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Effect of Alternative Fuels on Marine Engine Performance

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Abstract

Marine transportation sector is highly dependent on fossil-based energy carriers. Decarbonization of shipping can be accomplished by implementing biobunkers into an existing maritime fuel supply chain. However, there are many compatibility issues when blending new biocomponents with their fossil-based counterparts. Thus, it is of high importance to predict the effect of fuel properties on marine engine performance, especially for new fuel blends. In the given work, possible future solutions concentrated on liquid fuels are taken into account. Under consideration are such fuels as biodiesel (FAME), hydrotreated vegetable oil (HVO), straight vegetable oil (SVO), pyrolysis oil, biocrude, and methanol. Knowledge about the behavior of new fuel in an existing engine is notably important for decision makers and fuel producers. Hence, the main goal of the present work is to create a model, which can predict the engine performance from the end-user perspective. For the purpose of modeling, only the latest research on marine fuels is taken into account. In the current approach, results from a representative measurement set-up are compared in order to create a uniform model. As a result, all the provided data are expressed in relative changes in reference to standard marine fuel – heavy fuel oil (HFO). The modeling Is performed by means of multilinear regression and accuracy of the model is relatively high, with a coefficient of determination over 0.9. The outcomes provide a prediction of final engine performance for the specified fuel blend. Knowing the final properties of fuel (such as calorific value, density, viscosity), it is attainable to estimate fuel consumption, carbon dioxide emissions and determine possible fuel compatibility issues. Moreover, the model enables estimation of carbon dioxide (CO_2) tailpipe emissions, which should be included in the whole Life Cycle Analysis (LCA) while assessing the renewability index of the fuel.

Introduction

At the moment, a lot of attention is paid to decrease greenhouse gas (GHG) emissions, which can be associated with global warming and climate change. Within different sectors, transportation is the second largest energy consumer when comparing total final energy consumption. It is responsible for 29% of shares in 2015 contributing significantly to anthropogenic CO_2 emissions [1]. Moreover, fossil-based liquid fuels dominated the transportation sector in recent decades, their share of total fuel market accounts for over 92%, at the same time biofuels represent only 2.8% [2]. Thus, there is a clear need for advanced biofuels and other alternative fuels to enter the market as soon as possible. Up-to-date EU policy expresses in a call for the market roll-out of renewable fuels, which will not only reduce emissions but also contribute to more sustainable global development, reinforcement of local economy and energy security.

In this study, the marine transport sector is considered with special attention. According to statistical data, it is consuming around 10% of the total energy used in whole transportation, while significant growth is predicted for freight shipping in coming years, especially for non-OECD countries [3]. At the moment, almost all fuels are fossil-based including heavy fuel oil (HFO) and marine diesel oil (MDO) [4]. Decarbonization of the shipping sector can be accomplished by implementing biobunkers (bunker fuels originating from bio-sources) into existing maritime infrastructure. Drop-in biofuels have a great advantage because they can be immediately introduced into the existing fuel supply chain [5]. In addition, they are considered to contribute to a decrease in CO_2 emissions in the near future. This approach may be visible in recent global actions, including many assessments of biofuels as energy carriers [6]. However, there are only a few reported demonstrations of biofuel usage in the marine engines, i.e. listed by the EU Commission [7]. Besides that, the utilization of alternative fuels in the shipping sector is still far from the commercial stage at the moment.

This research focuses on possible future fuel options for the shipping sector. Main attention is paid on liquid fuels originating from bio-feedstock. The possible alternatives are analyzed from the end-user perspective. In this paper, also an examination of the marine engine performance in terms of CO_2 emissions and fuel consumption is presented, while reference fossil fuels and alternative SVO-type fuels are tested. The analysis is done by means of mathematical modeling - in this study the black box approach was applied. Measured physical and chemical properties of tested fuels are treated as input data. The model does not explain combustion phenomena, it utilizes only input data. The main aim of this work is to predict engine performance based on final fuel properties.

Alternative Fuels for Marine Sector

European Commission (EC) lists 4 main alternative solutions for decarbonization of the shipping industry: biofuels, electricity, hydrogen, and natural gas [8]. Among all above-mentioned energy carriers, only biofuels and natural gas seem a viable option in the near future. Hydrogen is the least mature technology and is not even taken into account in the mid-term perspective. Electricity can be used for instance in inland navigation purposes, some concepts of hybrid energy technology were already assessed [9]. However, it rather does not have potential in overseas freight vessels, which are the most significant fuel consumers for shipping. Natural gas is already utilized in a liquefied form of LNG, usually in natural gas tankers. It is motivated by fuel handling and storage issues, whereas in other types of vessels extra infrastructure is required, what makes this technology less attractive. Moreover, the CO_2 emission reduction gains are not so remarkable as natural gas is still a fossil-based energy carrier. In addition, concerns about methane slip should be raised while the whole fleet and infrastructure will expand. Thus, at the moment the most promising option is foreseen in liquid drop-in fuels originating from biomass. Main advantages and drawbacks of various alternative liquid biofuels for shipping purposes are listed in Table 1.

