Evaluating the impact of lubricating oil formulation on gas engine particle emissions through experimental and machine learning methodologies

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Abstract
Biomethane and hydrogen fueled engines represent valid and clean solutions in heavy-duty transportation, like commercial long-haul or off-road vehicles, offering features that make them competitive with technologies like electrification or fuel cell. Since these engines must comply with future EURO regulations, technological advancement in emission control is necessary, especially for particulate emissions control. The formation and emission of particles from gas fueled engines is strictly correlated with lube oil consumption and combustion phenomena. Following an experimental campaign for the characterization of a matrix of lubricating oils, several Machine Learning models were trained, among which a convolutional neural network (CNN) was selected due to its superior performance. The goal is to develop a predictive model of particle emissions based on the composition of the lubricating oil. Machine Learning represents one of the most promising technologies nowadays under development to provide automation processes and facilitate human activities in all branches of knowledge. Although the study is still at an early stage, the initial results showed that the CNN predictions were quite accurate, effectively capturing the experimentally observed trends in particle emissions as the oil formulation varied.

Lubricants matrix and experimental layout
Table 1 describes the matrix of tested oils, comprising the reference oil (REF), a standard commercial lubricant, and 12 prototypes, differently formulated. Kinematic viscosity (KV) and base oil viscosity (BV) values are reported, because directly linked to oil leakage phenomena in combustion chamber and consequently to engine particle emissions [1].

Table 1. Oil matrix

	REF	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12
KV *cSt*	13.5	13.8	9.6	9.7	9.5	13.5	13.3	9.7	9.5	9.6	9.6	9.7	12.8
BV mm^2/s	6.0	8.0	4.0	4.0	4.5	3.0	5.9	4.2	2.9	3.0	3.6	4.0	4.0

The engine is a heavy-duty (HD) spark-ignition (SI) 6-cylinder natural gas engine, EURO VI compliant, typically installed in buses or trucks. A scheme of the laboratory setup is shown in Figure ***1***, while Table 2 reports the main engine specifications.

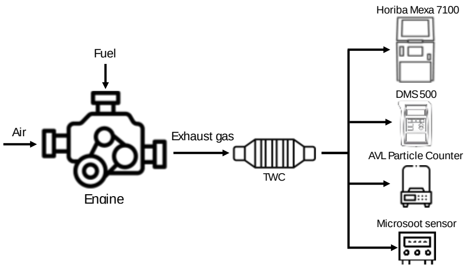

Figure 1. Experimental setup

Table 2. Main engine specifications

Engine configuration	6 cyl in line
Displacement	5883 cm³
Bore x Stroke	102 mm x 120 mm
Valves per cylinder	2
Rated power	147 kW @ 2400 rpm
Rated torque	750 Nm @ 1500rpm
Compression ratio	10:1
Piston rings	3 compression rings + 1 oil ring
Aftertreatment	Standard TWC

The laboratory is equipped with advanced instruments to fully characterize particle emissions in terms of mass (soot), number (PN), and size (PSDF). PN is measured using the AVL Particle Counter (APC), PSDF is analyzed with the Cambustion DMS 500, and soot concentration is measured with the AVL Micro-soot Sensor.The specifications of these sensors are provided in [2], previous work of the authors. The test methodology foresaw to run the engine in transient conditions, along the World Harmonized Transient Cycle (WHTC), in cold and hot start conditions, as the current homologation procedure imposes [3].

Machine Learning data analysis

Following data collection, a convolutional neural network (CNN) was trained to develop a predictive model of particle emissions based on the formulation of the lubricating oil. The first step involved the selection of oil properties, for which a Pearson analysis [4] was carried out to evaluate the relationship between oil features and emissions. This analysis highlighted a strong correlation with oil viscosity, particularly the base oil viscosity (without additives) and the overall kinematic viscosity, revealing particle emissions reduction lowering the oil viscosity. After data selection, the dataset of 13 oils, was split into three parts: a training set (7 oils) used to train the model, a validation set (3 oils) for optimizing the training parameters, and a test set (3 oils) to evaluate the final performance. Ultimately, the model estimates particulate emissions in terms of Particle Number (PN), expressed as #/kWh, and Soot, expressed as mg/kWh, based on the aforementioned lubricant viscosities.

