2019-01-2308 Published 19 Dec 2019

Modeling the Impact of Alternative Fuel Properties on Light Vehicle Engine Performance and Greenhouse Gases Emissions

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Citation: Kroyan, Y., Wojcieszyk, M., Larmi, M., Kaario, O. et al., "Modeling the Impact of Alternative Fuel Properties on Light Vehicle Engine Performance and Greenhouse Gases Emissions," SAE Technical Paper 2019-01-2308, 2019, doi:10.4271/2019-01-2308.

Abstract

The present-day transport sector needs sustainable energy solutions. Substitution of fossil-fuels with fuels produced from biomass is one of the most relevant solutions for the sector. Nevertheless, bringing biofuels into the market is associated with many challenges that policy-makers, feedstock suppliers, fuel producers, and engine manufacturers need to overcome.

The main objective of this research is an investigation of the impact of alternative fuel properties on light vehicle engine performance and greenhouse gases (GHG). The purpose of the present study is to provide decision-makers with tools that will accelerate the implementation of biofuels into the market. As a result, two models were developed, that represent the impact of fuel properties on engine performance in a uniform and reliable way but also with very high accuracy (coefficients of determination over 0.95) and from the end-user point of view. The inputs of the model are represented by fuel properties, whereas output by fuel consumption (FC). The parameters are represented as percentage changes relative to standard fossil fuel, which is gasoline for spark ignition (SI) engines and diesel for compression ignition (CI) engines. The methodology is based on data-driven black-box modeling (input-output relation). The multilinear regression was performed using the data from driving cycles such as the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) and New European Driving Conditions (NEDC). The FC of SI engines proved to be dependent on mass-based Net Calorific Value (NCV), Research Octane Number (RON), oxygen content and density. However, CI engines performance is affected by NCV, density and Cetane Number (CN). The models were additionally subject to quantitative analysis, where input parameters in both models turned out to be statistically significant (p-value below 5%). Additionally, the validation stage consisted of residual analysis confirmed the accuracy of both models. The GHG part estimates the change of carbon dioxide emissions based on fuel consumption, which represents the tailpipe emissions.

Introduction

The transport sector is responsible for 29% [1] of the Total Final Energy Consumption (TFEC) in the world, whereas in Europe it accounts for about 33% [2]. When comparing the transport sector's CO_2 emissions from 1990 to 2015, emissions are almost two times higher and the growth continues with upcoming years. Therefore, it is of high interest to reduce the use of fossil fuels and mitigate the GHG effect.

In order to achieve climate targets, research and development that supports the commercialization of sustainable energy solutions become an essential part. Fuels produced from renewable sources such as biomass, catch progressively more attention, as they represent great potential in transportation-greening processes. Their production capacities and use are growing strongly from year to year. Biofuels can be used directly in engines and existing refueling systems. However, in some cases, higher concentrations require some adjustments. Many advanced biofuels are so-called drop-in fuels, which means that they can be freely blended with standard fossil fuel (in the full scale of concentration) and used in existing engines and refueling systems without any adjustments. The most promising biofuels represent not only strong environmental benefits, but they have also better fuel properties than standard fossil-based ones. A good example is ethanol that has a higher octane number (ON) than gasoline and Hydrotreated Vegetable Oil (HVO) that has a higher cetane number (CN) than diesel fuel. Thus, biofuels are a very promising solution for the current transportation sector, but their implementation into the market is associated with some challenges. Knowledge about the impact of alternative fuels on engine performance and GHG emissions is a very important topic for the commercialization of biofuels. It is especially significant for prediction of how new fuels will affect existing engines. Additionally, having a tool that can predict those impacts, would highly contribute to the accelerated implementation of renewable fuels.

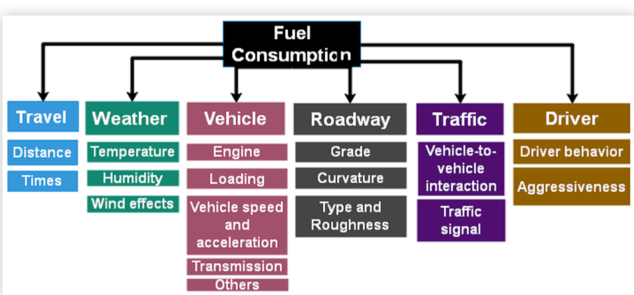
The engine performance of light vehicles could be represented by Fuel Consumption (FC). There are many parameters influencing FC, and they could be related to the vehicle, weather, roadway, driver, traffic or travel (Figure 1).

Structure from Figure 1 was published by Zhou, M., Jin, H., & Wang, W in *"A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing"* [3]. That article represents many models estimating fuel consumption dependency on factors listed in Figure 1. Nevertheless, that structure diagram does not include a very important parameter that nowadays plays a growing role - the alternative fuel. This research is focused on the use of alternative fuels in current spark-ignition (SI) and compression-ignition (CI) engines without modifications. The main task is the development of models (one for SI and one for CI) representing the impact of alternative fuel properties on fuel consumption and carbon dioxide emissions. Similar approaches to the one presented in the current paper were studied in the Master Theses by Y. Kroyan [4] and M. Wojcieszyk [5].

Methodology

Present studies are focusing on a very challenging and fundamental problem. Thus, careful selection of proper methodology is an essential part of this research. The methodology consists of four main parts, the first one is related to literature study, where all necessary data and knowledge are collected. Subsequently, the next stage focuses on the selection of approach. Modeling the impact of alternative fuel properties on engine performance could be done by the steady-state approach, driving cycles or through analyzing combustion characteristics. The third step is related to the development of modeling procedure and validation techniques. In the final part, modeling is performed, and obtained models are analyzed and validated. The methodology used in this research was designed from the very beginning to meet certain criteria. **The first criterion concerned the universality of the final model**. The model should not be dependent on engine parameters, such as displacement, injection technique, number of cylinders, valves or compression ratio. Engine operation conditions (engine load and speed) should not affect as well. In that respect, solely type of engine, whether it is Otto (spark ignition) or Diesel (compression ignition) engine should affect the model.

FIGURE 1 Classification of factors affecting vehicle fuel consumption. Created based on [3].



The second criterion is that the model should represent the real impact, from the end-user perspective. Those two important criterions shaped the entire methodology. In order to take a closer look at the problem of this studies, it is good to think about the whole chain of involved relations. Blending standard fossil-based fuel (gasoline or diesel) with some alternative fuel, result in different values of final fuel (blend of fuels) properties. Subsequently, using that blend in an engine would result in different values of engine performance and GHG emissions. The relations are presented in Figure 2. The fuel X could be treated as a standard fossil-based fuel, where fuel Y as an alternative one (renewable fuel), fuel blend properties are marked as A,B,C and D. When analyzing different publications, it has been noticed that tested fuel blends properties were measured or specified. Additionally, those fuels were tested in engines, and the fuel performance outputs were also reported. Thus, purple lines describe information that was specified and known. However, how different fuel properties affect engine performance indicators is unknown and this research focuses on modeling that relation. Engine performance indicator was chosen to be represented by fuel consumption. While analyzing the relationships shown in Figure 2, one can realize that the nature of the problem could be represented by multiple inputs (represented by fuel properties) and a single output (characterized by fuel consumption).

