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THE ECONOMIC EFFECT OF USING BIOLOGICAL DIESEL OIL ON RAILWAY TRANSPORT

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Abstract. The tests performed by the authors have shown that diesel locomotive engines efficiently operate using a mixture of diesel oil and about 40% of rapeseed oil methyl ester (RME) while their ecological and economical parameters do not differ much from those of the locomotives operating on pure diesel oil. When biodiesel is used, the pollutants released into the atmosphere by an engine are less harmful. Therefore, the respective laws of the Republic of Lithuania provide for some financial incentives and allowances to transport enterprises using biological diesel oil. The paper presents a mathematical model for determining the expenses associated with the use of biological diesel oil.

Keywords: locomotive engine, biodiesel, RME, fuel consumption, fuel expense, economic effect.

1. Introduction

In recent years, biological diesel oil has been widely used as an alternative fuel in the diesel engines of automobiles in Europe (Labeckas *et al.* 2006; Lebedevas and Vaicekauskas 2006; Butkus *et al.* 2007). At the same time, efforts were made to use it in the powerful engines of rail vehicles. The tests performed by the authors (Lingaitis and Pukalskas 2007, 2008) have shown that diesel locomotive engines efficiently operate using a mixture of diesel oil and about 40% of rapeseed oil methyl ester (RME) while their ecological and economical parameters do not differ much from those of the locomotives operating on pure diesel oil. When biodiesel is used, the pollutants released into the atmosphere by an engine are less harmful. Therefore, the respective laws of the Republic of Lithuania provide for some financial incentives and allowances to transport enterprises using biological diesel oil. Thus, the latter do not pay the tax on polluting the environment or it is reduced in accordance with the amount of biofuel consumed (Lietuvos Respublikos… 1999 and 2002). Therefore, it is profitable for transport enterprises to use biological diesel oil. The paper presents a mathematical model for determining the expenses associated with the use of biological diesel oil.

2. Biodiesel Effect on the Power-Producing and Environmental Indicators of the Diesel Engine

Studies carried out by the Austrian company *AVL LIST* and the Swedish company *MTC* (Zelenka *et al.* 1990; Kerstin 1999) demonstrate that the content of particulate matter (PM) in oxides is proportionate to the sulphur content in fuel. After increasing the sulphur content by 0.1 mass %, PM emission increases by 0.027 g /kWh). By using alternative fuel PM emissions could be considerably reduced (Xiao, 2000). Studies (Kerstin 1999) carried out by the Swedish scientists demonstrate that by using ethanol, gas or dimetilether (DME) in the diesel engine, PM emissions can be reduced 7 times as compared to the engine using the strictest standard Ec1 diesel fuel or RME. Besides, the results of these studies state that when using 15% ethanol and 85% diesel mixture, PM emissions reduce by 30 …50%, CO emission reduces insignificantly, HC content increases, whereas NO_x remains the same as using pure diesel fuel.

A comprehensive study was carried out in the USA to summarize the studies of 80 different investigators (EPA420-P-02-001 2002). This examination was performed by the *Environmental Protection Agency*, an institution prominent throughout the states and engaged in environmental studies. The data of different studies was collected and analyzed for this generalizing research investigating different diesel vehicles from heavyweight tractors to cars. All these cars were intended to use diesel, yet during the experiment, they used pure biodiesel or different mixtures with diesel fuel.

Vegetable or animal origin biodiesel was used in these studies; therefore its calorific value ranged from

33.25 to 33.230 MJ/l, meanwhile, an average calorific value of diesel fuel was 36.094 MJ/l.

After the analysis of the existing data, it turned out that an increase in fuel consumption by using pure diesel fuel accounted for only 4.6%. Theoretical assumptions stated that this difference could be bigger since the calorific value of vegetable origin biodiesel is less by 7.9% and of animal origin less by 10.6% than that of mineral diesel fuel.

Professor Dr. Reinhard Reich from the Nurtingen University of Applied Sciences investigated the effect of different biofuel (bioethanol, canola methyl ester) on the performance indicators of the diesel engine.

The carried out studies of the tractor engine using pure diesel and pure RME demonstrate (Fig. 1) that when the engine uses RME, its power decreases by 14-16% as compared to the power of pure diesel fuel. It is understandable that at the moment of torsion, the difference is also similar (Fig. 2).

