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Cognitive tools for enhancing sustainability in liquid fuel and internal combustion engine development

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Abstract

This paper reviews the literature on cognitive tools applied in developing internal combustion engines (ICE) and liquid fuels, focusing on modeling, simulation, data collection, and AI applications. Methods include 0D and 1D models, 3D-CFD (Computational Fluid Dynamics) simulations, real-world calculations, advanced data acquisition, and AI frameworks. Results indicate that these tools enhance development efficiency, reduce environmental impact, and promote sustainable technologies. The conclusion highlights the transformative potential of cognitive tools for sustainable mobility solutions.

Keywords

cognitive tools, sustainability, mobility, liquid fuels, internal combustion engine

1. Introduction

With the interplay between mobility and advancements in information technology, the cognitive dimension of mobility is getting stronger. Modern mobility, transport and its management, the development and production of vehicles, related social sciences, artificial intelligence and its applications, and cognitive info-communication are intertwined. This space is described by the concept of cognitive mobility (Zöldy et al., 2024). The main purpose of this concept is to give a holistic picture of mobility and interpret it in a broad space. This approach reveals what new cognitive abilities can be built into mobility and how transport can be optimised at the system level. A cognitive approach to fuel and motor propellant development helps bridge the gap between chemical engineers who develop liquid propellants and vehicle engineers who develop vehicles (Zöldy and Baranyi, 2023).

The increasing importance of safety aspects was the first driving force that positively influenced the cognitive level of vehicles. The safety devices were mainly mechanical aids for the driver at the beginning. In recent decades, the role of driver assistance devices in vehicles has increased. Research has increasingly focused on the potential benefits and pitfalls of using artificial and natural approaches to designing intelligent systems that can perceive, interact, learn, and make decisions.

Cognitive tools play an increasingly important role in development as well. They speed up the development processes, reduce asset costs, and increase the possibility of variation. Making the development process more efficient reduces its environmental footprint and helps new results spread more quickly, thus reducing the environmental impact. This study reviews the literature on cognitive tools used during virtual engine development, focusing specifically on the applicability of modeling and validation tools, advanced data collection, and artificial intelligence.

2. Modeling and Simulation Tools

The cognitive approach in virtual engine development is based on a well-considered integration of three main simulation areas: (i) 0D and one-dimensional models, (ii) 3D-CFD (Computational Fluid Dynamics) Simulations, and (iii) the real working process calculations. Due to their very different temporal and spatial resolution, these simulation areas have different modeling and input requirements; thus, their fields of application also vary. They differ widely in complexity, predictive ability, and computation time. The computation time comparison of the three areas is presented in Figure 1.

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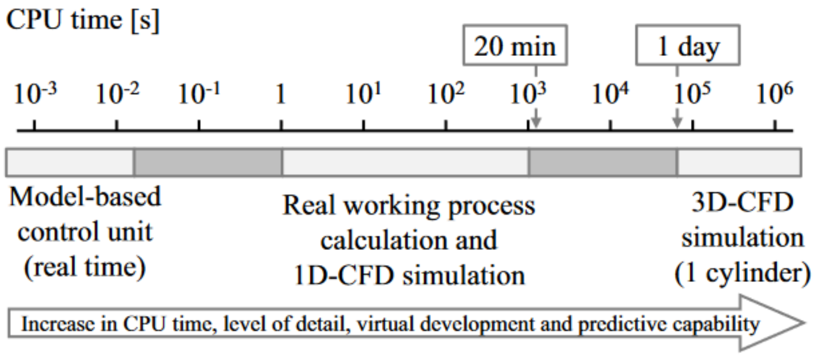

Figure 1. Computational time comparison (Wentsch, 2019)

Modelling and simulation are crucial in developing internal combustion engines and liquid fuels; thus, it is imperative to strengthen their role in future sustainable mobility. Simulation tools help in the development process to understand complex physical and chemical processes, optimise engine performance and reduce emissions. With the help of accurate, verified simulations and the increasing number of cases that can be examined, choosing a good solution for a wide array of problems will become easier.

2.1. 0D and 1D Models

0D and 1D models can be used for fast calculations and system-level simulations. Zero-dimensional (0D) models focus on the thermodynamic processes inside the engine. These models only consider time, not the spatial dependence of temperature and concentration distribution parameters. In these models, the variable conditions of the combustion chamber within an engine operating cycle are described by the generally valid differential equations of the mass and energy balance and the thermal equation of the state of the working fluid (Wentsch, 2019).

1D-CFD (Computational Fluid Dynamics) simulations of internal combustion engines are particularly convenient for investigating different engine strategies (gas exchange processes, i.e. valve timing, turbocharging). They are also well suited to investigating transient engine operating conditions and their prediction to optimise the entire characteristic field. They can also be used, mainly due to their versatility, to study the entire behaviour of the vehicle (Nyerges and Zöldy, 2020).