Driving cycles were selected as a general approach. Thus, input and output parameters are coming from driving cycles such as the New European Driving Cycle (NEDC) or Worldwide harmonized Light Vehicle Test Procedure (WLTP). Driving cycles reflect driving in busy European roads and cities, thus the outputs of fuel consumption for different blends are very reliable. Figure 3 represents velocity profiles for NEDC and WLTP.

The WLTP cycle is newer and more accurate cycle than NEDC. Nevertheless, NEDC is much better according to methodology criterions than outcomes from steady state measurements.

In NEDC the total traveled distance is 11.03 km which takes 1180 s having an average speed of 33.6 km/h. Whereas, the distance of WLTP is 23.27 km, traveled during the 1800 s with an average speed of 46.5 km/h [6]. Important parameters of NEDC and WLTP are listed in Table 1.

The outputs from driving cycles help to meet both the first and the second criterion. Furthermore, to make the data from different sources comparable and reduce the impact of engine parameters on results, it was decided to represent both input and output parameters as percentage changes relative to standard fossil-based fuel.

FIGURE 2 Structure of the modeling problem.

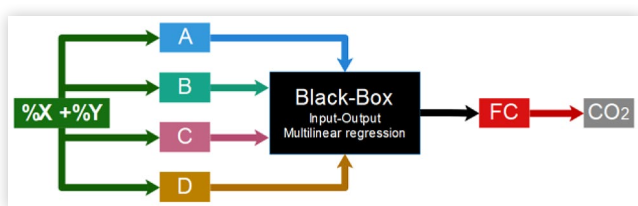


FIGURE 3 Velocity profiles of NEDC and WLTP [4].

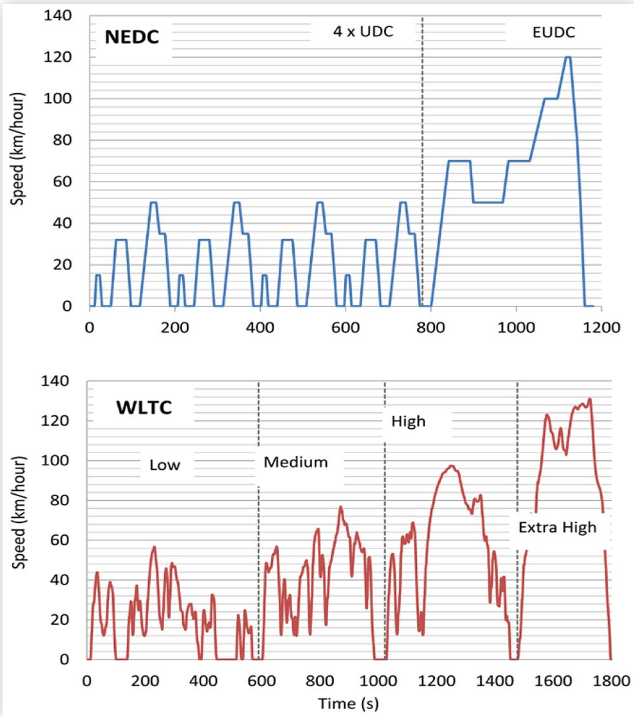


TABLE 1 Parameters of NEDC and WLTP [6].

Parameters	NEDC	WLTP
duration (s)	1180	1800
distance (km)	11.03	23.27
average speed (km/h)	33.6	46.5
maximum speed (km/h)	120.0	131.3
stop duration (%)	23.7	12.6
constant driving (%)	40.3	3.7
acceleration (%)	20.9	43.8
deceleration (%)	13.1	39.9
average positive acceleration (m/s^2)	0.39	0.41
maximum positive acceleration (m/s^2)	1.04	1.67
average positive “speed·acceleration” (m^2/s^3)	1.04	1.99
maximum positive “speed·acceleration” (m^2/s^3)	9.22	21.01
average deceleration (m/s^2)	-0.82	-0.45
minimum deceleration (m/s^2)	-1.39	-1.50

The next step in methodology is related to fuel properties. Selection of the most relevant ones is a part of the modeling procedure. Fuel properties affecting engine performance are slightly different in the case of SI and CI engines. In general heating value and density affect the duration of fuel injection. Ignition characteristics and quality are affected by octane number, octane index, cetane number, cetane index, auto-ignition temperature, and flammability limits. Combustion characteristics are influenced by the heat of vaporization, vapor pressure, viscosity, volatility, density, and oxygen content. Operational aspects are strongly affected by existent gum content, cloud point, Cold Filter Plugging Point (CFPP), lubricity, density, viscosity, and freezing point. Exhaust emissions and fouling are dependent on existent gum, aromatics and sulfur contents, additionally carbon residue, ash, and total contaminants. Finally, safety, storage, and refueling are influenced by flash point, corrosiveness, toxicity, oxidation stability and compatibility with materials.

Selection of Fuel Properties

The aforementioned properties of fuels constitute quite a large group, from which one should choose those that have the greatest impact on engine performance. Consequently, for SI engines octane number, the heat of vaporization (or Reid Vapor Pressure - RVP), auto-ignition temperature, oxygen content, net calorific value, density, and carbon content are properties that have the strongest impact on combustion processes. Whereas, for CI engines, cetane number, viscosity, density oxygen content, net calorific value and carbon content represent the highest impact on engine performance.

The final state of input fuel properties is determined in the following manner:

1. For analysis, there will be taken into account only **measured** fuel properties at each data source. Using simulated fuel properties instead of measured ones leads towards high errors of the model.
2. The final state of inputs is decided during the modeling procedure, where based on the **quantitative analysis** (statistical significance tests) final fuel properties are selected.

According to previous considerations, the study case consists of multiple input parameters (fuel properties) and one output parameter (fuel consumption). In this research, only experimental data were used for modeling purposes. Thus, the data-driven black-box modeling based on the input-output relation of experimental data was performed. The selected function is linear, where in this case the stepwise multi-linear regression was chosen for modeling procedure [7]. The following equation is adjusted to the data from driving cycles in order to obtain the impact of fuel properties on engine performance:

$$y(x) = \varnothing_1(x) \cdot \beta_1 + \cdots + \varnothing_n(x) \cdot \beta_n + \in(x)$$

where,
y - dependent variable,
x - independent variable,
$\o_i(x)$ - explanatory variable,
β_i - parameter of the explanatory variable,
$\in(x)$ - error.