In general, biofuels are a major possible option as a residual oil or diesel oil substitution in the marine sector. Particularly, taking into account stricter upcoming emission regulations, there may be a room and special need for new biocomponents in the market. Currently, few options can be considered. On the one hand, there are well-established products such as SVO, FAME, HVO or methanol, which can be already tested in existing engines. Nevertheless, few factors hinder the uptake of those alternatives. SVO and FAME suffer from compatibility issues related to handling, storage, and engine operational issues due to their biodegradability, cold start problems, and fouling – those liquids are not considered as drop-in fuels, meaning that their implementation requires modification of whole refueling infrastructure. The price is a limiting factor when speaking about hydrogenated fuels

TABLE 1 Main advantages and disadvantages of marine biofuels - SVO, FAME, HVO, methanol, pyrolysis oil.

Fuel	Advantages	Disadvantages
SVO	+Reduction of GHG +Improved lubrication properties +Low SO_x emission +Lower PM emissions	-Long-term storage and water separation challenges -Lower energy content of approximately 10% -Microbiological growth increased -Higher acidity and risk of damage to certain rubber materials
FAME	+Reduction of GHG +Improved lubrication properties +Possibility of blending with MDO or HFO	-Long-term storage and water separation challenges -Lower energy content of approximately 10% -Microbiological growth increased
HVO	+High quality paraffinic fuel +No blending wall, easily mixable with MDO +Commercially available	-Higher price than fossil diesel -Limited feedstock when using only vegetable oils
Methanol	+Can be produced from lignocellulosic feedstock (TRL reaches 8th level) +Feasible in dual fuel concept	-Major production from natural gas (currently) -Low flashpoint -Toxicity
Pyrolysis oil & HTL biocrude	+Potential substitute for HFO and also as a blending component (no need for retrofit is expected) +Abundant feedstock	-Not yet certified for use -Fuel stability not known completely -Relatively low TRL (5/6), first commercial plant expected after 2025

(HVO) due to the fact that the hydrogenation process adds extra costs. Methanol has also its drawbacks, the major one is directly related to the feedstock – at the moment the majority of methanol is produced from the natural gas or crude oil. On the other hand, there are other fuels worth considering such as pyrolysis oil and biocrude from hydrothermal liquefaction process (HTL). However, the technology readiness level of the two above mentioned fuels is quite low, 5 and 6 respectively, meaning that they are not ready for full commercialization yet [10].

Demonstration of Biofuel Usage in Shipping

Despite the fact that many biofuels are identified as HFO or MGO replacement, their future is still uncertain. Many commercial projects aim at the identification and testing of new biocomponents. However, the main drawbacks of biofuels are related to their economic analysis. In other words, the competitiveness of new liquid alternatives is rather low and investors are not willing to utilize new energy carriers unless new regulations come into force. The main demonstrations were done with SVO, FAME, and HVO so far. Nevertheless, each of the above-mentioned fuels has its own limitations. For HVO, which can be considered as high-quality fuel without blending wall with standard diesel, the final price turns out to be the most limiting factor. If the development of technology allows lowering the costs, then this fuel could be easily blended with marine gas oil (MGO). Successful operation of the vessel on 50% blend of MGO and hydrotreated fuel from wood industry (HVO type fuel) was reported [11]. Another fuel type is SVO, which could be in some cases price competitive but biodegradability and thermal oxidation stability issues are the major drawbacks of those low-processed liquids. Even blending with fossil fuels induces some operational problems, which were reported by marine engine manufacturers [12]. SVO due to high viscosity should be heated before feeding into the engine. Hence, in blends with MGO there is a risk of cavitation in fuel supply lines and as a result inappropriate engine operation. On the other hand, HFO operates even with higher temperatures than SVO and polymerization of liquid biofuel can occur in the elevated temperature range. In general, differences in viscosity may lead to clogging of pipes and breakage of filters. Despite above-mentioned drawbacks, some tests were performed using SVO fuels due to their price competitiveness. FAME is more refined fuel than SVO but it still contains oxygen in the molecular structure, meaning that there is a higher risk of unwanted biodegradability, lower oxidation stability, increased corrosiveness and microbiological growth in storage tanks. All those properties also promote avoidance of FAME-type fuel in marine engines. New potential biofuels such as pyrolysis oil will rather not gain significance in the market share within the next 10 years as their technology readiness level is low.

