AVL Boost: a powerful tool for research and education

G Bellér¹, I Árpád², J T Kiss³ and D Kocsis¹

¹Department of Environmental Engineering, Faculty of Engineering, University of Debrecen, Hungary
² Department of Mechanical Engineering, Faculty of Engineering, University of Debrecen, Hungary
³ Department of Engineering Management and Enterprise, Faculty of Engineering, University of Debrecen, Hungary
E-mail: kocsis.denes@eng.unideb.hu

Abstract. AVL Boost is a fully integrated simulation software in the field of internal combustion engines. At the University of Debrecen, it has been roughly a year since the launch of the Partnership Program with AVL Advanced Simulation Technologies. Although 2020 made us face unusual and unexpected challenges, the use of Boost has begun both in research projects and in engineering courses. The software provides a wide range of applications in engine performance, tailpipe emissions and acoustics. It is inherently appropriate only for internal combustion engines including both spark-ignition and compression-ignition engines. However, with a link to other AVL software packages (e.g. Cruise or Fire), hybrid vehicles can be studied too. Boost enables the user to perform a solely computational approach, as well as the comparison of experimental findings with simulation results. The software offers a high level of flexibility of the fuel type and fuel composition, including the possibility to use both conventional and alternative fuels. Our paper provides an overview of the software including a general introduction, a review of selected publications from recent years and a discussion of the application of Boost, in engineering courses and student projects.

1. Introduction

AVL (Anstalt für Verbrennungskraftmaschinen List) is an Austrian-based independent research institute and an automotive consulting firm. Although simulation is one of their main competencies, the privately owned company is also working on the development and testing of powertrain systems with internal combustion engines (ICEs). Their software packages offer solutions for various applications and provide detailed insights into the behavior and interactions of elements, systems and entire vehicles.[1]

Their simulation tools include:[1]

- Boost™: integrated simulation software of engine performance, tailpipe emissions and acoustics,
- Cruise™: driveline simulation solution, prediction of the energy management of a vehicle concept,
- Cruise™ M: powertrain concept analysis, sub-system design and virtual component integration,
- Excite™: multi-body dynamics software solution for powertrain analysis,
- Fire™: computational fluid dynamics (CFD) simulations,
• Fire™ M: CFD simulations supporting the development of both conventional and electrified powertrains,
• Tabkin™: enhancing CFD simulations with combustion chemistry,
• Spa™: driveability optimization,
• VSM™: balancing efficiency with driving characteristics by using virtual prototypes.

Within the frame of the AVL University Partnership Program, a given number of licenses of the AVL Boost software is available at the University of Debrecen, and in this paper; it is our aim to provide an overview of the potential applicability of this software in teaching as well as in research.

The paper is organized as follows: Chapter 2 gives a general overview of the AVL Boost software. This will be further elaborated in Chapter 3, by listing the main elements of AVL Boost and the key steps, when working with it. Chapter 4 summarizes the publications on AVL Boost, available in the literature and demonstrates the variety of fields where it is applied. Meanwhile, in Chapter 5, we review two theses completed at our Faculty by the help of the software and mention potential utilization of AVL Boost in the teaching of engineering courses.

2. Overview of AVL Boost
AVL Boost is a well-known, fully integrated simulation software in the ICE field. It provides sophisticated models enabling accurate prediction of engine performance, exhaust gas emissions and duct acoustics under steady-state and transient operating conditions.[2] For the latter two purposes, Aftertreatment and Acoustics sub packages of Boost can be used, respectively.[3] Boost allows scientists to simulate all types of combustion engines, including both spark ignition (SI) and combustion ignition (CI) engines; 4-stroke or 2-stroke engines; ranging from small capacity engines for motorcycles[4] through aircraft engines[5] up to large ones for marine propulsion.[6] Thanks to an internal solver for chemical reactions, a high level of flexibility of the fuel type and fuel composition is offered, including the possibility to use both conventional (e.g. diesel or gasoline) and alternative fuels (e.g. hydrogen, ethanol, methanol etc.).[3] For each fuel, default values for the lower heating value and for the stoichiometric air/fuel ratio are also available. If more accurate data are needed, the default values may be overwritten. Additionally, further fuels such as 2,5-dimethylfuran, DMF[7] or P. moriformis microalgal oil, PMO[8] can be defined by adding the corresponding thermodynamic parameters.