The iteration procedure is done by the least-square method using Levenberg-Marquardt Algorithm (LMA) [8]. The accuracy of the model is measured by R-square (also called the coefficient of determination -COD) and standard error. The r-square, in this case, is a percentage of the variance in the dependent variable (fuel consumption) that could be predicted by all independent variables (fuel properties). Statistical significance analysis of chosen properties are performed by t-tests and analyzing p-value for a t-test while applying the significance level of 5%. Subsequently, the validation process is done by residual analysis. The CO_2 emissions are calculated based on outcomes from fuel consumption model.

$$C = FC \cdot \rho \cdot z \cdot \frac{44}{12}$$

where
C - CO_2 emissions,
FC - fuel consumption,
ρ - density of the fuel,
z - mass-based carbon content in the fuel blend.

The last factor of 44/12 is a molar mass-based ratio of carbon dioxide and carbon. Data analysis, modeling and results presentation were performed using OriginLAB software.

Chosen Sources of Data

The methodology requires modeling based on driving cycles data, thus all chosen sources have outcomes from experimental tests. Table 2 contains collective information about selected sources, test SI engine characteristics, applied driving cycles and tested fuels Two SAE publications ([9] and [10]) tested gasoline blends with alcohols (ethanol (E), n-butanol (nBu), and iso-butanol (iBu)) under NEDC. Whereas the third source [11] focuses on ethanol and methanol blends with gasoline under the WLTP cycle. The numbers next to the fuels' symbols indicate their concentration.

Sources chosen for CI modeling purposes are summarized in Table 3. In all publications, NEDC was chosen as a driving cycle. Fuels such as regular biodiesel (marked as B), biodiesel produced with the use of enzymes (marked as BE) hydrotreated vegetable oil (marked as H), Gas To Liquid (marked as GTL), diesel fuel produced from hydrocracking process (marked as HCK), and the same fuel enriched with cetane improver (marked as HCKcni).

Results and Discussion

This chapter combines results for both SI and CI modeling. Selection of input properties in each part was driven mainly be real measured values, that were specified in a respective source. The modeling was performed based on experimental values (taken from the source), not assumed nor simulated.

SI Engine Performance

In the case of SI fuels, RON, RVP, NCV, density, oxygen, and carbon content were measured and given by each source, thus they were selected to further analysis. Carbon content is used to calculate carbon dioxide emissions based on the FC model.

Modeling procedure was performed using relative to standard gasoline changes of alternative fuel properties and resulting fuel consumption.

Based on the data specified in table 5, the impact of each property on fuel consumption was presented in the following figures.

It could be noticed in Figure 4 that with the growth of RON fuel consumption increases as well. This effect proves

TABLE 2 Information about used sources: engine characteristics, applied driving cycles and tested fuels for spark-ignition engines (N.S. means Not Specified).

Information about the source	**Ref.**	**[9]**	**[10]**	**[11]**
	Publisher	**SAE**	**SAE**	**IEEE**
	Year	**2016**	**2012**	**2016**
	Involved institutions	Indian Oil Corp. Ltd.	Mahle Powertrain Ltd.	Nanjing University College of Energy and Power Engineering
			BP Powertrain Ltd.	Research Academy of Environmental Sciences
Test engine characteristics	Model or year	475SI	14 DOHC 16V	2015
	Euro standard	Euro III	Euro IV	Euro IV
	Injection method	MPFI	DI	MPFI
	Max. Torque [Nm/rpm]	102/2600	280/1700	N.S.
	Nr. Of cylinders	4	4	N.S.
	Nr. Of valves	16	16	N.S.
	Bore [mm]	75	82.5	N.S.
	Stroke [mm]	67.5	92.8	N.S.
Driving cycle		NEDC	NEDC	WLTP
Tested fuels		nBu5	95RON gasoline	E10
		nBu10	102RON gasoline	M15
		nBu20	E10	
			E22	
			E85	
			iBu16	
			iBu68	

TABLE 3 Information about used sources: engine characteristics, applied driving cycles and tested fuels for compression-ignition engines (N.S. means Not Specified).

Information about the journal publication	Ref.	[12]	[13]	[14]	[15]
	Publisher	SAE	ASCE	SAE	IEA AMF
	Year	2013	2014	2015	2015
	Involved institutions	Politecnico di Torino	University of Castilla-La Mancha	Istituto Motori CNR	Danish Technological Institute
		General Motors		ENI SpA	
		Universitá di Perugia	Universidad de Antioquia (UdeA)	ENI Div. R&M	University of Rostock
Test engine characteristics	Model or year	N.S.	Nissan Qashqai	N.S.	VW Passat
	Euro standard	Euro 5	Euro 5	Euro 5	Euro 6
	Injection method	CRDI	CRDI	CRDI	CRDI
	Max. Torque [Nm/rpm]	230/2250	323/2000	380/2000	320 / 2000
	Nr. Of cylinders	4	4	4	4
	Nr. Of valves	16	16	16	16
	Bore [mm]	70	84	83	81
	Stroke [mm]	82	90	90	96
Driving cycle		NEDC	NEDC	NEDC	NEDC
Tested fuels		B30	B100	HCK100	BE100
		H30	GTL100	HCK85H 15	B100
			H100	HCK70H 30	H100
				HCKcni100	

TABLE 4 Data regarding tested fuels, their properties and measured engine performance (based on sources).

	Fuel Properties							
	RON	RVP	NCV vol	NCV mass	Density	O2	C	FC
FUEL		kPa	MJ/L	MJ/kg	kg/m3	%m/m	%m/m	L/100km
Gas.	91.0	55.7	32.9	44.4	741.7	0.00	84.3	6.33
nBu5	91.2	53.3	33.0	44.0	750.0	1.08	83.3	6.36
nBu10	91.5	41.7	32.7	43.6	751.3	2.16	82.4	6.48
nBu20	91.8	38.8	32.4	42.7	758.5	4.33	80.4	6.52
Gas.	95.0	48.0	32.0	43.2	740.0	0.10	86.6	8.81
E10	99.0	52.0	31.1	41.4	750.0	4.00	82.7	9.19
E22	102.0	53.0	29.6	39.4	750.0	8.10	78.5	9.49
E85	106.0	39.5	23.1	29.6	780.0	30.10	56.9	12.88
iBu16	98.0	43.0	31.1	41.5	750.0	5.30	82.9	8.99
IBU68	104.0	35.0	28.8	36.9	780.0	22.50	73.1	9.87
Gas.	96.2	53.4	31.5	43.5	724.8	0.00	85.9	8.69
E10	93.3	54.6	30.4	41.7	729.8	3.85	82.4	9.26
M15	103.0	69.4	30.2	39.8	759.3	7.97	79.1	9.80

that the impact of RON on fuel consumption is not big, and the effect is mainly disturbed by other properties such as the calorific content. The Impact of RON on fuel consumption, in general, has reverse effect than the one presented in Figure 4 (with the growth of RON fuel consumption decreases) and it could be observed in the fuels having similar calorific content. Additionally, using high octane number fuels in engines tuned to take advantage of octane benefit, this relation could be even more apparent.