It can be concluded that shipping fuel market is dominated by fossil fuels and renewable liquids are at the early stage of utilization. In global research, there is a lot of attention paid to the properties of new fuels, their compatibility, and emissions. Nonetheless, the availability of public data is low and it is caused by high operational costs while testing new fuels. In contrary to the automotive sector, a real marine engine requires an order of magnitude higher volumes of samples – a few cubic meters for a single test. Demonstration plant, which could supply enough novel fuel for the single vessel's overseas operation, seems at the moment challenging – it was recently reported by the EU Commission [8]. It is also evident that shipping is far behind road transportation when speaking about renewables' implementation. Even aviation has tested biofuels on many commercial flights [13]. Nevertheless, recently there are also positive signals from the market and marine bio-oil compatible with HFO can be mentioned as an example [14]. After an extensive literature review, few publicly available sources were found, which investigate the impact of new liquid fuels and their properties on the existing marine engine performance. Main findings are put together below.

Sirviö et al. [15] investigate new liquid fuel blends for a medium-speed marine engine. In the study, five fuel blends are analyzed based on their physicochemical properties. The research tries to determine the suitability of novel blends in shipping transportation. Among fossil substitutes, RME and renewable naphtha are examined. Those fuels are blended with light fuel oil (LFO), marine gas oil (MGO) and kerosene. Moreover, MGO is produced from used lubricants, fuel from similar feedstock was tested in other academic research [16]. Particularly interesting is RME-naphtha blend, highly renewable fuel tested for the first time, which seems promising future alternative.

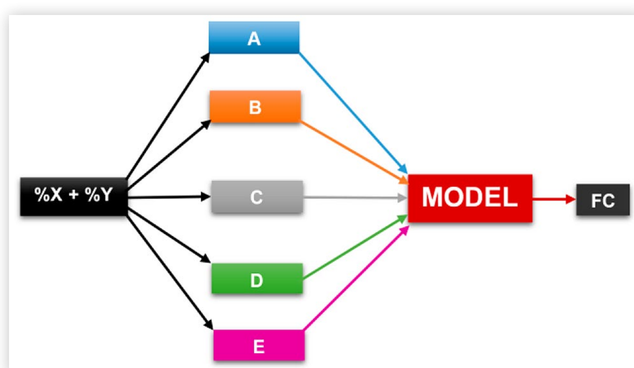
Petzold et al. [17] test 6 alternative fuels in a medium-speed marine engine. Emission measurements encompass two fossil-based fuels (HFO and MGO) and four alternatives, which are low-processed liquids SVO-type fuels (palm oil, soybean oil, sunflower oil, animal fat). Representative tests are run on a medium-speed marine engine, while CO_2 and other emissions are compared between different fuels. The LCA approach is mentioned in the publication.

Jayaram et al. [18] measure the emissions from the ferry's propulsion engine (EPA Tier 2) of 18.9 L displacement and 367 kW power. In the study, blends of soy-based methyl esters are examined in terms of PM and NO_x emissions. Moreover, the study reveals that emissions in real operation (cruising) are highly dependent on sea currents. That is why standard emission measurements according to ISO 8178 are recommended over real operational conditions.

Modeling Approach

The behavior of new fuel or fuel blend in an existing marine engine is of key importance for the shipping company or single vessel operator. While considering the implementation of new biocomponent, a crucial thing is the engine performance from the end-user perspective. It would be valuable to have a model, which can predict fuel consumption and emissions for the new blend based on its final physicochemical properties. This task can be approached in different ways. The main approach applied in this study is presented in Figure 1. Considered new fuel can be a blend of alternative and fossil-based component (i.e. FAME with MGO blend) and their concentrations are marked as X and Y, respectively. The specific mixture results in the final blend properties denoted as A, B, C, D, E, which may refer for instance to density or viscosity. Moreover, each

FIGURE 1 Structure of the problem.



blend behaves differently in the engine and it can be represented by engine performance indicator such as CO_2 emissions. The relation between final engine performance and each consecutive physicochemical property of the blend is unknown. Hence, the model should indicate empirical correlations and connect a set of properties with end-use effectiveness. Based on the model it should be possible to predict CO_2 emissions for novel fuels, of which final properties can be estimated beforehand. In turn, it is possible to calculate fuel consumption (FC), an important indicator for fleet operators.

