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R E P O R T
on the British Scholarship Trust – sponsored
research visit at the University of Bath

Name of the grantee	Nikola Manev
Home institution	Faculty of Mechanical Engineering – Skopje, University "Ss. Cyril and Methodius" - Skopje
Host institution	Advanced Automotive Propulsion Systems – Centre for Doctoral Training, Department of Mechanical Engineering, University of Bath
Field of research	Internal Combustion Engine's Model-based Calibration and Optimization
Home Supervisor	Prof. Dame Dimitrovski, PhD
Host Supervisor	Prof. Richard Burke, PhD
Visit period	07.11-09.12.2022

Short summary and impressions

Students from Macedonia, and I would also say most of the remaining ex-Yugoslavian member states, are seldom provided opportunities to perform scientific research outside the borders of their own country. And in that case, the quality of the research performed is significantly lessened by not being able to afford the required resources such as up to date scientific literature, facilities and testing equipment. This was particularly true regarding my thesis and the progress I was making up to my visit at the University of Bath and its Institute for Advanced Automotive Propulsion Systems (IAAPS). In fact, the amount of applicative research I conducted in Bath using the most up to date engine testing methodologies over the period of 5 weeks would have taken me a whole semester, if not more, back home. Even more so, the research environment and the support of my peers and supervisor guided, challenged, and stimulated a thought process that would not have been possible if it were not for the opportunity I was awarded. Furthermore, this experience acted as a steppingstone toward gaining recognition among leading research and academia professionals for my work in internal combustion engines and facilitated multiple opportunities for future research and collaboration.

Introduction to the field of research

Mankind's need for fast and efficient transport has led to the intensified development of transport infrastructure, the improvement of transport policies and the modernization of the means of transport. Practically in parallel, the tendency in the development of automotive propulsion systems has been aimed at greater economy, increased power, smaller mass, and longer service life. In addition, low emissions of local pollutants and greenhouse gases (GHGs) have proved no less important. Currently, there is a massive expansion of the passenger and light commercial vehicles market, where the presence of fully or partially electric (hybrid) vehicles is increasing at the expense of vehicles driven by internal combustion (IC) engines - the most common propulsion variant to date.

Given the increasingly restrictive measures to limit the amount of direct harmful emissions from road transport, the electric vehicles (EVs) sales expansion seems justified. But lithium batteries, fuel cells, and highly efficient electric motors, while promising are extremely expensive, the availability of the rare materials used to produce them is controversial, and emission rates over the EVs entire life cycle remain high. Nevertheless, in spite of the EVs stable penetration on the market of passenger and light commercial vehicles, some 65-70 % of light vehicles and as much as 95% of the newly sold heavy vehicles for 2021 were driven by IC engines. Given that the transport infrastructure is not yet fully ready for the transition to EVs, a more likely scenario in the near future is greater presence of hybrids and the use of biofuels as appropriate alternatives to reduce local and global emissions.

According to this data, IC engines are not likely to go out of use in the near future. While the number of vehicles driven by IC engines might drop, special machines, construction equipment, ships and other heavy vehicles that rely on the power and durability of diesel engines will almost certainly stay in use. This in turn means that most of the shortcomings related to the use of IC engines will remain, including above all, their ability to pollute.

The exacerbation of air pollution and global warming as a result of the transport sector and particularly road transport emerged as a major environmental concern around the 1980s and has remained a relevant topic ever since. That is when most Western European countries, USA, Japan and others, started to introduce specific maximum allowable concentrations of certain elements and compounds in the exhaust emissions of IC engines for passenger and freight vehicles, first limiting the exhaust opacity, and later introducing strict limits on components such as: carbon monoxide, carbon dioxide, nitrogen oxides, particulate matter, sulfur dioxide, volatile compounds, and unburned fuel.

The presence of lead and sulfur oxides in the ambient air was reduced drastically after a complete ban on petrol with lead additives and sulfur in diesels. However, air pollution today and the rest of the harmful components from an IC engine's exhaust emissions are a byproduct of the combustion process. Catalysts, filters, and other filtering solutions in the engine's exhaust manifold, provide a partial reduction to these components, but a complete reduction could only be achieved by adjusting (or calibrating) the engine's operating variables. This emphasizes the need for new methods to adjust the engine's combustion and optimize its operation in accordance with the environmental norms and regulations, but also meet the operational needs of the vehicle and the driver.