The 1D-CFD models allow the rapid determination of many engine parameters and general design features, but they are limited when assessing the geometric effects on the flow field. The injection processes are highly three-dimensional and cannot be adequately described by 1D-CFD simulations (Kondor, 2024).

2.2. 3D-CFD Simulations

3D-CFD simulations are currently the most complex and comprehensive modelling approach for the numerical investigation of fluid dynamics problems. For this purpose, the internal combustion engine or its investigated part is discretised into a computational grid of many finite volumes. Its number of grid cells can reach the order of millions. This is the basis for calculating the reactive flow field, calculated using partial differential equations as a function of time and three spatial coordinates. Coupling mass, momentum and energy conservation equations with state equations enables a thorough description of the fluid flow inside the engine.

Three-dimensional computational fluid dynamics (3D-CFD) simulations provide detailed insights into combustion, fuel spray dynamics, and heat transfer. Tools like Ansys Forte and Converge CFD are commonly used for these simulations (Wentsch, 2019).

2.3. Real Working Process Calculations

This approach models the processes inside the cylinder using empirical and phenomenological models. It is also suitable for modelling combustion and emissions.

Thermodynamic modelling can be performed for one, two or more zone calculations. During the calculation, we assume perfect temperature and gas composition homogeneity within each zone. During combustion, the two-zone calculation divides the cylinder charge without spatial division of the zones into a burned zone containing high-temperature exhaust gas and an unburned zone containing fresh charge and residual exhaust gas. In the model, we assume that the flame front's

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thickness is negligible and can also be omitted thermodynamically. In contrast to the single-zone approach, this model provides information on the formation of emissions (primarily NO and CO) and the heat transfer of the wall, operating under the simplifying assumption that pressure p remains constant throughout the combustion chamber.

3. Data Acquisition Techniques

Data acquisition is essential for validating models and simulations and for real-time engine control and diagnostics.

3.1. Engine Test Benches

One of the keys to engine and fuel development is engine brake pad measurements. The task is to keep all parameters constant except for the variable parameter (for example, octane number or density or compression end pressure on the engine side, injection time) to establish the sensitivity to the examined parameter (Valeika et al., 2024). With the development of modelling and simulations, an ever-increasing proportion of the researcher's work can be transferred to the virtual space. Key test values measure engine performance parameters such as torque, power, fuel consumption and emissions (Shepel et al., 2022). These systems almost always include pressure, temperature and flow sensors (Nagy, 2019). IC engine testing involves acquiring data from various engine-mounted sensors, the bench system, and IC engine control (Kaisan et al., 2020). The systems can be self-developed or purchased from the market. The most used sensors measure:

- braking torque,
- engine speed,
- engine performance,
- exhaust temperature,
- intake air pressure and temperature,
- coolant temperature,
- oil pressure and temperature,
- fuel and air mass flow,
- air-fuel ratio.

3.2. In-Cylinder Pressure Sensors

Developing new technologies to reduce emissions and fuel consumption in internal combustion engines poses exciting challenges. In the case of spark-ignition engines, it is possible to increase combustion efficiency by approaching the knock limit. Alcohols mixed with or substituted for gasoline, with their high octane numbers, are a good example of accurate knocking and pressure loss monitoring.

Knock detection can be done using in-cylinder pressure sensors for effective combustion control in spark-ignition engines. However, their high cost and sensitivity to environmental influences limit their practical use on roads. Among the possible applications, the most cost-effective approach is to use accelerometer sensors placed on the surface of the motor. These can show sensitivity to knock. Although some gasoline vehicles are already equipped with knock sensors, the existing detection techniques require further improvements, such as improving the robustness of noise and speed, the ability to adapt to combustion conditions, and above all, the binary classification of "knock" or "non-knock" (Mrdja et al., 2019).

3.3. Vibration and Acoustic Sensors

Acoustic sensors form the basis of time-frequency analyses, a technique better suited than standard Fourier transforms for capturing vibration signals with fixed non-stationary characteristics from accelerometers. Time-frequency plots offer deeper insights into vibration phenomena associated with knocking. The information provided by time-frequency techniques is essential for providing real-time closed-loop control methodology (Agocs et al., 2023). Time-frequency analysis of both the pressure traces and the vibration data is performed, and the results provide useful insights into the vibration signals associated with knocking (Ker et al., 2006). Leveraging this improved understanding, a real-time knock detection approach may be developed.

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4. Use of AI in Internal Combustion Engine and Liquid Fuel Development

Artificial intelligence (AI) and machine learning (ML) are increasingly used to enhance the development and optimisation of internal combustion engines and fuels. Introducing these cognitive tools in these areas also requires many resources due to the large data requirement of learning. However, using the devices directly (faster and more efficient developments) and indirectly (developing renewable, carbon dioxide-neutral propellants through them) promotes more sustainable mobility.