The procedure utilized in the study is black box modeling. In principle, the black box approach requires only input data, which in that case are CO_2 emission and set of measured physicochemical properties of tested fuels. In other words, the model does not explain what is happening inside the engine (does not analyze the injection, for instance) but instead it processes all the input data. In turn, as an outcome from modeling, the correlation between CO_2 emissions and fuel properties is obtained by a selected mathematical procedure. During analysis, measured fuel properties (such as heating value, density, oxygen content, etc.) are tested. The black box methodology is supposed to indicate all the properties relevant to CO_2 emissions.

Having schematic representation of the problem, the next step involves acquiring of data necessary for modeling. For the purpose of this paper, only results from publically available external sources were used. While analyzing data from other experiments it is beneficial to express all the numerical values in relative changes referred to the standard fuel (i.e. HFO). Hence, all data necessary for modeling are collected in the form of a matrix and are in line with the following guidelines:

- Fuel properties (except elemental components such as oxygen or carbon, which are expressed in mass based percentages) are expressed in relative changes, while HFO is standard reference marine fuel
- The same applies to engine performance in terms of fuel consumption. It is expressed in relative change compared with the performance of HFO for the same engine.
- Model is supposed to show the relative change in CO_2 emissions and fuel consumption for alternative fuels (in reference to HFO).

After clarifying the structure of the problem, data collection and their preparation in the matrix form (relative values), the appropriate mathematical methodology should be selected. It was observed that properties are interrelated and their impact on engine performance cannot be treated separately. It means that all properties should be investigated at the same time. After careful consideration and initial data analysis, multilinear regression was found as the most suitable modeling technique. The multilinear regression can be described by the following equation [19]:

$$y(x) = \varnothing_1(x) \cdot \beta_1 + \cdots + \varnothing_n(x) \cdot \beta_n + \epsilon(x) \tag{1}$$

where,
y – dependent observable variable,
x – independent variable,
$\varnothing_i(x)$ – explanatory variable,
β_i – parameter corresponding to the explanatory variable,
$\epsilon(x)$ - error.

In the approach of this study, relative changes (HFO as reference fuel) of fuel properties can be treated as input data necessary for analysis. The relative change of engine performance can be treated as a single output and CO_2 emissions are used as a representative indicator. All the modeling data are put together inside a matrix utilized in a multilinear regression procedure. Taking into account all the aforementioned considerations, the previous equation can be rewritten in a form presented below:

$$\alpha = a \cdot A + b \cdot B + c \cdot C + d \cdot D + e \cdot E \tag{2}$$

where,
α - CO_2 emissions (in respect to g/kWh),
$A...E$ - fuel property value (relative change) dependent on alternative fuel concentration,
$a...e$ - parameter corresponding to each consecutive fuel property.

The target of the multilinear regression method is to estimate parameters $a...e$, which are unknown and found by the means of the least-square method [19]. Regression can be executed in OriginLAB software, where coefficients are monitored. The algorithm used to solve the problem is Levenberg-Marquardt [20]. In general, the quality of the model can be determined either by the residual analysis or cross-validation technique [21]. However, due to limited availability of data, only the residual analysis was executed. On the one hand, the accuracy of the model was checked by R-square parameter, which is a coefficient of determination. The R-square measures a percentage of the variance for a dependent variable, which can be predicted by all independent variables. For each property, also the standard error was investigated. On the other hand, significance analysis of selected properties was executed by t-test and p-value, while accepted significance threshold was 5%.

The fuel consumption is calculated based on outcomes from CO_2 emissions model:

$$FC = \alpha / z \tag{3}$$

where,
FC - fuel consumption,
α - CO_2 emissions (kg per kWh),
z - conversion factor from CO_2 emissions per kWh to CO_2 emissions per kg of fuel.

It is important to highlight that the created model predicts tailpipe CO_2 emissions, which should be included in the whole LCA in order to assess the sustainability of the novel fuel or fuel blend. When comparing different new energy carriers, also the compatibility of the fuels should be examined, what is not further reported in this paper.

Data Selected for Modeling

For modeling purposes, it is crucial to select a representative engine and its performance with the use of alternative liquids. During this study, data for modeling were acquired from other measurements found in the publically available literature.

Only one source fulfilled the criteria of the representative engine. The measurements were conducted on existing marine medium-speed engine provided by MAN. It was a one-cylinder engine with a power output of 400 kW at 750 rpm. The steady state operation under 75% of engine load was selected as a representative condition for the vessel operating at the overseas freight [17]. Specification data of the engine are shown in Table 2.