AVL Boost allows users to treat the flow in the pipes as one-dimensional (1D): i.e. pressures, temperatures and flow velocities, obtained from the solution of the gas dynamic equations, represent mean values over the cross-section of the pipes. Flow losses due to 3D effects are calculated by appropriate flow coefficients.[3] Furthermore, a link to AVL Fire is also available, which enables 3D simulations of flow and heat transfer effects in pipes, manifolds and combustion chambers. Combining Boost and Fire is an excellent choice when reliable estimations are needed for engine thermodynamics and combustion/emission development.[2] The simulations serve as virtual testing of a large number of prototypes, thus reducing the need for expensive and time-consuming experiments.

3. Working with AVL Boost
Depending on the simulation tasks, at least one of the following should be selected before starting with the model[3]:
• Cycle simulation: gas exchange and combustion calculations.
• Aftertreatment analysis: simulation of chemical and physical processes for aftertreatment devices.
• Linear acoustics: frequency domain solver to predict the acoustic performance of components.

To create the corresponding simulation model of the test engine (figure 1), the following steps are needed[3]:
1) Selection of all the relevant elements of the actual engine from the Components Tree and connecting the elements with pipes.
2) Adding the specifications for each element (e.g. bore and stroke of the cylinder, Air/Fuel ratio etc.)
3) Setting appropriate boundary conditions (e.g. ambient pressure, ambient temperature).

![Engine simulation model on AVL-Boost software](image)

Figure 1. An engine simulation model on AVL-Boost software

The main elements include: engine, cylinder, pipes, measuring points (to access flow data and gas conditions over the crank angle at a certain location in a pipe), boundaries, transfer elements (e.g. throttle, injector, restriction), volume elements (e.g. plenum), assembled elements (e.g. air cleaner, air cooler, catalyst, diesel particulate filter) and charging elements (e.g. turbocharger, turbine, turbo compressor). Furthermore, the user can add external elements (link to AVL Cruise or Fire), control elements (e.g. engine control unit, monitor, temperature sensor) or acoustic elements (e.g. microphone).

As a result of the calculation of the defined model, the following reports are available[3]:
- Summary: analysis of global engine performance data.
- Transients: analysis of global calculation results over the cycles calculated.
- Traces: analysis of calculation results over the crank angle.
- Acoustic: analysis of orifice noise.
- Case Series: analysis of the results of a case-series calculation.
- Animation: analysis of animated results.
- Messages: analysis of messages from the main calculation program.

A more detailed, step-by-step manual of AVL Boost is available in ref [3].

4. Review of the publications using AVL Boost
As of January 2021, almost 150 papers (articles and proceeding papers) were found by Web of Science, and more than 270 items (articles and conference papers) were listed in Scopus, when the term “AVL Boost” was used to search the databases. Although the increase of the number of publications by year is not monotonous (figure 2.), the 5-year moving average is steadily rising (figure 3.) which demonstrates the growing interest for the software in research. It is obviously out of the scope of the present paper to discuss each of them, but by means of selected examples, the wide variety of applications will be demonstrated.
Figure 2. Publications reporting the use of AVL Boost per year (grey: according to Scopus between 2005-2021; black: according to Web of Science between 2008-2020).

Figure 3. 5-year moving average of the publications reporting the use of AVL Boost per year (square: according to Scopus, triangle: according to Web of Science).

Although Boost is inherently used for SI\cite{4,7,9-13} and CI\cite{6,8,14-21} internal combustion engines, there are some cases, when the software was involved in studies concerning hybrid electric...
vehicles (HEVs).[22], [23] In these cases, AVL Cruise was the supplementary software. In one study, Arat proved that hydrogen (H₂) enrichment on diesel engines is a solution for both minimizing undesirable emissions and fuel consumption.[22] Four types of vehicles (stock diesel vehicle, hydrogen enrichment diesel vehicle, HEV which contains the same diesel engine, and HEV powered by hydrogen enrichment diesel engine), were compared by the performance and emission values. Boost served to verify the effects of the addition of hydrogen to the diesel engine. In another work of Arat,[23] simulations and experimental results on an HEV powered by hydrogen enriched SI ICE were compared. Boost was used for the simulation and validation of the experimental observations of the ICE, then Cruise was applied for the hybridization of the H₂ enriched ICE.