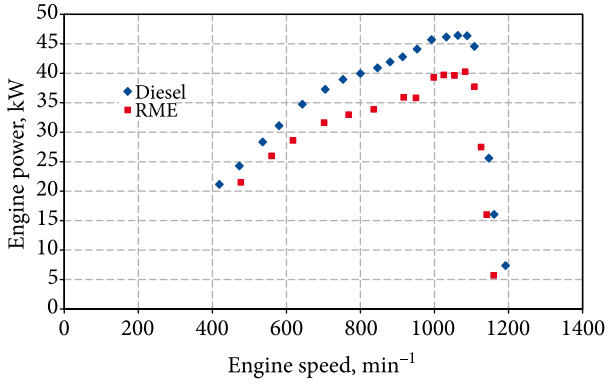

Fig. 1. Comparison of the engine power using pure diesel fuel and pure RME

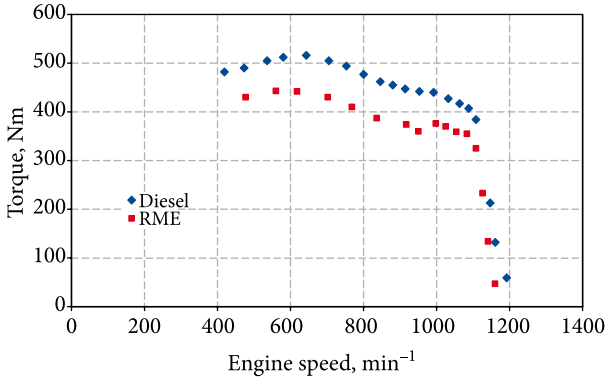

Fig. 2. Comparison of the torque of the engine using pure diesel fuel and pure RME

Since biodiesel is distinguished for good dissolving qualities, when using mineral diesel, the sediments composed in the fuel tank and supply system dissolve. Thus, fuel filters may get clogged, and therefore shortly after starting using biodiesel, it is necessary to change fuel filters. When using biodiesel only at a later stage, the filter does not get clogged. Biodiesel that meets the standard requirements may be also used during the cold season up to –20°C. Yet, experience of Graco (Austria) city communication companies demonstrates that biodiesel made of oil used for cooking is suitable to be used during the winter time when the temperature is not lower than –4°C. In case of lower temperatures, 'mixed operation' is usually applied and during the cold season, only mineral diesel is used. In such case, fuel filters are changed regularly every spring after starting using biodiesel that may dissolve varnish and paint, and therefore the splashes of biofuel should be immediately cleaned.

By using diesel in the engine, a small amount of fuel gets into the engine oil via piston rings. Mineral diesel easily evaporates from the oil. The evaporation temperature of biodiesel is high; therefore biodiesel dilutes oil after it gets there. Such an effect on the engine is regularly discussed. There are opinions that a negative dilution effect is compensated by the good lubrication qualities of biodiesel itself, yet no exhaustive studies were carried out. Thus, for the sake of safety, the majority of manufacturers recommend to shorten the oil change periods if biodiesel is consistently used.

The calorific value of biodiesel is less by approximately 10% than that of mineral diesel. On the other hand, biodiesel is distinguished for a greater cetan number. Also, it contains oxygen, and therefore burns better in the engine. Car manufacturers foresee an increase in fuel consumption up to 10% depending on the engine type. Some users, however, notice that biofuel consumption does not increase. For example, in the Graco bus fleet that has used biodiesel for ten years, the biofuel consumption increased by approximately 7-8%. Yet, this difference is compensated by a smaller biodiesel price as compared to mineral diesel.

Studies carried out in the Czech Republic demonstrated that when using a mixture of RME and mineral diesel (30:70), no negative effect on biodiesel was noticed, and such mixture may be used in conventional engines without changing their construction and operation requirements.

When using biodiesel and 30% biodiesel mixtures with mineral diesel in the engine of Audi 80 TDi, it was established that in case of average engine loads (more than 100 Nm) and using 30% biodiesel mixture with mineral diesel, fuel consumption remained the same as using pure mineral diesel (Makarevičienė *et al.* 2001). If using pure RME, fuel consumption increased from 2.2-7.6% depending on the load.