During the research 6 different fuels were tested: heavy fuel oil (HFO), marine gas oil (MGO), palm oil (PO), animal fat (AF), soybean oil (SBO) and sunflower oil (SFO). Alternatives to HFO are one fossil-based low sulfur fuel (MGO) and 4 fuels of SVO-type (PO, AF, SBO, SFO). The important properties of the examined fuels are presented in Table 3.

All input fuel properties were measured in the experiment before running a marine engine. However, the viscosity of the MGO was given in lower temperature of 40°C (instead of 50°C reported for other fuels). The Vogel equation was used to obtain the correct viscosity in the corresponding temperature:

$$\ln(v) = A + B/(T + C) \tag{4}$$

where,
v - kinematic viscosity,
A,B,C - empirical constants,
T - temperature in K.

Using empirical constants for diesel-like fuel [22], the equation can be rewritten in the form presented below:

$$\ln(v) = -2{,}384 + 574{,}351/(T - 140{,}27) \tag{5}$$

TABLE 2 Test engine specification and operational conditions (based on [17]).

Engine type	Medium-speed marine CI
Number of cylinders	1
Bore x Stroke	320 x 440 mm
Displacement volume	35.4 l
Compression ratio	16.2
Nominal power	400 kW
Selected engine's operational conditions	
Applied test load	75%
Applied test speed	750 rpm

Results from Modeling

For modeling purposes, 6 different marine fuels were analyzed. The relative changes (in reference to HFO) of main properties are presented in Table 4. Also, the relative change of engine performance in terms of CO_2 emissions is presented in the same table. Based on numerical values from Table 4, a relation between CO_2 emissions and fuel properties can be plotted – Figures 2-4.

A relation between CO_2 emissions and energy content (NCV both mass- and volume-based) is plotted in Figure 2. Calorific value is an important property influencing fuel consumption. It informs about the energy contained in a specified mass of the fuel. Generally, the higher is NCV, the lower CO_2 emissions are observed. One could expect that CO_2 emissions are directly proportional to NCV, which can be deducted from the physical relation described by the equation below:

$$\alpha = E \cdot (44/12)/(\eta \cdot C) \tag{6}$$

where,
α – CO_2 emissions,
η – brake thermal efficiency,
C – NCV,
E – carbon content.

This straightforward relation would be true if the only changing property is NCV. However, for alternative fuels also other properties are varying simultaneously. There is no clear trend in Figure 2. It confirms the hypothesis that fuel properties are interrelated and their effect on engine performance cannot be examined separately. The impact of mass-based NCV is screened by other properties, i.e. density or oxygen content. Even though the SVO-type fuels have lower calorific value, the tailpipe CO_2 emissions are lower when comparing with HFO.

Density is a physical property, which determines the mass of the fuel per specific volume unit. It affects the mass of the injected fuel, especially when using standard engine control unit (ECU) calibration, not optimized for alternative fuel. In general, the higher the density, the more CO_2 is emitted to the atmosphere while applying the same engine operational conditions – it is presented in Figure 3. In that respect, MGO with the lowest density among all tested fuels exhibits the lowest CO_2 tailpipe emissions.

TABLE 3 Tested marine fuels, their properties and measured engine performance (based on [17]).

	Fuel Properties						
	Viscosity @50C	Density @15C	NCV	O2	Carbon	NCV vol	CO_2 emissions
FUEL	mm2/s	kg/m3	MJ/kg	% m/m	% m/m	MJ/l	g/kWh
HFO	719,0	982,00	40,44	0,00	86,94	39,71	679
MGO	2,1	838,00	42,97	0,00	87,08	36,01	639
PO	29,0	916,00	37,14	11,50	77,30	34,02	652
AF	31,0	914,00	37,29	11,60	77,00	34,08	651
SBO	23,0	923,00	37,26	10,50	78,10	34,39	662
SFO	23,0	924,00	37,27	10,50	78,30	34,44	669

TABLE 4 Final modeling matrix necessary for the multilinear regression procedure.

	Fuel Properties						
	Viscosity @50C	Density @15C	NCV	O2	Carbon	NCV vol	CO_2 emissions
FUEL	% CHANGE						% CHANGE
HFO	0,0	0,00	0,00	0,00	86,94	0,00	0,00
MGO	-99,7	-14,66	6,26	0,00	87,08	-9,32	-5,89
PO	-96,0	-6,72	-8,14	11,50	77,30	-14,31	-3,98
AF	-95,7	-6,92	-7,77	11,60	77,00	-14,16	-4,12
SBO	-96,8	-6,01	-7,84	10,50	78,10	-13,38	-2,50
SFO	-96,8	-5,91	-7,83	10,50	78,30	-13,28	-1,47

FIGURE 2 Relation between CO_2 emissions and fuel's energy content (NCV mass- and volume-based).