In the case of RVP, based on the data from table 5, it is difficult to observe a clear trend.

The next property is mass-based NCV. In both volume and mass-based cases it could be clearly observed that the growth of NCV results in lower fuel consumption, and the relation is linear.

Subsequently, with the growth of density, fuel consumption increases. Unfortunately, similarly to the case of RON, this result is most probably affected by NCV. Alcohols have lower net calorific value than gasoline, which is associated with higher fuel consumption. Nevertheless, alcohols have a higher density than gasoline, which increases the calorific content per volume of fuel and in a result, the increase of

TABLE 5 Final modeling matrix for SI part.

	Fuel Properties						
	RON	RVP	NCV vol	NCV mass	Density	O2	FC
FUEL	% CHANGE						% CHANGE
Gas.	0.0	0.0	0.0	0.0	0.0	0.00	0.00
nBu5	0.2	-4.3	0.2	-0.9	1.1	1.08	0.60
nBu10	0.5	-25.1	-0.6	-1.9	1.3	2.16	2.44
nBu20	0.9	-30.3	-1.6	-3.8	2.3	4.33	3.12
Gas.	0.0	0.0	0.0	0.0	0.0	0.10	0.00
E10	4.2	8.3	-2.9	-4.2	1.4	4.00	4.36
E22	7.4	10.4	-7.6	-8.8	1.4	8.10	7.76
E85	11.6	-17.7	-27.8	-31.5	5.4	30.10	46.26
iBu16	3.2	-10.4	-2.6	-3.9	1.4	5.30	2.09
iBu68	9.5	-27.1	-10.0	-14.6	5.4	22.50	12.08
Gas.	0.0	0.0	0.0	0.0	0.0	0.00	0.00
E10	-3.0	2.2	-3.5	-4.1	0.7	3.85	6.57
M15	7.1	30.0	-4.2	-8.5	4.8	7.97	12.85

FIGURE 4 The impact of RON on fuel consumption.

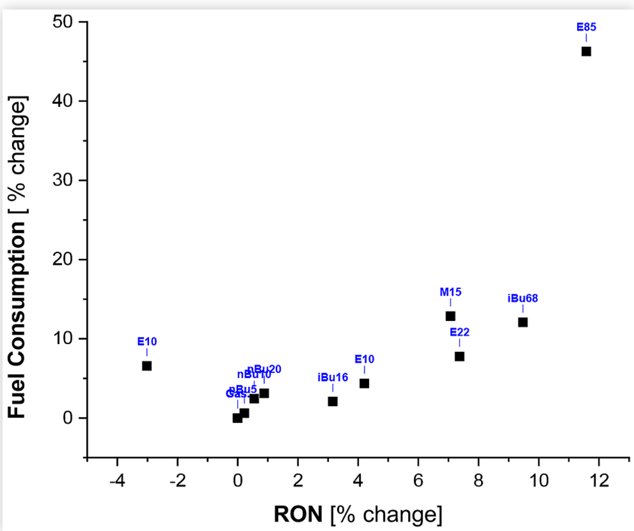
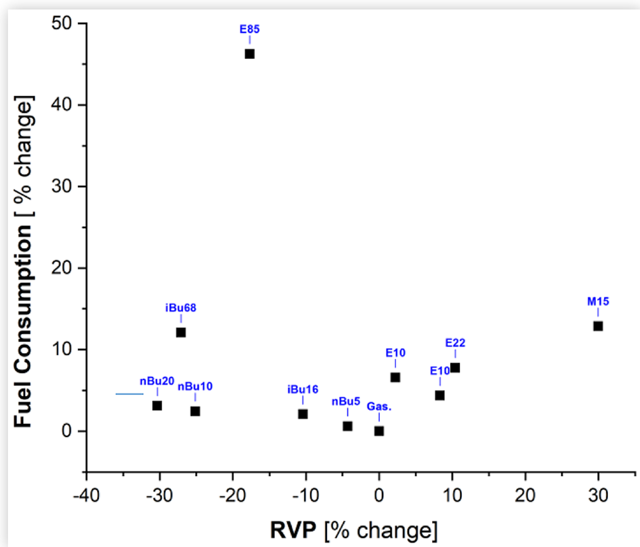


FIGURE 5 The impact of RVP on fuel consumption.



density should slightly reduce fuel consumption. It is worth mentioning that density plays also other important roles in the engine, such as influence on injection, mixing and combustion process. From the fuel supply systems perspective, density is also an important factor.

The growth of oxygen content in the fuel results in increased fuel consumption. This is a completely logical outcome and the trend is linear as it should be in the real case.

The final properties selected during modeling procedure are RON, density, NCV volume based and oxygen content. Those properties affect the most fuel consumption and pass the significance level of the p-value.

The Coefficient Of Determination (R-Square) is equal to 0.99123 whereas adjusted R-Square 0.9883. Those values are high and prove a good accuracy of the model.

The final model could be presented in the following form:

$$\alpha = -0.47 \cdot A + 2.75 \cdot B - 2.39 \cdot C - 1.0 \cdot D$$

Where,
α - fuel consumption (FC),
A - RON,
B - Density,
C - NCV volume based (NCVvol),
D - Oxygen content (O2),

All units are represented as a percentage changes relative to standard gasoline. Figure 10 represents the compatibility of the created model with measured values.

It could be seen that there is excellent coverage between data and model. The average error is just 0.82 of % change (Table 7).

CI Engine Performance

In the case of Compression Ignition fuels, density, viscosity, cetane number, NCV, and oxygen content were selected for

FIGURE 6 The impact of volume-based NCV on fuel consumption (SI case).