While most of the published work involves the comparison of experimental observations with simulation results, there are some publications relying purely on calculations. [7], [13], [17], [19], [20]. Nguyen et al. presented how the fuel properties and loads affect the combustion of DMF-gasoline blends in a four-cylinder SI engine.[7] This work fills a research gap: although DMF is a potential alternative fuel source to replace traditional fuels such as gasoline and diesel, the combustion and emission properties of DMF have rarely been characterized. Qadiri and Wani focused on the computational and parametric research on a single-cylinder spark ignition engine using alternative dual-fuel.[13] They studied the effect of fuel composition (increasing the amount of propane in gasoline) on performance and emission characteristics (such as nitrogen oxides, carbon monoxide, hydrocarbons) of a SI engine. The study was carried out at a varying percentage load and a varying compression ratio for constant engine speed.

Composition of the exhaust gas is of interest in other works too.[4], [11], [12], [18] Khoa et al. studied the combustion duration effects on the performance and emission characteristics of motorcycle engines.[4] From the results, one can estimate the best combustion duration value, that gives the target engine torque, NOₓ, CO and hydrocarbon emission. To achieve this goal, an experimental system was installed within a dynamo testing system, and a simulation model was established using the software. The simulation model was used to determine the residual gas ratio, effective release energy, and engine emission characteristics in variable combustion durations. Niculae et al. developed a thermodynamic combustion model in order to evaluate the pollutant emissions, performance and efficiency parameters of a SI engine Renault K7M-710 fueled with hythane (blends of compressed natural gas and hydrogen).[11] It was concluded that as the percentage of hydrogen in hythane is increased, the power of the engine rises, the brake specific fuel consumption, CO₂, CO and total unburned hydrocarbon emissions decrease while NOₓ increases. Karagöz et al. used Boost to validate their experimental measurements on a single cylinder, naturally aspirated, SI engine.[12] In the study, a test engine was operated with gasoline fuel at full load and different engine speeds. Using obtained engine performance, emission values and in-cylinder pressure, a 1D engine model was built and validated by the software. Finally, a comparison was made between the emission, performance and combustion values of operations with pure hydrogen fuel and those of the operations with unleaded gasoline. The effects of using hydrogen on the composition of exhaust gas were also studied. The work of Juknelevičius et al. was triggered by the recent diesel emission scandals (as manufacturers falsified laboratory test results), which initiated the discussions about sustainable and environmentally friendly diesel engines.[18] The purpose of their study is to use a hydrogen - diesel mixture in an Audi/VW 1.9 TDI turbocharged CI engine and examine the performance and emission indicators. The effect of hydrogen fraction on the combustion and emission characteristics of the diesel - hydrogen mixture was validated by AVL Boost.