PhD Thesis

Today's diesel engines contain numerous subsystems that enable better performance, optimal fuel economy and compliance with strict emissions targets. But with each new subsystem (such as high-pressure fuel injection, exhaust gas recirculation, charge cooling and turbocharging), the number of input variables in the engine's electronic control unit (ECU) increases. This leads to an increase of the dimensions of the control matrix and poses a challenge for rapid calibration and optimization of the engine, which in turn is vital in adjusting the engine's performance across its operational range of speeds and loads.

Modeling and computer simulations are tools that allow for better understanding of the dynamics of engine operation and lead to the creation of a comprehensive picture of the challenge of controlling their subsystems with the required level of complexity and abstractness. Consequently, an understandable and easily adaptable model provides a much-needed basis for successful engine design and calibration.

Therefore, my PhD is aimed at developing a mean-value engine model (MVEM) of a diesel engine built in Matlab's Simulink environment, which models the turbo-charging process and the combustion that takes place in a test engine. The model should respond to input excitation from the driver, sensor data and predict the quantity of different pollutants in the exhaust emission. Moreover, the model introduces a novel approach that relies on the use of artificial neural networks and Volterra serries modeling to estimate a certain number of its parameters through statistical regression, thereby significantly improving the model's accuracy while reducing simulation computational cost and running time. The model itself facilitates an engine's calibration process, while allowing for the optimized settings to be fed into the test engine's ECU for real world application.

The scientific value of this research is foremost in understanding the inter-dependence of engine control with the output engine operating characteristics and output emission. At the same time this research will lead to determining the accuracy of the simulation techniques used in the design of new diesel engines, in order to provide more accurate tools that can be used to design more efficient diesel engines in the future.

Research visit goals

By the time I visited the University of Bath, my home university had already approved my PhD thesis, which meant that I was able to start the research envisioned to achieve the goals set out in my PhD. Due to their popularity in the IC engine research circles, I had been following the University of Bath's Institute for Advanced Automotive Propulsion Systems research and publications, so I had a pretty decent idea of their capabilities as a scientific research institution, and their vast contribution to the automotive industry especially when it came to the testing and calibration of IC engines.

This allowed me to identify the following goals regarding the time I was looking to spend at IAAPS:

- Benefit from my supervisor's and my peer researchers' knowledge and experience to improve and expand on my original thesis idea;
- Take full use of the university's access to some of the world's leading technical literature databases to identify the newest and the emerging trends in automotive propulsion and IC engine's ecological calibration and optimization through modeling and control; and finally
- Identify and access the appropriate modelling tools for 0 and 1-Dimensional IC engine modeling and the methodological research steps to gather IC engine data in order to validate my model.

In summary, I tried having concise and realistic aims ahead of my visit, which allowed me to approach them in a successive manner and eventually achieve them. The expected end results on my part included publishing our results, sharing our findings, and applying them to my thesis. Furthermore, I was hoping to take part in an active scientific-research project where my knowledge and skillset good be put to use, to sort of return the favor and build a foundation for future joint cooperation between my home university and the University of Bath.

Results

As soon as I arrived at the University of Bath, I was attached to one of Prof. Richard Burke's (my supervisor) teams as a visiting postgraduate researcher working on a British government sponsored project (APC Trident) performed in cooperation with Cummins Turbo Technologies. The project's focus was on the engine's air handling devices, which are critical in managing the combustion process which dictates overall efficiency and pollutant emissions. The work spanned conventional Diesel engines where the greatest impact can be had in the short term, but also covered alternative fuels like Natural Gas and future fuels including Hydrogen.

Very early on in my visit we decided that we can improve my model's accuracy by training the artificial neural networks and the Volterra series emissions model using a larger engine parameters dataset. Additionally, I had only considered using steady state engine data for my model, but thanks to my peer researchers' input we decided that it would be best to use transient (or dynamic) state engine data, since most of the driving consists of engine transient operation and the fuel economy and exhaust emissions during transient conditions are much worse compared with those in the steady state.