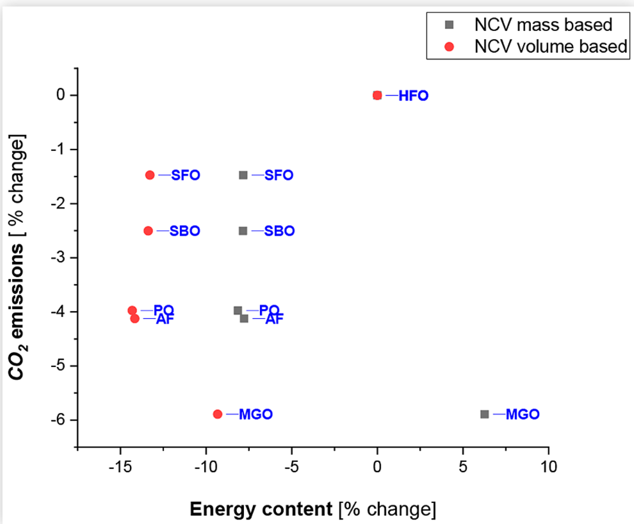


FIGURE 3 Relation between CO_2 emissions and fuel's density.

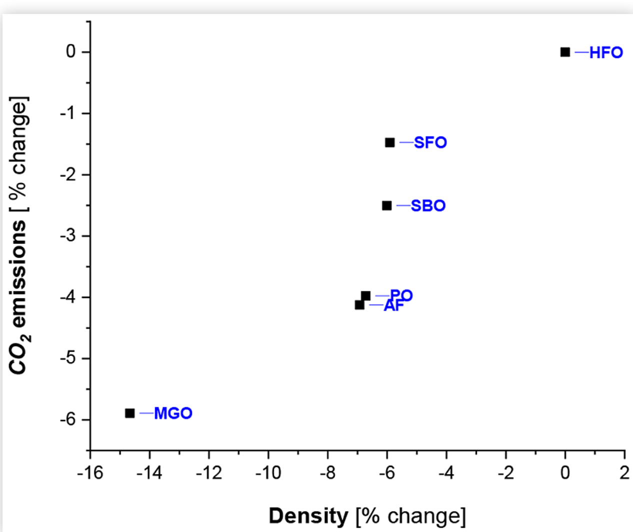
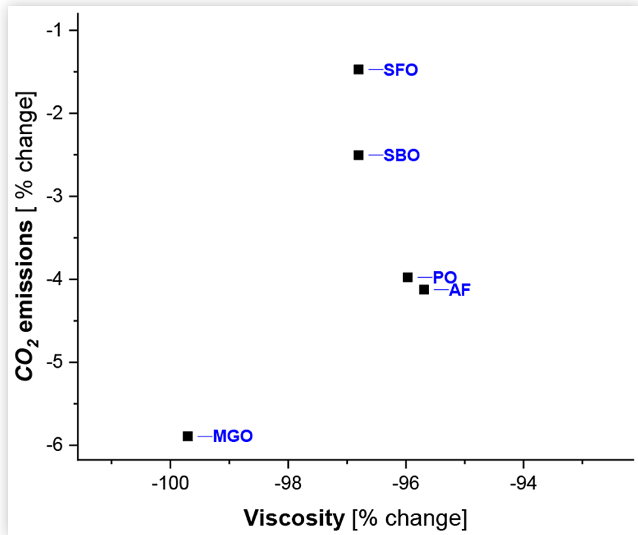


FIGURE 4 Relation between CO_2 emissions and fuel's viscosity.



All alternatives and MGO are characterized by significantly lower viscosity than HFO. There is a huge variation in viscosity values and relative change can reach over 90% – this behavior can be observed in Figure 4. Moreover, MGO and SVO type fuels differ with the viscosity, too. When it comes to the viscosity, the explanation of its effect on emissions is not so obvious as in the case of NCV and density. Viscosity as physical property is related to droplet size and vapor formation. Fuels with lower viscosity are characterized by better mixing with air in the combustion chamber improving the combustion process. So intuitively one could expect slightly lower CO_2 emission for low viscosity fuels - the trend can be observed in Figure 4.