4.1. Fuel Design

Data-driven artificial intelligence (AI) frameworks facilitate the development of liquid propellants with tailored properties (Virt and Arnold, 2022). When used in an internal combustion engine, these increase efficiency and reduce carbon dioxide emissions (Zöldy, 2009; Yakovlieva et al., 2019). In one approach, fuel design can be viewed as a constrained optimisation problem (Kuzhagaliyeva et al., 2022)) with two main parts: (i) deep learning (DL) to predict the properties of pure components and mixtures and (ii) search algorithms to efficiently navigate the chemical space. This approach constructs the mixture hidden vector as a linear combination of the vectors of each component in each mixture. AI fuel design methods can be used to examine rapidly changing fuel compositions to optimise engine efficiency and reduce emissions. Artificial intelligence (AI) and machine learning (ML) are increasingly being used to enhance the development and optimisation of internal combustion engines and fuels (Cipriano et al., 2022).

4.2. Engine Performance Optimisation

The use of artificial neural networks in solving complex internal combustion engine problems is becoming increasingly widespread (Bhatt and Shrivastava, 2022). The processes taking place in the most widespread and researched engines, such as spark-ignition (SI), compression-ignition (CI) and homogeneous charge compression ignition (HCCI) engines, are investigated with various propellants, biodiesel, alcohol and gaseous fuels. The literature has shown different artificial neural network (ANN) models, such as multi-input–single-output and multi-input–multi-output approaches. Application of ANN can provide power and emission predictions, valve timing modelling, exhaust gas recirculation (EGR) rate estimation, knock intensity detection, noise prediction, , misfire detection, wall flux estimation, heat transfer coefficient modelling, engine wear determination and optimisation problems. Based on the literature analysis (Kumar et al., 2023), the number of neurons in the hidden layer between 10 and 20, as well as the logarithmic and tangent sigmoid transfer functions, give optimal results. Based on this, ANN can effectively predict the engine's complex performance, combustion, and emission characteristics and help cost-effectively search for sustainable alternative fuels that ensure advanced engine characteristics.

4.3. Co-optimisation of fuels and engines

The need to reduce the computation time and extend the simulated domain to the entire engine (including the 0D or the 3D turbocharged model) gave rise to combined development environments. Thanks to the combination of numerical models of injectors, fuels and combustion processes, these solutions meet the requirements of a fast and pragmatic virtual approach to promoting the industrial development of sustainable and environmentally friendly internal combustion engines of the future (Chiodi et al., 2024). Combined simulations have a robust methodology. They can simultaneously help engine development, optimise and characterise individual components, and discover new fuel solutions to optimise combustion efficiency and emissions. The effect of various fuels (hydrogen, methanol, synthetic and biofuels) on different engine geometries can be modelled and analysed through these systems.

Conclusions

This study offered an overview of the cognitive tools whose application can facilitate the transformation of traditional technologies to more environmentally friendly solutions, such as the application of CO_2-neutral internal combustion engines and liquid fuels. The presented cognitive tool system is spreading daily and helps make processes and results more sustainable.

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References

Agocs, A., Nagy, A. L., Ristic, A., Tabakov, Z. M., Raffai, P., Besser, C., Frauscher, M. (2023). Oil Degradation Patterns in Diesel and Petrol Engines Observed in the Field – An Approach Applying Mass Spectrometry. *Lubricants*. 11(9), 404. DOI: 10.3390/lubricants11090404

Bhatt, A. N., Shrivastava, N. (2022). Application of Artificial Neural Network for Internal Combustion Engines: A State of the Art Review. *Archives of Computational Methods in Engineering*. 29, 897–919. DOI: 10.1007/s11831-021-09596-5

Chiodi, M., Tortorella, C., Haro, E. H., Pipolo, M. (2024). Advancing Internal Combustion Engines and Fuel Innovation: A Modular Approach to 3D Virtual Prototyping for a Carbon-Neutral Future. In: Kulzer, A. C., Reuss, H. C., Wagner, A. (eds) *2024 Stuttgart International Symposium on Automotive and Engine Technology*. ISSYM 2024. Proceedings. Springer Vieweg, Wiesbaden. 85–101. DOI: 10.1007/978-3-658-45010-6_6

Cipriano, E., da Silva Major, T. C. F., Pessela, B., Barros, A. A. C. (2022). Production of Anhydrous Ethyl Alcohol from the Hydrolysis and Alcoholic Fermentation of Corn Starch. *Cognitive Sustainability*. 1(4). DOI: 10.55343/cogsust.36

Kaisan, M. U., Abubakar, S., Umaru, S., Dhinesh, B., Mohamed Shameer, P., Sekar, K., Nishath, P. M., Senophiyah, M. J. (2020). Comparative Analysis of Experimental and Simulated Performance and Emissions of Compression Ignition Engine Using Biodiesel Blends. In Ghosh, S. K. (ed.): *Energy Recovery Processes from Wastes*. Springer Singapore. 85–100.