This was followed up by a thorough literature review on regression modelling using neural networks and the tools used in the process. Moreover, I studied the newest transient driving cycles such as the New European Driving Cycle (NEDC) and the Worldwide harmonized Light-duty vehicles Test Cycles (WLTC) to be able to use them in my thesis. Being a part of APC Trident meant I could use one of the engine test cells set up through this project, so I was able to test two different sized diesel engines (the 2.2l and 2.0l Ford Duratorq). Being sufficiently modern in terms of the subsystems both engines used, especially their turbochargers and the exhaust gas recirculation systems, made them very relevant to the current emissions output based on the share of light-duty vehicles on today's roads driven by such and similar-sized engines. The testing data was gathered using state of the art measuring equipment in a controlled environment that limited almost all external influences on the engine's operation.

The next and final step was aimed at improving a 0-Dimensional model built in Matlab Simulink's simulation environment I had developed prior to visiting Bath. The additions to my model included a more detailed turbocharger subsystem model, as well as an update to the Neural Networks and the Volterra series emission model using the data gathered through the transient engine tests. The fit for the neural networks showed a coefficient of determination $R^2=0.988$ indicating almost an ideal fit of the data. This increased the overall accuracy of the model by roughly 15-20 % and it performed particularly well in estimating the emissions output from the engines.

Future work

I know I made the most of my 5 weeks at the University of Bath to further my research towards the completion of my PhD thesis in virtually all aspects and I can confidently say that I managed to achieve all the goals I set prior to visiting. In fact, the time spent in the UK allowed me to significantly better the quality of my thesis and apply its results back in Macedonia. There are still, however, multiple aspects of my research that need smoothing out, but thanks to my input on APC Trident where I am lending my engine calibration and optimization skills in Matlab's Model-based calibration toolbox, Prof. Burke prolonged my visiting postgraduate researcher status to the end of February 2023, so I should be able to address these challenges (such as validating my model) in the next couple of months.

A small segment of the results achieved with the use of neural networks and their training using larger datasets has already been submitted for publication at an industry and academia leading conference - The 26th conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction - PRES'23 which will be held in Thessaloniki, Greece in October of 2023. The amount of engine testing data collected and the accuracy of the MVEM model, along with presenting a novel approach in regression modeling is a very relevant topic that facilitates emissions control in IC engines. Securing funding can be quite challenging for a PhD student, but I am optimistic that if a new funding opportunity arises this will allow us to publish at least two more scientific papers in leading scientific journals and conferences.

Furthermore, we discussed a future visit by prof. Burke to Macedonia and the Faculty of Mechanical Engineering in Skopje, as a member of my PhD thesis evaluation committee, which in most likelihood will take place at the start of 2024. Multiple avenues of securing funding for joint projects between my home university and the University of Bath in the field of future propulsion technologies, are also currently being looked at and considered, however with neither the UK nor Macedonia being a part of the EU, finding common funding sources has so far been quite difficult.

Conclusion

Visiting the University of Bath and IAAPS was an experience unlike any other. This statement should not be taken lightly, as I am certain that the amount of applicative research I conducted in Bath over the period of 5 weeks would have taken me a whole semester, if not more, back home.

First, I successfully achieved all the goals of my research visit. This included updating and improving my MVEM diesel engine model through the introduction of neural networks that were trained using a transient engine data set based on the most recent driving cycles (NEDC and WLTC). In itself, this meant that I improved my understanding of the methodology used to test IC engines, collect IC engine data, and use this data to build a statistical regression model that I used to improve the accuracy and reduce the computational cost of the MVEM model.

Additionally, we defined concrete steps to further the cooperation between my home university and the University of Bath. This includes but is not limited to my participation in the APC Trident project which ends in February of 2023, jointly publishing the results of our findings (at least one research article per year), hosting prof. Burke in Macedonia as a member of my PhD thesis evaluation committee and very hopefully securing funding in 2023 for a joint research project in the field of future propulsion technologies.

Moreover, an event that I found very special to be a part of, was being invited to address the 4 cohorts of PhD students at the Advanced Automotive Propulsion Systems - Centre for Doctoral Training on my experience of visiting and doing research at the University of Bath. What I loved about this event was that I could stress how important it was for me both as a person and as a professional working in research and academia to conduct a part of my PhD research abroad and the personal growth associated with this event.