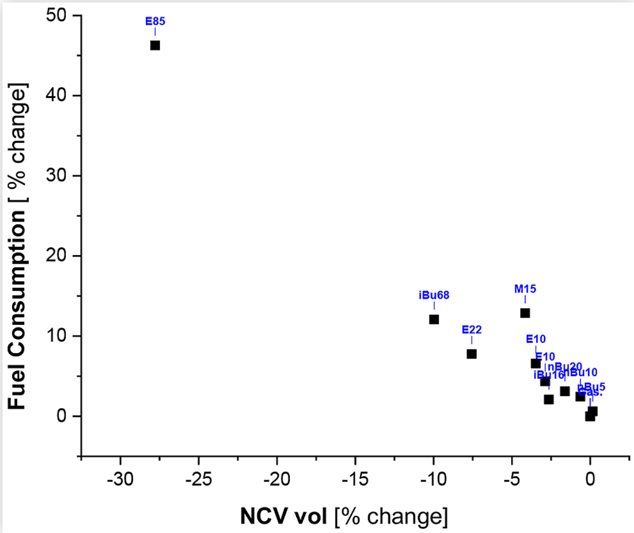
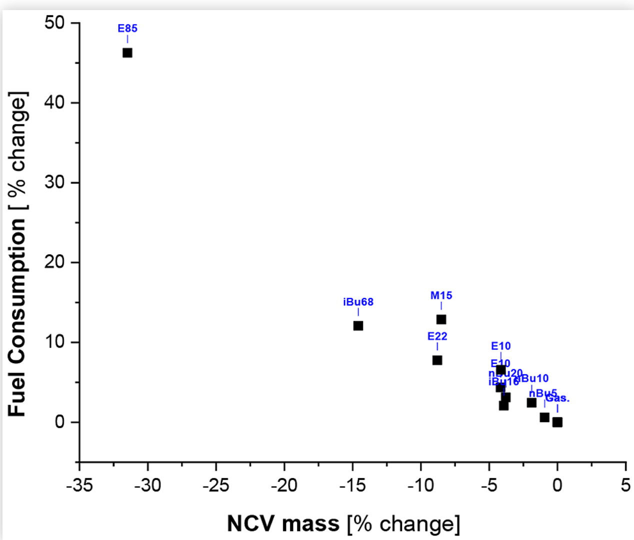


FIGURE 7 The impact of mass-based NCV on fuel consumption (SI case).



further analysis. In addition, similarly like in SI case, the carbon content was also taken into the matrix for CO_2 emissions calculation purposes.

The modeling procedure was performed using relative to standard diesel changes of alternative fuel properties and resulting fuel consumption. Table 9 represents the final modeling matrix for CI case.

In the compression ignition case, the growth of density similarly as in SI case resulted in higher fuel consumption. The reasons behind this effect are similar as in SI case (influence of NCV). However, the order of magnitude is lower in CI case, which is associated with smaller differences in calorific contents comparing alternative SI fuels to gasoline versus alternative CI fuels to diesel.

FIGURE 8 The impact of density on fuel consumption (SI case).

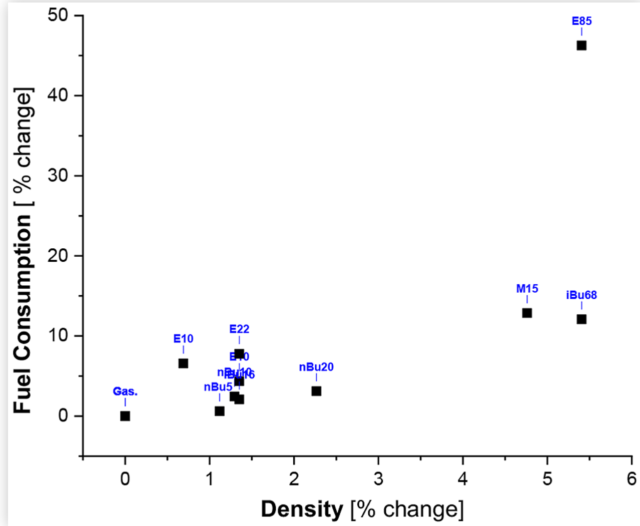


FIGURE 9 The impact of oxygen content on fuel consumption (SI case).

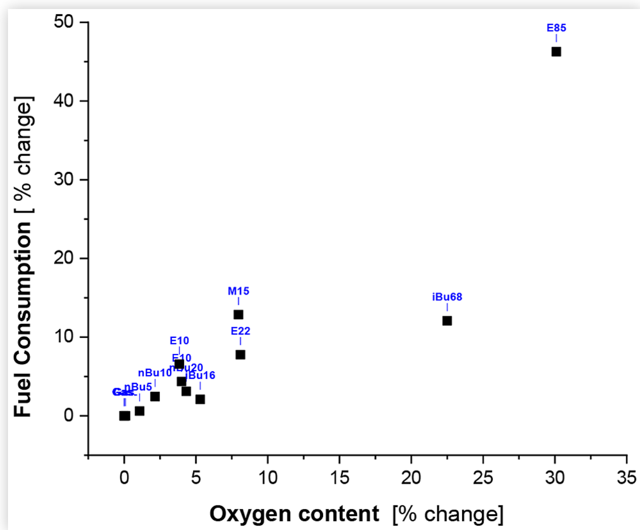


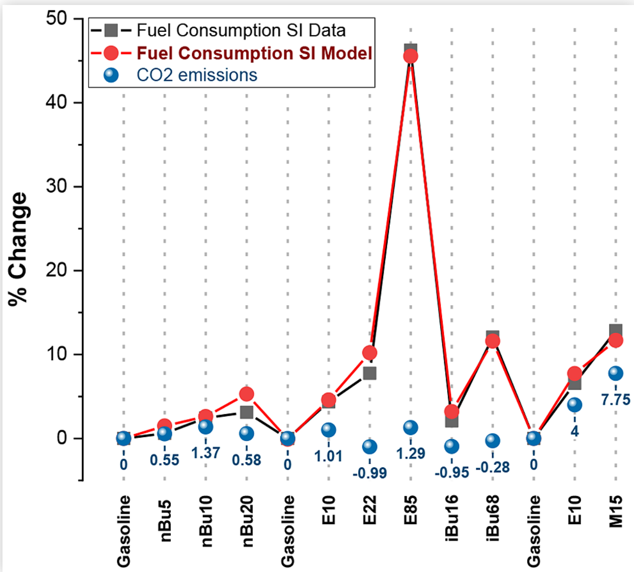
TABLE 6 Modeling outcomes for SI part (coefficients, related errors and results of quantitative analysis).

	Coefficient	Standard Error	T-value	P-value
RON	-0,466	0,188	-2,474	0,03533
Density	2,751	0,463	5,945	2,17E-04
NCVvol	-2,392	0,175	-13,647	2,56E-07
O2	-1,009	0,203	-4,966	7,74E-04

Similar effect to density could be observed when analyzing the impact of viscosity on fuel consumption. The growth of viscosity increases FC.

The growth of net calorific value both in volume and mass-based forms reduces fuel consumption. The linear relation could be observed in Figures 13 and 14. It confirms

FIGURE 10 Validation - compatibility of the model with measured values (SI case). Carbon dioxide emissions are calculated based on the FC from data sources.



that the calorific content is among the most essential fuel properties affecting engine performance from the fuel consumption point of view.

The growth of oxygen content increases fuel consumption significantly.

The higher oxygen content in the fuel the lower calorific value, which in turn forces to inject more fuel into the engine in order to maintain requested power.