Results

To evaluate the model's performance, the model outputs were compared with the average of the experimental measurements for each individual oil. For confidentiality reasons, the results are presented in a dimensionless form, where the values have been normalized with respect to those of a reference oil (REF). Figure 2 show the comparisons between the predicted PN values and the experimental data, while Figure 3 show the comparisons for soot.

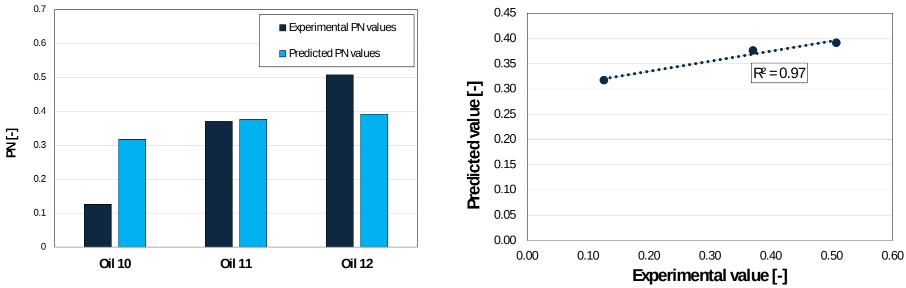

Figure 2. Predicted vs experimental PN

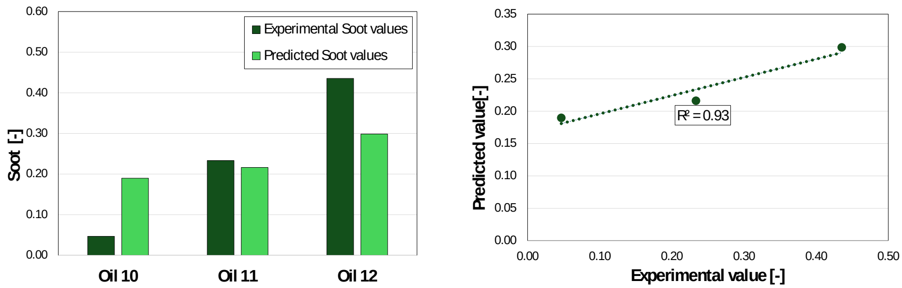

Figure 3. Predicted vs experimental soot

The predicted values are close to the experimental values in most cases. It can be observed that the trends are generally captured by the model, especially for PN, where an R^2 of 0.97 is achieved. The lower accuracy in soot prediction can be ascribed to the very low soot emissions values, often approaching the minimum sensitivity limits of the instrument, resulting in increased data uncertainty.

Conclusions

This study combines extensive testing on 13 lubricants with machine learning methods to investigate on the relation between oil formulation and particle emissions from natural gas heavy-duty engines. Once appraised that lube oil properties as base oil viscosity and kinematic viscosity mainly influence particles emissions, they were chosen as model inputs, while Particle Number and Soot were indicated as the final outputs. The CNN model showed good accuracy in predicting particle emissions, with a strong linear correlation to experimental data. While this study is a first step in ML-based particle emissions prediction, the promising results encourage further research with larger datasets and additional oil properties to enhance model inputs and accuracy.

Abbreviations

APC	AVL Particle Counter
BV	Base oil Viscosity
CNN	Convolutional Neural Network
DMS	Differential Mobility Spectrometer
HD	Heavy-Duty
KV	Kinematic Viscosity
PN	Particle Number
PSDF	Particle Size Distribution Function
REF	Reference oil
SI	Spark-Ignition
WHTC	World Harmonized Transient Cycle

References

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[2] Guido, C., Napolitano, P., Di Domenico, D., Di Maio, D., Beatrice, C., Griffaton, B., & Obrecht, N., "Exploiting Lubricant Formulation to Reduce Particle Emissions from Gas Powered Engines", *Energies (19961073)*, *17*(15) (2024).

[3] Addendum 48: Regulation No. 49. E/ECE/324/Rev.1/Add.48/Rev.6−E/ECE/TRANS/505/Rev.1/Add.48/Rev.6.

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