In conclusion, the support I got from both the members of the APC Trident project team, as well as prof. Burke as my supervisor, really made me feel at home in Bath. It was foremost the change of scenery and the different professional backgrounds, opinions and ideas I came in contact with that made this experience so remarkable. I am sure that these are lasting friendships and professional connections that can only grow and that will benefit every one of us in the future.

Appendices

Appendix 1 Photos of the research conducted in the engine test cell

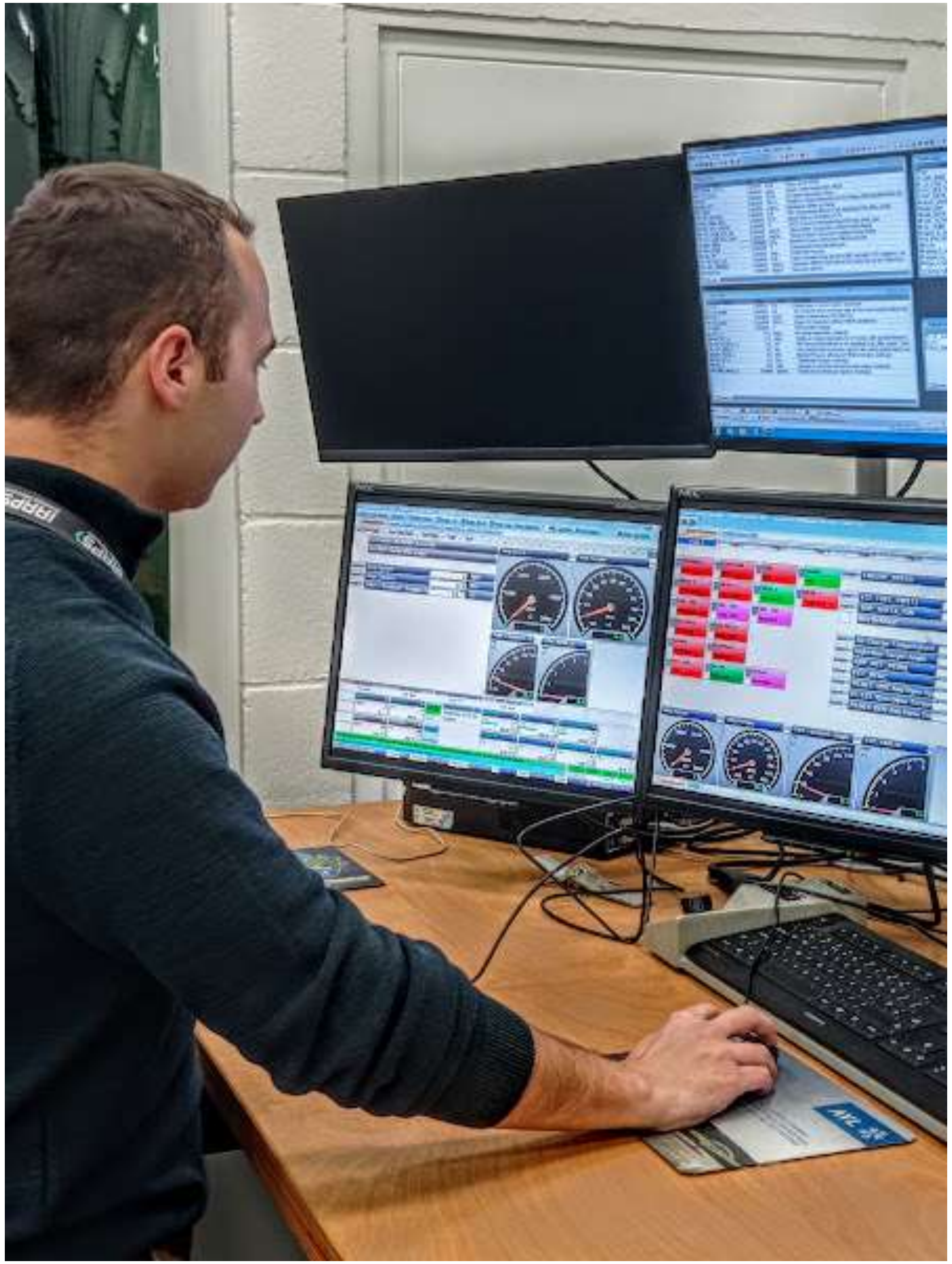