The impact of CN on FC is more complex, as it could be seen in Figure 16. However, high CN fuels such as HVO or GTL have lower FC compared to low CN fuels such as biodiesel.

TABLE 7 Validation table (SI case).

Fuel Consumption [% change]			
Fuel	**Data**	**Model**	**Absolut error**
Gas.	0.00	0.00	0.00
nBu5	0.60	1.50	0.89
nBu10	2.44	2.61	0.17
nBu20	3.12	5.29	2.17
Gas.	0.00	-0.10	0.10
E10	4.36	4.59	0.23
E22	7.76	10.20	2.44
E85	46.26	45.55	0.71
iBu16	2.09	3.21	1.12
iBu68	12.08	11.59	0.49
Gas.	0.00	0.00	0.00
E10	6.57	7.74	1.16
M15	12.85	11.68	1.7
		Average error:	**0.82**

After the modeling procedure, three CI properties proved to be statistically significant to CI engine performance. Those are cetane number, density, and net calorific value mass based.

The R-Square is equal 0.96581 whereas adjusted R-Square 0.96055. Those values are also high such as in SI case and correspond to excellent accuracy.

The final model for CI can be presented in the following form:

$$\alpha = -0.076 \cdot A - 1.075 \cdot B - 1.11 \cdot C$$

Where,
α - fuel consumption (FC),
A - CN,
B - Density,
C - NCV mass based (NCVmass).

TABLE 8 Data regarding tested CI fuels, their properties and measured engine performance (based on sources).

	Fuel Properties							
	Density	Viscosiy	CN	NCV vol	O2	NCV mass	C	FC
FUEL	kg/m3	mm2/s		MJ/L	%m/m	MJ/kg	%m/m	L/100km
Diesel	837,5	2,68	51,20	42,84	0,00	35.88	86,20	
B30	853,0	3,18	52.80	41,24	3,40	35.18	83,40	
H30	812,2	2,55	60.70	43,29	0,00	35,16	86,40	
Diesel	845,0	2,51	54,20	42,43	0,66	35,85	86,14	7,94
B100	877,0	4.03	65,60	36,83	11,03	32,30	76,14	8,73
GTL100	774,0	2.34	89,20	44,03	0,00	34,08	84,82	7,87
H100	780,0	2,99	94,80	43,95	0,00	34,26	84,68	7,83
Diesel	831,2	2,69	52,60	42,95	0,00	35,70	86,20	5,96
HCK100	830,7	3,01	53,00	43,28	0,00	35,95	86,20	5,86
HCK85H15	827,9	3,58	60,60	43,34	0,00	35,88	86,20	5,87
HCK70H30	822,3	4,02	68,40	43,47	0,00	35,75	86,00	5,76
HCKcni100	830,7	3,01	64,50	43,28	0,00	35,95	86,20	5,85
Diesel	838,8	2,71	53.10	42,52	0,00	35,66	86,20	
BE100	882,3	4,25	51,90	37,31	11,00	32,92	77,07	
B100	876,0	4,54	61.00	37,40	10,90	32,76	77,07	
H100	778,8	2,87	74,70	43,85	0,00	34,15	84,61	

TABLE 9 Final modeling matrix for the CI part.

	Fuel Properties						
	Density	Viscosity	CN	NCV vol	Oxygen	NCV mass	FC
FUEL	% CHANGE						% CHANGE
Diesel	0,0	0,00	0,00	0,00	0,00	0,00	0,00
B30	1,9	18,72	3,12	-1,95	3,40	-3,73	2,07
H30	-3,0	-5,07	18,55	-2,00	0,00	1,05	2,19
Diesel	0,0	0,00	0,00	0,00	0.00	0,00	0,00
B100	3,8	60,56	21,03	-9,93	10,44	-13,20	9,92
GTL100	-8,4	-6,77	64,58	-4,94	-0,66	3,77	-0,88
H100	-7,7	19,12	74,91	-4,38	-0,66	3,58	-1,33
Diesel	0,0	0,00	0,00	0,00	0,00	0,00	0,00
HCK100	-0,1	11,79	0,76	0,71	0,00	0,77	-1,54
HCK85H15	-0,4	33,06	15,21	0,51	0.00	0,91	-1,47
HCK70H30	-1,1	49,57	30,04	0,13	0,00	1,21	-3,25
HCKcni100	-0,1	11.79	22,62	0,71	0,00	0,77	-1,85
Diesel	0,0	0,00	0,00	0,00	0,00	0,00	0,00
BE 100	5,2	56,41	-2,26	-7,70	10,93	-12,26	6,94
B100	4,4	67,26	20,53	-8,11	10,93	-12,01	7,18
H100	-7,2	6,67	40,68	-4,25	0,00	3,13	1,14

FIGURE 11 The impact of density on fuel consumption (CI case).

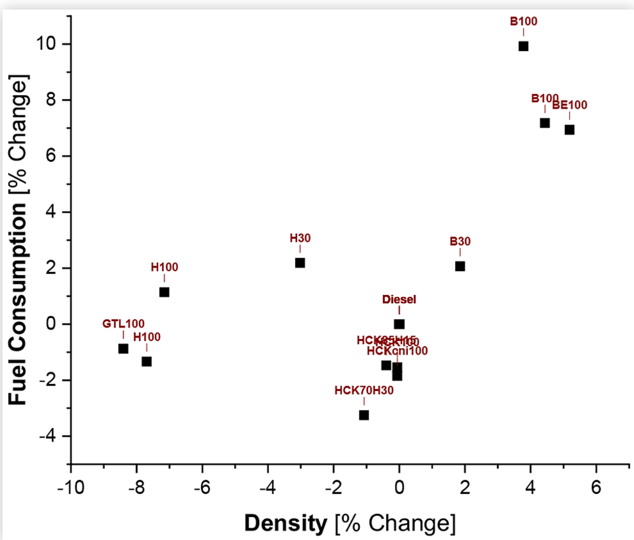
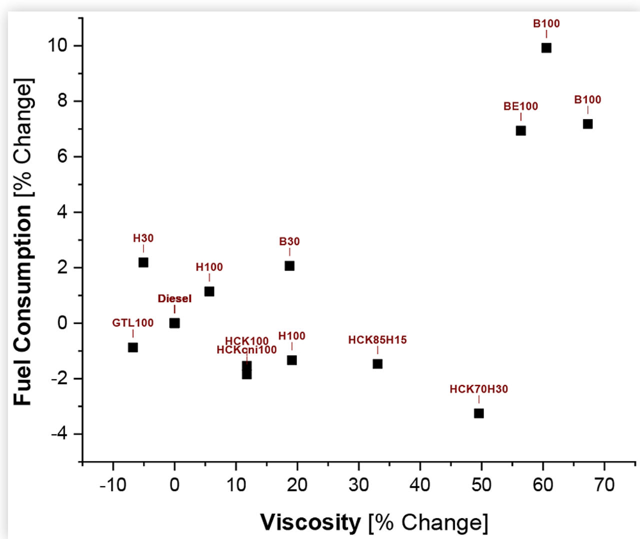


FIGURE 12 The impact of viscosity on fuel consumption.