To sum up, it may be stated that 5% biodiesel improves fuel lubrication that is very important when using mineral diesel with a small content of sulphur compounds which to the EU demand is regularly reduced in the mineral diesel due to environment pollution. ***30% biodiesel mixture does not cause any operational problems: fuel consumption slightly increases, lubrication increases and environment pollution decreases.*** A methodology for calculating a correlation of biodiesel consumption with the RME content is further provided.

3. Developing a Mathematical Model

The economic effect of using biological diesel oil can be accurately calculated only for some past period of time because the prices of both diesel oil and RME vary considerably and can be hardly predicted. However, given the annual fuel consumption B_{diesel} and fuel cost K_{diesel}, the annual fuel expenses of an enterprise using certain amounts of biodiesel can be calculated by the suggested model. This means that the costs of diesel oil and varying RME amounts can be predicted.

Thus, given the amount of the consumed fuel B_{diesel} and fuel cost K_{diesel}, the annual fuel expenses of an enterprise Z (EUR/year) can be calculated:

$$Z = B_{diesel} \cdot K_{diesel}, \quad (1)$$

where: B_{diesel} – is the annual fuel consumption of diesel locomotives, t/m.; K_{diesel} – is the cost of diesel oil, EUR/t.

According to the law of the Republic of Lithuania (Lietuvos Respublikos… 1999 and 2002) on environment pollution taxes, all physical and juridical persons engaged in commercial activities and using mobile equipment causing environment pollution should pay the environmental tax depending on the type of transport facilities used. The annual fixed tax of 7.53 EUR per one ton of burnt fuel should be used for rail transport in the period from 2005 to 2009. Consequently, to calculate enterprise expenses on fuel, the above tax should be taken into account. Then, we get:

$$Z = B_{diesel} \cdot K_{diesel} + B_{diesel} \cdot M, \quad (2)$$

where: M – is the pollution tax, M = 26 EUR/t.

Moreover, point 3 of article 5 of this law states that physical and juridical persons using environmentally unfriendly transport facilities operating on biofuel satisfying the specified standards are exempt from the above tax if they produce a document certifying the use of a certain amount of biofuel. Hence, the higher is the amount of biodiesel used, the smaller is the amount of biodiesel oil consumed and the smaller are the expenses of an enterprise on paying the environmental tax (collected only in case of using diesel oil). It means that, generally, when using biofuel, fuel expenses should be calculated with an account of a particular amount of additionally consumed diesel oil:

$$Z = B_{diesel} \cdot K_{diesel} + B_{diesel} \cdot M + B_{RME} \cdot K_{RME}$$

or

$$Z = B_{diesel} \cdot (K_{diesel} + M) + B_{RME} \cdot K_{RME}, \quad (3)$$

where: B_{RME} – is the annual consumption of RME, t/year; K_{RME} – is RME cost, EUR/t.

Given the amount of diesel oil used in the last year and a relative RME amount (in percentage of the total amount of fuel used), the absolute values of the consumed diesel and biological diesel oil can be easily calculated. However, when using RME, fuel consumption increases because the calorific value of biodiesel is lower than that of diesel oil. Therefore, the above variation of fuel consumption should be taken into account in calculation.

The experimental research has demonstrated that when RME is used, fuel consumption usually increases by about 2.95%, compared with pure diesel oil consumption (in diesel locomotive engines of the type 12VFE17/24). Therefore, the above increase should be accounted for calculating annual fuel consumption. When using RME, total fuel consumption does not vary proportionally to the amount of this material but changes according to the relationship presented in Fig. 3.

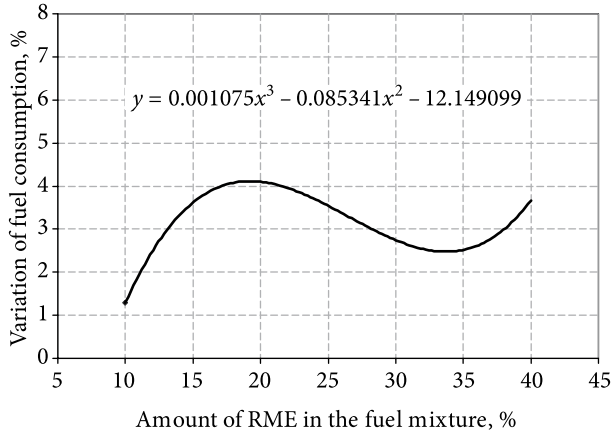

Fig. 3. The relationship between the variation of fuel consumption and the amount of RME, compared to pure diesel oil consumption

The curve in Fig. 3 shows that when 20% of RME is added, fuel consumption grows by about 4%, compared to pure diesel oil consumption while the use of 30% of RME in the mixture with diesel oil increases fuel consumption by about 2.5%. A further increase in the percentage of RME in the mixture leads to a further increase in fuel consumption.