As mentioned in Chapter 2 [7], [8] and also shown above[7], [11], [13], [22], [23] simulations of engines running on biofuels or alternative fuels are getting considerable attention. In addition to the discussed studies, a large number of papers are dedicated to this topic. Raslavicius et al. conducted an extensive experimental study on a CI engine that was running on low, average and high load modes and used diesel fuel, a microalgal oil (PMO100), and their 30% and 70% blends.[8] Variation of different parameters of the engine’s operational performance (net efficiency, air mass flow, exhaust gas temperature etc.) and emissions of five chemical compounds (smoke, NOₓ, hydrocarbons, CO₂, O₂) were established. In order to explain the thermochemical processes within engine cylinders and to support the
experimental findings, various indicators (i.e. in-cylinder temperature, pressure and pressure rise rate, mass fraction burnt, etc.) were assessed by using BOOST. Lesnik et al. focused on numerical and experimental analyses of biodiesel fuel’s influence on the injection characteristics of a mechanically-controlled injection system, and on the operating conditions of a heavy-duty diesel engine.[14] The influence of biodiesel fuel on the engine operating condition of a heavy-duty diesel engine and its emission formation was tested experimentally on an engine test-bed, and numerically. Rinkus et al. analyzed the physical-chemical and direct injection diesel engine performance parameters, when fueled by pure diesel fuel and retail hydrotreated vegetable oil (HVO).[16] The energy, pollution and in-cylinder parameters were studied under medium engine speed and brake torque load regimes. Boost was used to determine the heat release characteristics. In another study, Rinkus et al. compared the results of the physical–chemical and direct injection (DI) diesel engine properties of diesel fuel and biomass-to-liquid blend.[24] The energy, ecological and in-cylinder parameters were analyzed under the given conditions, and the experimental results were matched with the data obtained by the simulations. The engine exhaust gas composition was also studied in detail.

5. Use of AVL Boost for teaching

Our institute has been participating in the University Partnership Program of the AVL company since the beginning of 2020 and working on the utilization of the software for educational purposes.

As shown above, the simulations run in AVL Boost can help in investigating the effects of parameter settings, without the need of an endless number of prototypes. Finding the optimal parameters and later testing the settings on model engines can be of immense importance for mechanical and vehicle engineering students. In addition, the quantitative and qualitative composition of the exhaust gas is of interest to environmental engineers too. The long-term goal of our institute is to incorporate the software in both theoretical (lectures) and practical courses.

Sadly, the COVID-19 pandemic made us drastically change teaching routines. The national measures taken to mitigate the spread of the virus involved higher educational institutes too; requesting that the previously face-to-face university courses, be taught online. Online teaching was necessary for most of 2020, which prevented the regular use of the software installed in computer classrooms. Although only sporadic discussion of AVL Boost was feasible in courses throughout the previous two semesters, two bachelor’s theses were written by the help of the software. Despite the fact that such work obviously involves research, thus they clearly could have been mentioned in the previous chapter; we decided to discuss them separately, because very often; writing a bachelor level thesis is more of a project assignment, instead of comprehensive and complete research work.

The thesis of Dániel Márk Hawrlant titled “Thermal and fluid mechanical simulation of the internal combustion engine BMW N40B16” focused on the improvement of the power and motor torque of a SI engine, by optimizing the settings of the valve lift curve and the diameters of the intake and exhaust valves.[25] This particular engine is accessible for the students of the Faculty and studied during practical courses. A model was created in the AVL Boost software in accordance with the actual elements of the motor, including the engine, 4 injectors, 4 cylinders, 4 plenums, a throttle, a catalyst, an air cleaner, 2 system boundaries, pipes, and restrictions. In addition, measuring points were added to complete the model. The parameters of the defined elements such as geometric (length, volume, diameter etc.) or thermodynamic (temperature, pressure etc.) data were either measured or estimated. The heat release characteristics were approximated by the Vibe function, which is a 1-zone, 0D combustion, very frequently used model, but inappropriate for estimation of pollutant evaluation.

After creating the model and setting the necessary parameters, two working points (4300 rpm and 6100 rpm) were chosen for further investigation of the motor. The results of the preliminary simulation (e.g. maximum combustion pressure and temperature) were in acceptable agreement with the expected values. In the next step, the diameters of the intake and exhaust valves were systematically modified in order to improve the power and motor torque. It was found that the increase of the diameters of the valves compared to the default settings (from 32 to 33 mm and from 29 to 32 mm for the intake and
exhaust valves, respectively) leads to 1.78% of power gain and 2.61% of motor torque gain. It should also be mentioned that due to the modifications, the fuel consumption increased too.

