energy content compared to diesel oil/biodiesel. As regards the emissions, biodiesel confirmed its negative effect on NOx (it raises the value, as in [6]), while bioethanol effect could be positive or negative on the NOx concentration (respectively, lowering or rising the concentration) depending on the biodiesel quantity in the mix: bioethanol has a positive contribution (i.e., it lowers the NOx concentration) only if biodiesel is present in the blend with percentages above a threshold ranging from 8.46 and 11.98% in the inquired engine speed range. In conclusion, contrasting effects of these biofuels on the observed quantities are highlighted, as in [8]; in addition, the proposed methodology allowed to find a biodiesel concentration limit causing a change in the bioethanol influence on NOx emissions. The regression models granted to obtain reliable torque and NOx predictions; hence, they can be used to optimize the engine performances and limit the NOx emissions at the same time, which represents a crucial point to the diffusion of biofuels on a large scale.

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