In the initial stage of modeling, the properties were analyzed separately. Physical considerations are valid for the special case when only one fuel property changes. However, it does not reflect real-world conditions, where the whole set of fuel properties changes when switching fuel type. In practice, it means that properties are interrelated and cannot be changed freely. For instance, higher content of oxygen is usually followed by the lower calorific value of the fuel. That is why all significant properties should be analyzed simultaneously and it was accomplished by multilinear regression method. All properties listed in Table 4 were tested and fitting quality in each case was examined. After different combinations of input parameters, the most suitable model with the highest accuracy was selected – the corresponding equation can be presented in the following form:

$$\alpha = -0.19 \cdot A + 2.09 \cdot B + 0.97 \cdot C \quad (7)$$

where,
α – CO_2 emissions,
A – viscosity,
B – density,
C – NCV mass.

According to the final model, there are three most significant properties affecting CO_2 emissions in the medium speed marine engine: NCV mass-based, density and viscosity. Based on the outcome from the multilinear regression method and black box approach, it is possible to predict CO_2 emissions change in reference to standard HFO fuel. The only necessary parameters, which should be known are above mentioned three properties (or rather their relative changes to HFO).

For every model, there should be a specified applicability range. Generally, the model can be applied to SVO- and FAME-type fuels in their full concentration meaning from 0-100% in their blends with HFO or with MDO. However, it is important to remark that reference fuel should be always HFO-type according to ISO 8217 standard. Also, the model is valid for medium speed marine engine. It is not an exclusive model, meaning that can be further extended while testing additional properties, i.e. cetane number. Such a relation has been observed in the previous study regarding light-duty engines (with significantly higher availability of data), where besides NCV, viscosity, and density, also cetane number turned out to be significant for CO_2 emissions [23].

The ignition quality, usually represented by cetane number (CN), is an important fuel property, which certainly affects engine performance. Fuels with higher cetane number are more reactive, and it translates to shorter ignition delay. That in turn, leads to earlier heat release rate, higher pressure, more work extracted from end-gases and finally increased thermal efficiency. Following this reasoning, the dependency of CO_2 emissions from thermal efficiency is explained by Equation 6. End-user can observe it in terms of decreased CO_2 emissions while using higher CN fuel. Due to the lack of ignition characteristic of tested alternatives in this study, the reactivity of the fuel is not explicitly included in the model presented by Equation 7. However, the information about ignition quality is partially covered by other properties – correlation resulting from black box modeling approach exhibits high accuracy and is a good demonstration of CO_2 emission's prediction based on measured fuel properties.

The quality of the model was assessed based on the residual analysis. The coefficient of determination is high (R-square=0.985 and adjusted R-square=0.975) meaning that fitting has high accuracy. All the coefficients corresponding to input property parameters are significant according to established criteria – t-test for significance is passed (p-value below 5%). The standard error of coefficients is also below 20%. Coefficients obtained from multilinear regression with standard error and p-value can be found in Table 5. Moreover, absolute errors were also analyzed to check the result of fitting.

Based on the results from CO_2 emission model, the changes in fuel consumption were calculated. MGO has the lowest fuel consumption, relative change with reference to HFO reaches a value of -11.5%. For SVO-type fuels, the relative FC is increased in the range of 3.7-7.9% when comparing to HFO, whereas palm oil has the lowest increase and sunflower oil the highest one.

All the results regarding CO_2 emissions are presented in Table 6. The predicted values for CO_2 emissions are in line with experimental data. Resulting from black box modeling an absolute error is very low in all cases, what can be clearly seen in Figure 5. Only for SBO and SFO there are minor deviations.

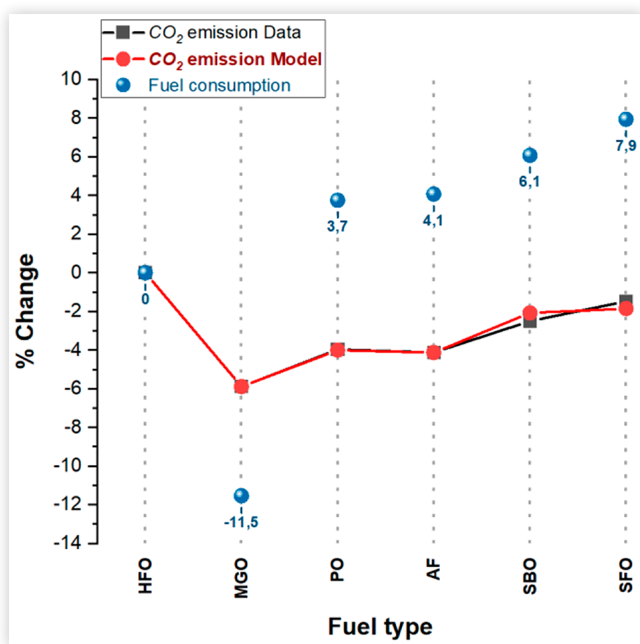
TABLE 5 Obtained coefficients, their significance and standard error.