All units are represented as a percentage changes relative to standard diesel.

Figure 17 represents the compatibility of the developed model with measured values.

Hydrotreated vegetable oil (HVO) and GTL fuels decrease total carbon dioxide emissions. The higher the concentration, the lower the total carbon dioxide emissions. In the case of H100, carbon dioxide emissions decrease by around 10%. The reason behind this outcome could be associated with the higher CN of those fuels that give shorter ignition delays, earlier heat release and higher pressures of expanding gases. This whole chain results in higher thermal efficiency, which in turn favors relatively lower fuels consumption. This FC connected with lower density and carbon-hydrogen (C/H) ratio of HVO and GTL compared to standard diesel ends-up in lower carbon dioxide emissions.

The average error in CI case is just 0.45 of % change in fuel consumption.

Conclusion

Modeling the impact of alternative fuel properties on light vehicles' engine performance was successfully performed. Two models were created, one for spark ignition and one for compression ignition engines. Both models are created based on the empirical data from driving cycles. The modeling

FIGURE 13 The impact of mass-based NCV on fuel consumption (CI case).

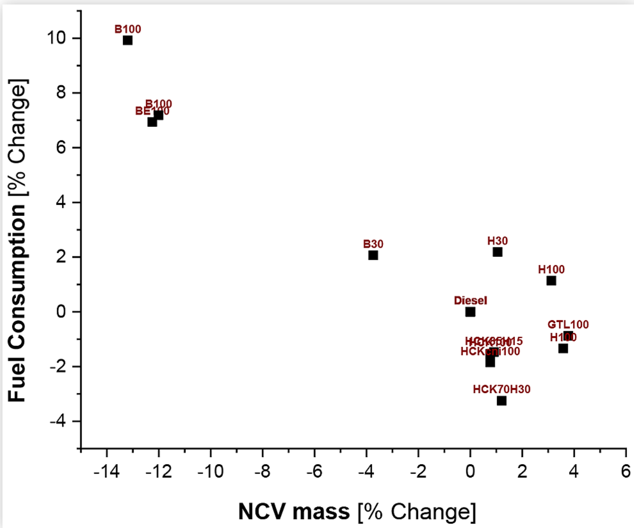
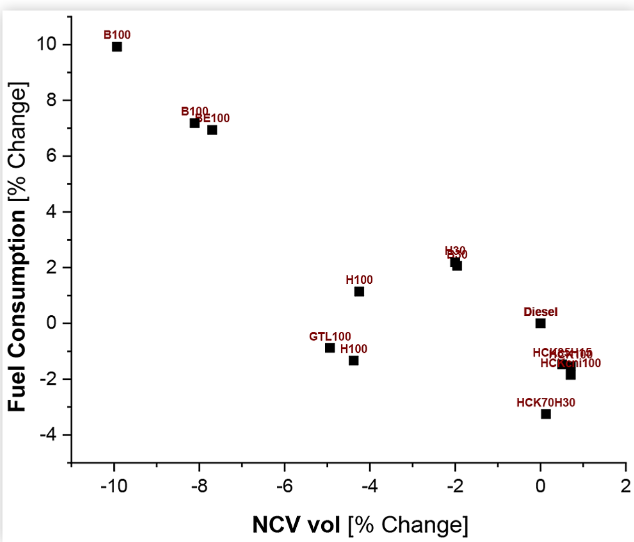


FIGURE 14 The impact of volume-based NCV on fuel consumption (CI case).



procedure was stepwise multiple linear regression, all independent variables were fuel properties, whereas the single dependent variable was fuel consumption. Both input and output parameters represent percentage change of properties and performance in respect to standard fossil-based fuel, which in a case of SI engines is gasoline and in CI case diesel fuel. If it comes to coverage, developed models can be used to evaluate the end-use fuel consumption, for all alternative fuels, that could be utilized in SI and CI light-vehicle engines without modifications. However, models will not define whether the fuel could be used as a drop-in fuel, or cause some damage to the engine due to the incompatibility issues. Developed models also are not applicable to prediction of FC in a steady state operation of the engine (constant load and speed points).

FIGURE 15 The impact of oxygen content on fuel consumption (CI case).

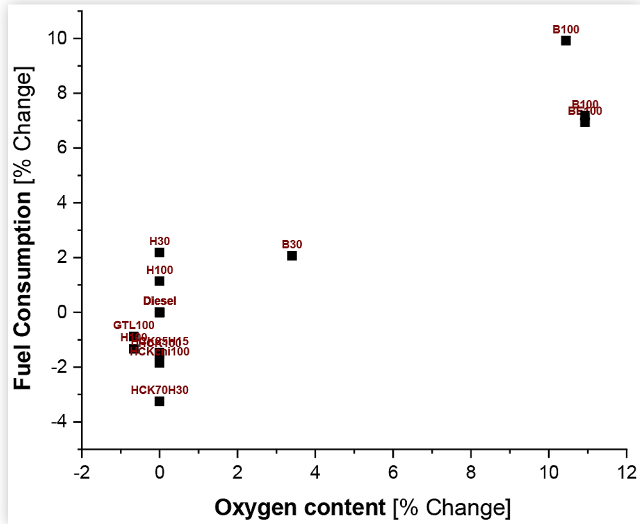
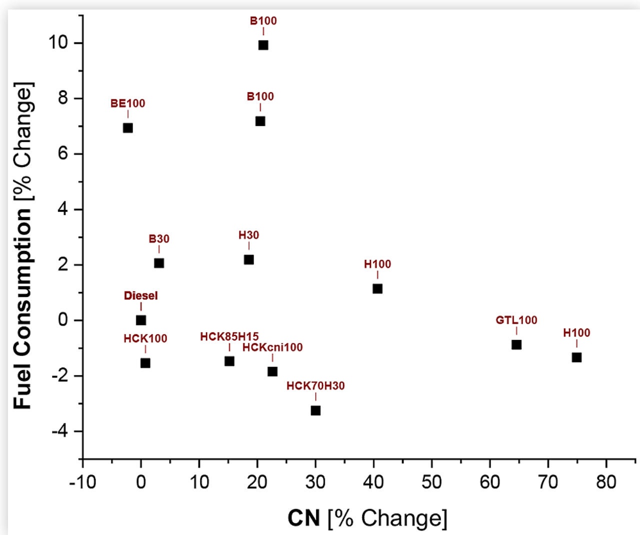


FIGURE 16 The impact of CN on fuel consumption.