As the title of Csaba Fekete’s thesis suggests (“Reducing emissions from diesel engines”), its primary goal was to propose solutions for the reduction of exhaust gas emissions, of an older diesel engine of Euro 4 rating, with special emphasis on soot, carbon monoxide (CO) and nitrogen monoxide (NO) emissions.[26] The engine tested in the study is for a 1997 Volkswagen Passat with 1900 cm³ cylinder capacity. The initial model of the motor consisted of multiple elements including the engine, 4 injectors, 4 cylinders, 4 junctions, 2 plenums, a throttle, a catalyst, an air cleaner, a turbocharger, a temperature sensor, a particulate filter, a monitor, 2 coolers, 2 system boundaries, pipes and measuring points. In general, reduction of emissions can be achieved by the optimization of the engine such as aligning or modifying the intake and exhaust valves, modifying the pistons, the injectors, the air supply system and/or the engine control unit (ECU). However, modification of these elements results in performance gain as well, which is against the current regulations.

Instead, the author was looking for legal ways to achieve a reduction of emissions, without the unpermitted modifications of the engine. Therefore, a retrofit diesel particulate filter (DPF) was chosen for the purpose. DPF is commercially available, and most of the necessary parameters required by the software can be found in online catalogues. The model was also drastically simplified to the following elements: 2 aftertreatment boundaries, the catalyst and the particulate filter. For the simulation tasks, the Aftertreatment sub package of Boost was applied. Results were obtained about the catalyst (temperature change, conversion of the hydrocarbons), the DPF (soot mass, pressure drop) and the exhaust gas composition (overall conversion of CO and NO). According to the simulations, the installation of a DPF could reduce the soot emission by 30%.

Both students highlighted in their theses that the usage of AVL Boost greatly helped their work, however, the confirmation of the simulation results would require further experiments on test engines. They also expressed their intention to continue the development.

6. Conclusion
AVL Boost software provides a wide range of applications in ICE-related fields. Although by far the majority of the published studies concerns SI and CI engines, there are examples of extending the investigation to hybrid vehicles with the help of other AVL programs. Boost enables the user to perform solely computational approach as well as the comparison of experimental results with simulations. The flexibility of the software regarding fuels, allows scientists to perform calculations with alternative fuels and defined mixtures of conventional and biofuels. Boost is appropriate to simulate engine performance and emission properties. Even though the application of Boost in acoustics is very rarely published, the software is suitable for such calculations too.

In the University of Debrecen, it has been roughly a year since the launch of the Partnership Program with AVL Advanced Simulation Technologies. Although introducing new software tools are sometimes not that straightforward as desired and the COVID-stricken 2020 required unusual teaching methods; the use of Boost in engineering courses has already begun, and students in their research projects had the opportunity to supplement the experimental work with the software.

Acknowledgements
The research was supported by the Thematic Excellence Programme (TKP2020-NKA-04) of the Ministry for Innovation and Technology in Hungary.

The results of refs [25] and [26] were obtained by the support of the “AVL Advanced Simulation Technologies University Partnership Program”.

References
[1] “AVL homepage.” [Online]. Available: https://wwwavl.com/simulation. [Accessed: 28-Jan-2021].
[2] “AVL Advanced Simulation Technologies: Tools and Methods for Next-Level Simulation Solutions.”

[3] AVL User Guide.

[4] Khoa NX and Lim O 2019 The effects of combustion duration on residual gas, effective release energy, engine power and engine emissions characteristics of the motorcycle engine Appl. Energy 248 54–63

[5] Czyż Z, Grabowski L, Pietrykowski K, Czarnigowski J and Porzak M 2018 Measurement of flight parameters in terms of toxic emissions of the aircraft radial engine ASz62-IR Meas. J. Int. Meas. Confed. 113 46-52

[6] Pagán Rubio JA, Vera-García F, Hernandez Grau J, Muñoz Cámara J and Albaladejo Hernandez D 2018 Marine diesel engine failure simulator based on thermodynamic model Appl. Therm. Eng. 144 982-95

[7] Nguyen DC, Dong HV and Tran QV 2019 Combustion characteristics of SI engine fueled with 2,5-dimethylfuran and gasoline blends using AVL-boost simulation J. Mech. Eng. Res. Dev. 42 34–37

[8] Raslavičius L, Felneris M, Pukalskas S, Rimkus A and Melaika M 2019 Evaluation of P. moriformis oil and its blends with diesel fuel as promising contributors to transportation energy Energy 189 116196.