Ker S., Guillemin F., Duval L. (2006) Combustion diagnosis for internal combustion engines with real-time acquisition and processing. *Proceedings of ISP 2006*. URL: http://laurent-duval.eu/Articles/Ker_S_2006_p-isma_combustion_dicertap-combustion-diagnostic-engine-real-time-acquisition-processing.pdf

Kondor, I. P. (2024). Experimental Investigation on the Effect of Heating Oil and Tyre Pyrolysis Oil Combustion in an Evaporative Combustion Chamber. *Fuels*. 5(2), 210–221. DOI: 10.3390/fuels5020012

Kumar, S., Sharma, P., Pal, K. (2023). Application of Machine Learning Approach in Internal Combustion Engine: A Comprehensive Review. In: Kumar, A., Zunaid, M., Subramanian, K.A., Lim, H. (eds). *Recent Advances in Manufacturing and Thermal Engineering*. RAMMTE 2022. Lecture Notes in Mechanical Engineering. Springer, Singapore. 165–178. DOI: 10.1007/978-981-19-8517-1_12

Kuzhagaliyeva, N., Horváth, S., Williams, J., Nicolle, A., Saratrhy, S. M. (2022). Artificial intelligence-driven design of fuel mixtures. *Communications Chemistry*. 5, 111. DOI: 10.1038/s42004-022-00722-3

Mrdja P., Milji N., Popovic S., Kitanovic M. (2019). Internal Combustion Engine Test Bench Control, Data Acquisition, and Engine Control Unit Calibration. *National Instruments*. URL: https://www.ni.com/en/solutions/transportation/case-studies/internal-combustion-engine-test-bench-control-data-acquisition.html?srsltid=AfmBOooJPCSNJw2Vrlay5Rb562Q_q1QKSAX7maT6YagoNiGB0o7Yy4JJ

Nagy, A. L. (2019). Development of an artificial aging process for automotive lubricants. *Spring Wind Conference*, Debrecen 2019. 771–775. URL: https://www.researchgate.net/publication/342832489_Development_of_an_artificial_aging_process_for_automotive_lubricants

Nyerges, A., Zöldy, M. (2020). Model development and experimental validation of an exhaust brake supported dual loop exhaust gas recirculation on a medium duty Diesel engine. *Mechanics*. 26(6), 486–496. DOI: 10.5755/j01.mech.26.6.25017

Shepel, O., Matijošius, J., Rimkus, A., Orynycz, O., Tucki, K., Świć, A. (2022). Combustion, ecological, and energetic indicators for mixtures of hydrotreated vegetable oil (HVO) with duck fat applied as fuel in a compression ignition engine. *Energies*. 15(21), 7892. DOI: 10.3390/en15217892

Valeika, G., Matijošius, J., Orynycz, O., Rimkus, A., Kilikevičius, A., Tucki, K. (2024). Compression Ignition Internal Combustion Engine's Energy Parameter Research Using Variable (HVO) Biodiesel and Biobutanol Fuel Blends. *Energies*. 17(1), 262. DOI: 10.3390/en17010262

Virt, M., Arnold, U. (2022). Effects of oxymethylene ether in a commercial diesel engine. *Cognitive Sustainability*. 1(3). DOI: 10.55343/cogsust.20

Wentsch, M. (2019). Simulation of Internal Combustion Engines. In: Wentsch, M.: *Analysis of Injection Processes in an Innovative 3D-CFD Tool for the Simulation of Internal Combustion Engines*. Wissenschaftliche Reihe Fahrzeugtechnik Universität Stuttgart. Springer Vieweg, Wiesbaden. 7–20. DOI: 10.1007/978-3-658-22167-6_2

Zöldy, M. (2009). Potential future renewable fuel challenges for internal combustion engine. *Járművek és Mobilgépek*. 2(4), 397–403.

Zöldy, M., Baranyi, P. (2023). The Cognitive Mobility Concept. *Infocommunications Journal* (HTE), (SP), 35–40. DOI: 10.36244/ICJ.2023.SI-IODCR.6

Zöldy, M., Baranyi, P., Török, Á. (2024). Trends in Cognitive Mobility in 2022. *Acta Polytechnica Hungarica*. 21(7), 189–202. DOI: 10.12700/APH.21.7.2024.7.11

Yakovlieva, A., Boichenko, S., Zaremba, J. (2019). Improvement of Air Transport Environmental Safety by Implementing Alternative Jet Fuels. 2019 *Modern Safety Technologies in Transportation (MOSATT) Conference*. 424. DOI: 10.1109/MOSATT48908.2019.8944122