	Coefficient	Standard Error	T-value	P-value
Viscosity	-0,187	0,036	-5,25	1,35E-02
Density	2,087	0,317	6,58	7,15E-03
NCV mass	0,972	0,179	5,45	1,22E-02

TABLE 6 Comparison of model results with measured values.

CO_2 emissions [% change]			
Fuel	**Data**	**Model**	**Absolut error**
HFO	**0,00**	**0,00**	**0,00**
MGO	**-5,89**	**-5,89**	**0,00**
PO	**-3,98**	**-4,01**	**0,03**
AF	**-4,12**	**-4,13**	**0,01**
SBO	**-2,50**	**-2,08**	**0,43**
SFO	**-1,47**	**-1,86**	**0,38**

FIGURE 5 CO_2 emissions and FC – conformity of the model with measured values.



Conclusion

New emission regulations and targets of GHG reductions foster implementation of biocomponents in a maritime fuel supply chain. Thus, it is of high importance to investigate alternative fuel options for near and more distant future. At the moment there are reported only a few demonstrations of liquid biofuels as substitutes for fossil MGO and HFO. There is also a visible lack of knowledge, which fuels will gain significance in the sector in the coming years. Those facts in combination with the lack of clear international regulations delayed the introduction of renewables in the shipping sector in the past decades. However, the situation has changed in the last few years, as an example the global sulfur cap of 0.5% can be mentioned. New regulations on the international level are supposed to change that situation and speed up the market roll-out of new biocomponents. Some successful commercial-scale demonstrations are proving a fact that in 2030 liquid renewable fuels can be visible in the marine fuel mix. While testing new components it is important to check their compatibility with current infrastructure. The most wanted are drop-in fuels because no modifications in fuel handling, distribution and storage are required. When speaking about in-engine performance, compatibility with pumps, fuel supply lines, injectors, and engine blocks should be prioritized. Besides that, fuel consumption and emissions are crucial for fleet operators. That is why the estimation of those indicators would be very helpful in future considerations. The current work tries to address the above-mentioned specific need by means of mathematical modeling.

Key findings from modeling work are as follows:

1. While considering new fuel blends from the end-user point of view, it is of high interest to estimate the performance of an existing marine engine. Black box modeling and multilinear regression can be applied in predicting marine engine performance based on fuel property characteristic.
2. The model demonstrated in this paper has good accuracy, while the coefficient of determination is over 0.98 meaning the good quality of fitting. All parameters passed t-test and reached a satisfactory significance level (p-value below 5%). It means that fitting for the given conditions can be used in the estimation of performance for SVO-type fuels and possibly also FAME biodiesel blends. Even though the monitored parameters of model quality are high, the results should be treated with caution due to the limited availability of input data used in multilinear regression.
3. Three properties turn out to be the most significant for CO_2 emissions. Modeling reveals that density, heating value (NCV) and viscosity play a key role. In turn, those properties have a high impact on fuel consumption.
4. CO_2 emissions are highly dependent on the density of the biobunker. A straightforward correlation can be observed: the lower density is, the lower CO_2 emissions are.
5. Within all tested fuels MGO has the highest energy content combined with the lowest density and viscosity. It results in lowest tailpipe CO_2 emissions and in turn also the lowest fuel consumption.
6. For SVO-type fuels, tailpipe CO_2 emissions are slightly lower than for reference fuel (HFO). However, fuel consumption is increased but not more than 8% in all cases.
7. The methodology demonstrated in this paper shows the potential to be applied to a larger scale when investigating new fuel blends for marine engine purposes.

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Abbreviations

AF - Animal Fat
CI - Compression Ignition
CN - Cetane Number
CO_2 - Carbon Dioxide
EC - European Commission
ECU - Engine Control Unit
EPA - Environmental Protection Agency
FAME - Fatty Acid Methyl Ester
FC - Fuel Consumption
GHG - Greenhouse Gas
HFO - Heavy Fuel Oil
HTL - Hydrothermal Liquefaction
HVO - Hydrotreated Vegetable Oil
LCA - Life Cycle Assessment
LFO - Light Fuel Oil
LNG - Liquefied Natural Gas
MDO - Marine Diesel Oil
MGO - Marine Gas Oil
NCV - Net Calorific Value
NO_x - Nitrogen Oxide
PM - Particulate Matter
PO - Palm Oil
RME - - Rapeseed Methyl Ester
SBO - Soybean Oil
SFO - Sunflower Oil
SO_x - Sulfur Oxide
SVO - Straight Vegetable Oil
TRL - Technology Readiness Level

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