Therefore, in further calculations, we will base ourselves on the determined fuel consumption variation. First, let us estimate the total fuel (diesel oil and RME) consumption B (t/year), taking into account its variation caused by the use of RME:

$$B = B_{diesel} \cdot (1.075 \cdot 10^{-3} \cdot B_{RME\%}^3 - 85.341 \cdot 10^{-3} \cdot B_{RME\%}^2 + 2.089374 \cdot B_{RME\%} - 12.149099), \quad (4)$$

where: $B_{RME\%}$ – is RME amount in fuel mixture, %.

To simplify the expression, let us denote the value in the brackets by α and get:

$$B = B_{diesel} \cdot \alpha. \quad (5)$$

Given that

$$B = B'_{diesel} + B_{RME}, \quad (6)$$

where: B'_{diesel} – is the amount of a petroleum oil, t/year, in the mixture with biodiesel when a general increase in fuel consumption due to differences in their calorific value is taken into account.

We can express the amount of RME in terms of diesel oil used (t/year):

$$B_{RME} = B - B'_{diesel}. \quad (7)$$

The amount of diesel oil consumed when using biodiesel B'_{diesel} and taking into account the overall fuel consumption increase due to differences in calorific values will be calculated as follows:

$$B'_{diesel} = B_{diesel} \cdot \left(\frac{\alpha}{100} + 1\right) \cdot \left(1 - \frac{B_{RME\%}}{100}\right), \quad (8)$$

while the amount of biodiesel used will be obtained as follows:

$$B_{RME} = B_{diesel} \cdot \left(\frac{\alpha}{100} + 1\right) \cdot \frac{B_{RME\%}}{100}. \quad (9)$$

Now, considering fuel consumption variation due to RME addition as well as the environmental tax and fuel cost fuel expenses, Z (EUR/year) can be calculated by the formula:

$$Z = B_{diesel} \cdot \left(1 + \frac{\alpha}{100}\right) \times \left(\left(1 - \frac{B_{RME\%}}{100}\right) \cdot \left(K_{diesel} + M\right) + \frac{B_{RME\%}}{100} \cdot K_{RME}\right)$$

or

$$Z = B_{diesel} \times \left(1 + \frac{1.075 \cdot 10^{-3} \cdot B_{RME\%}^3 - 85.341 \cdot 10^{-3} \cdot B_{RME\%}^2}{100} + \frac{2.089374 \cdot B_{RME\%} - 12.149099}{100}\right) \times \left(\left(1 - \frac{B_{RME\%}}{100}\right) \cdot \left(K_{diesel} + M\right) + \frac{B_{RME\%}}{100} \cdot K_{RME}\right). \quad (10)$$

Note: Formula (10) can be applied only if 10-40 % of RME is used. When smaller RME amounts are used, the expenses are increased insignificantly. Therefore, a simplified formula is used:

$$Z' = B_{diesel} \cdot \left(1 + \frac{0.128538 \cdot B_{RME\%}}{100}\right) \times \left(\left(1 - \frac{B_{RME\%}}{100}\right) \cdot \left(K_{dyz} + M\right) + \frac{B_{RME\%}}{100} \cdot K_{RME}\right). \quad (11)$$

A mathematical model allowing fuel costs to be determined for a locomotive engine using a certain amount of biological diesel oil was developed referring to the methods of economic effect calculation described in the present paper.

3. Conclusions

1. A methodology of calculating economic effect obtained by using biological diesel oil in the engines of traction rolling stock is presented.
2. A complex mathematical model developed for determining fuel costs depending on the amount of rapeseed oil methyl ester (RME) in diesel oil is described.

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