Main observations for SI part:

- Data from various articles represent high consistency and good trends.
- RON, density, NCV volume based and oxygen content turned out to be the most significant properties (p-value < 0.05).
- The model's accuracy is very high, R-square over 0.99. The validation procedure proved high model compliance with measurement data (average absolute error of 0.82%).
- The largest impact on engine performance has NCV and density of the fuel.
- The growth of octane number decreases slightly fuel consumption.
- The use of high concentration iso-butanol blends with gasoline reduces the total amount of emitted carbon

TABLE 8 Modeling outcomes for CI part (coefficients, related errors and results of quantitative analysis).

	Coefficient	Standard Error	T-value	P-value
Density	-1,075	0,166	-6,460	2,13E-05
CN	-0,076	0,016	-4,828	3,30E-04
NCV mass	-1,113	0,083	-13,385	5,58E-09

FIGURE 17 Validation - compatibility of the model with measured values (CI case). Carbon dioxide emissions are calculated based on the FC from data sources.

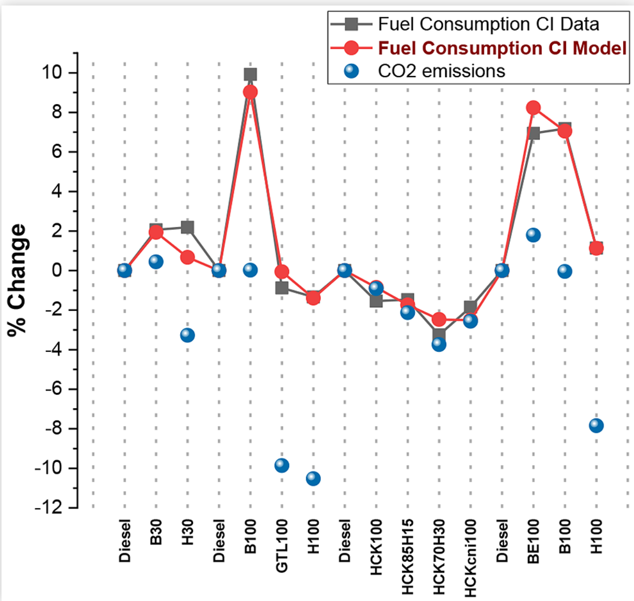


TABLE 9 Validation table (CI case).

Fuel	Fuel Consumption [% change] Data	Model	Absolut error
Diesel	0.00	0.00	0.00
B30	2.07	1.93	0.13
H30	2.19	0.67	1.51
Diesel	0.00	0.00	0.00
B100	9.92	9.03	0.89
GTL100	-0.88	-0.06	0.82
H100	-1.33	-1.39	0.06
Diesel	0.00	0.00	0.00
HCK100	-1.54	-0.85	0.69
HCK85H15	-1.47	-1.74	0.27
HCK70H30	-3.25	-2.47	0.78
HCKcni100	-1.85	-2.50	0.66
Diesel	0.00	0.00	0.00
BE100	6.94	8.23	1.29
B100	7.18	7.05	0.13
H100	1.14	1.13	0.01
		Average error:	**0.45**

dioxide, mainly caused by higher octane number and similar to gasoline calorific content.

- The blend of ethanol with gasoline E22 represents a good thermal efficiency. The total carbon dioxide emissions reduced by 1%, despite 7.76% higher fuel consumption.
- The 85% Ethanol blend with gasoline (E85), represent relatively high fuel consumption (growth of approximately 46%). The reason behind this outcome is that the engine was not tuned to E85

Main observations for CI part:

- In the case of CI, fuel properties represent slightly lower trends in relations with engine performance when comparing to the SI case. Nevertheless, data from various sources are relatively consistent.
- The final model includes density, CN and NCV mass based as independent input parameters. Those three properties passed the significance level of t-test (p-value < 0.05).
- The R-square of the model is very high (over 0.96), which ensures reliable outcomes. Additionally, the average absolute error is just 0.45%.
- Similarly, to SI case, the biggest impact on engine performance represents density and net calorific value.
- The total carbon dioxide emissions are generally not affected when using biodiesel, regardless of the degree of concentration in the blend.

Developed models both for SI and CI cases satisfy criterions of universality and representation of the real impact of alternative fuel properties on engine performance from the end-user perspective. Fuel utilization was the main scope of this work, nevertheless, the other important part of alternative fuels is related to the fuel production side - refineries. Especially when talking about carbon dioxide emissions of highly refined fuels (with high RON for example).

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Acknowledgments

This work is a part of an AdvanceFuel project, an European Union's Horizon 2020 project in response to the call for Low Carbon Energy. The AdvanceFuel project is a part of research and innovation programme under grant agreement N.°764799.

Definitions, Acronyms, Abbreviations

B100 - 100% FAME (biodiesel) fuel.
B30 - 30% blend of FAME (biodiesel) with 70% of fossil diesel.
BE100 - 100% FAME (biodiesel) fuel produced with the use of enzymes.
CO_2 - dioxide
CI - Compression Ignition.
CN - Cetane number
CRDI - Common Rail Direct Injection
DI - Direct Injection
E10 - 10% blend of ethanol with 90% of gasoline.
E22 - 22% blend of ethanol with 78% of gasoline.
E85 - 85% blend of ethanol with 15% of gasoline.
FC - Fuel Consumption
GTL - Gas To Liquid
GTL100 - 100% Gas To Liquid fuel.
H100 - 100% HVO fuel.
H30 - 30% blend of HVO with 70% of fossil diesel.
HCK - diesel fuel produced from hydrocracking process.
HCK100 - 100% of diesel fuel produced from hydrocracking process.
HCK70H30 - 70% blend of diesel fuel produced from hydrocracking process with 30% of HVO.
HCK85H15 - 85% blend of diesel fuel produced from hydrocracking process with 15% of HVO.
HCKcni100 - 100% of diesel fuel produced from hydrocracking process enriched with cetane improver.
HVO - Hydrotreated Vegetable Oil
iBu16 - 16% blend of isobutanol with 84% of gasoline.
iBu68 - 68% blend of isobutanol with 32% of gasoline.
LMA - Levenberg-Marquardt Algorithm
M15 - 15% blend of methanol with 85% of gasoline.
MPFI - Multi Port Fuel Injection
nBu10 - 10% blend of n-butanol with 90% of gasoline.
nBu20 - 20% blend of n-butanol with 80% of gasoline.
nBu5 - 5% blend of n-butanol with 95% of gasoline.
NCVmass - mass-based Net Calorific Value.
NCVvol - volume-based Net Calorific Value.
NEDC - New European Driving Conditions
O2 - Oxygen content
RON - Research Octane Number.
RVP - Reid Vapor Pressure
SI - Spark Ignition.
WLTP - Worldwide harmonized Light vehicles Test Procedure.

ISSN 0148-7191