Photo 1 Setting up the engine-testing software

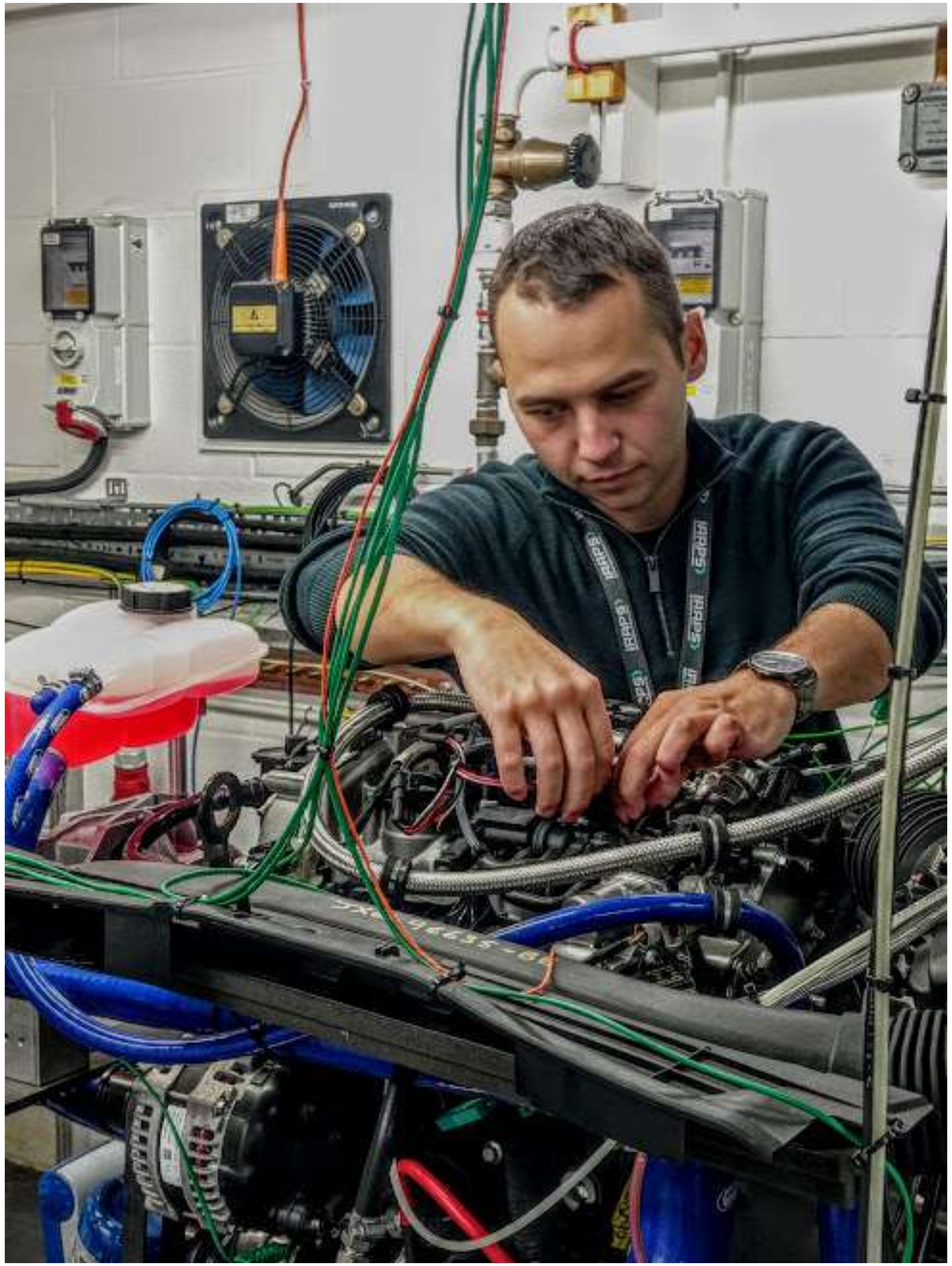

Photo 2 Connecting sensors to the engine

Photo 3 Ford Duratorg 2.0l Engine on ABB Engine Dynamometer

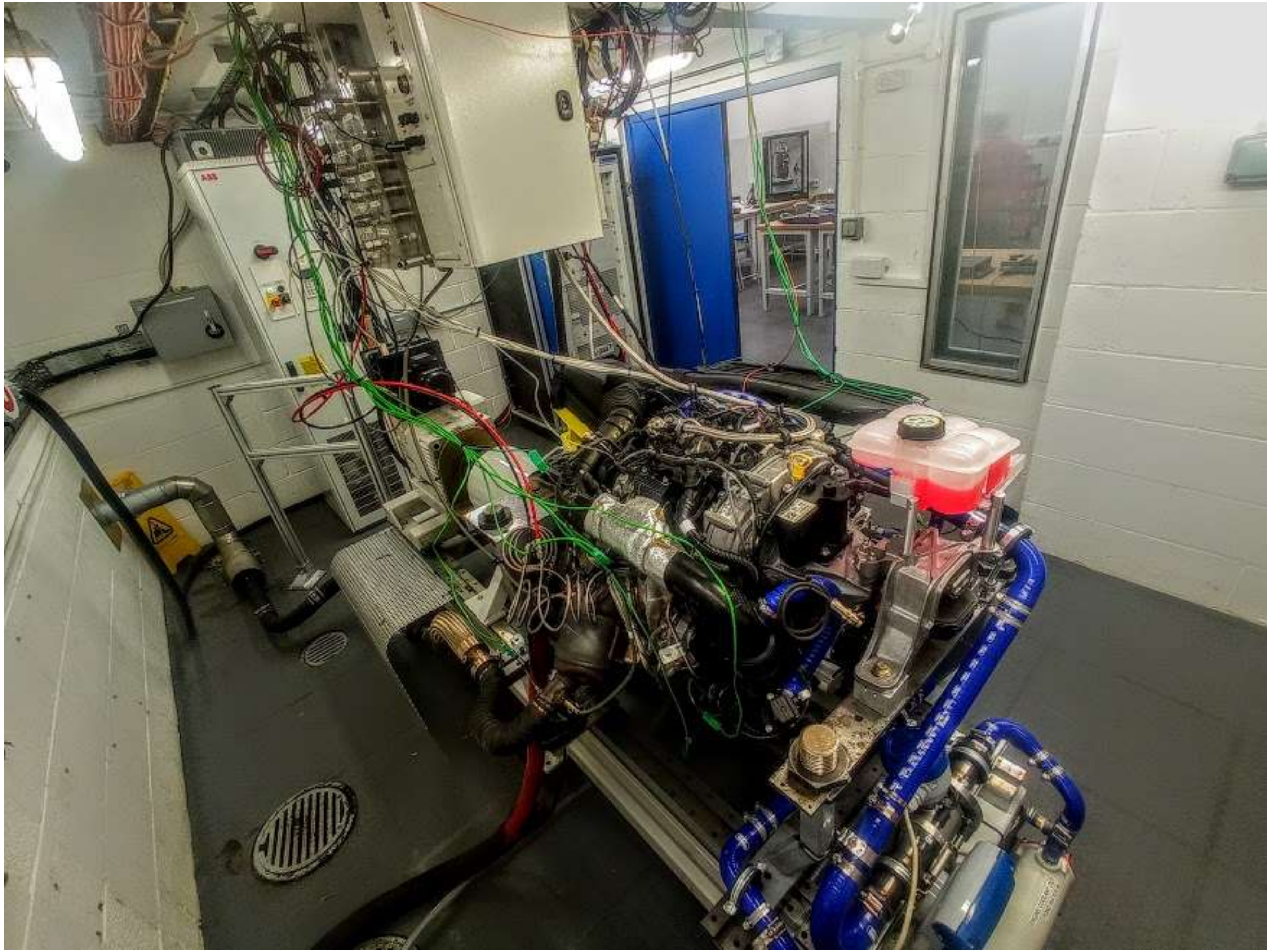

Photo 4 Engine sensors connecting to the engine management system