[9] Chen J, Wang Z and Tian F 2016 A new hydraulic variable valve timing and lift system for spark ignition engine Chem. Eng. Trans. 51 1249–54

[10] Melaika, Rimkus A and Vipartas T 2017 Air Restrictor and Turbocharger Influence for the Formula Student Engine Performance Procedia Eng. 187 402-07

[11] Niculae AL, Miron L and Chiriac R 2020 On the possibility to simulate the operation of a SI engine using alternative gaseous fuels Energy Reports 6 167-76

[12] Karagöz Y, Balci Ö and Köten H 2019 Investigation of hydrogen usage on combustion characteristics and emissions of a spark ignition engine Int. J. Hydrogen Energy 44 14243–56

[13] Qadiri U and Wani MM 2019 Computational Investigation on Single Cylinder Spark Ignition Engine Using Gasoline-propane in Dual Fuel Mode Int. J. Heat Technol. 37 457–65

[14] Lešnik L, Vajda B, Žunič Z, Škerget L and Kegl B 2013 The influence of biodiesel fuel on injection characteristics, diesel engine performance, and emission formation Appl. Energy 111 558–70

[15] Zhang H, Xing J and Guo C 2013 Thermal analysis of diesel engine piston J. Chem. Pharm. Res. 5 388–93

[16] Rimkus A, Žaglinskis J, Stravinskas S, Rapalis P, Matijošius J and Bereczky Á 2019 Research on the combustion, energy and emission parameters of various concentration blends of hydrotreated vegetable oil biofuel and diesel fuel in a compression-ignition engine, Energies 12, doi: 10.3390/en12152978.

[17] Praptijanto A, Muharam A, Nur A and Putrasari Y 2015 Effect of Ethanol Percentage for Diesel Engine Performance Using Virtual Engine Simulation Tool Energy Procedia 68 345-54

[18] Juknelevičius R, Rimkus A, Pukalskas S and Matijošius J 2019 Research of performance and emission indicators of the compression-ignition engine powered by hydrogen - Diesel mixtures Int. J. Hydrogen Energy 44 10129–38

[19] Petranović Z, Sjerić M, Taritaš I, Vujanović M and Kozarac D 2018 Study of advanced engine operating strategies on a turbocharged diesel engine by using coupled numerical approaches Energy Convers. Manag. 171 1-11

[20] Karagöz Y 2019 Analysis of the impact of gasoline, biogas and biogas + hydrogen fuels on emissions and vehicle performance in the WLTC and NEDC Int. J. Hydrogen Energy 44 31621–32

[21] Teo AE, Chiong MS, Yang M, Romagnoli A, Martinez-Botas RF and Rajoo S, 2019 Performance evaluation of low-pressure turbine, turbo-compounding and air-Brayton cycle as engine waste heat recovery method Energy 166 895-907
[22] Arat HT 2019 Simulation of diesel hybrid electric vehicle containing hydrogen enriched CI engine Int. J. Hydrogen Energy 44 10139–46
[23] Arat HT 2019 Alternative fuelled hybrid electric vehicle (AF-HEV) with hydrogen enriched internal combustion engine Int. J. Hydrogen Energy 44 19005–16
[24] Rimkus A, Žaglinskis J, Rapalis P and Skačkauskas P 2015 Research on the combustion, energy and emission parameters of diesel fuel and a biomass-to-liquid (BTL) fuel blend in a compression-ignition engine Energy Convers. Manag. 106 1109–17
[25] Hawrlant DM; Supervisors: Ailer PGy and Magyari A 2020 BMW N40B16 belsőégésű motor hő- és áramlástan modellezése és szimulációja (Thermal and fluid mechanical simulation of the internal combustion engine BMW N40B16) University of Debrecen, Faculty of Engineering, Debrecen
[26] Fekete Cs; Supervisors: Békési Zs and Berkes G 2020 Dizel motorok károsanyag kibocsátásának csökkentése (Reducing emissions from diesel engines) University of Debrecen, Faculty of Engineering, Debrecen