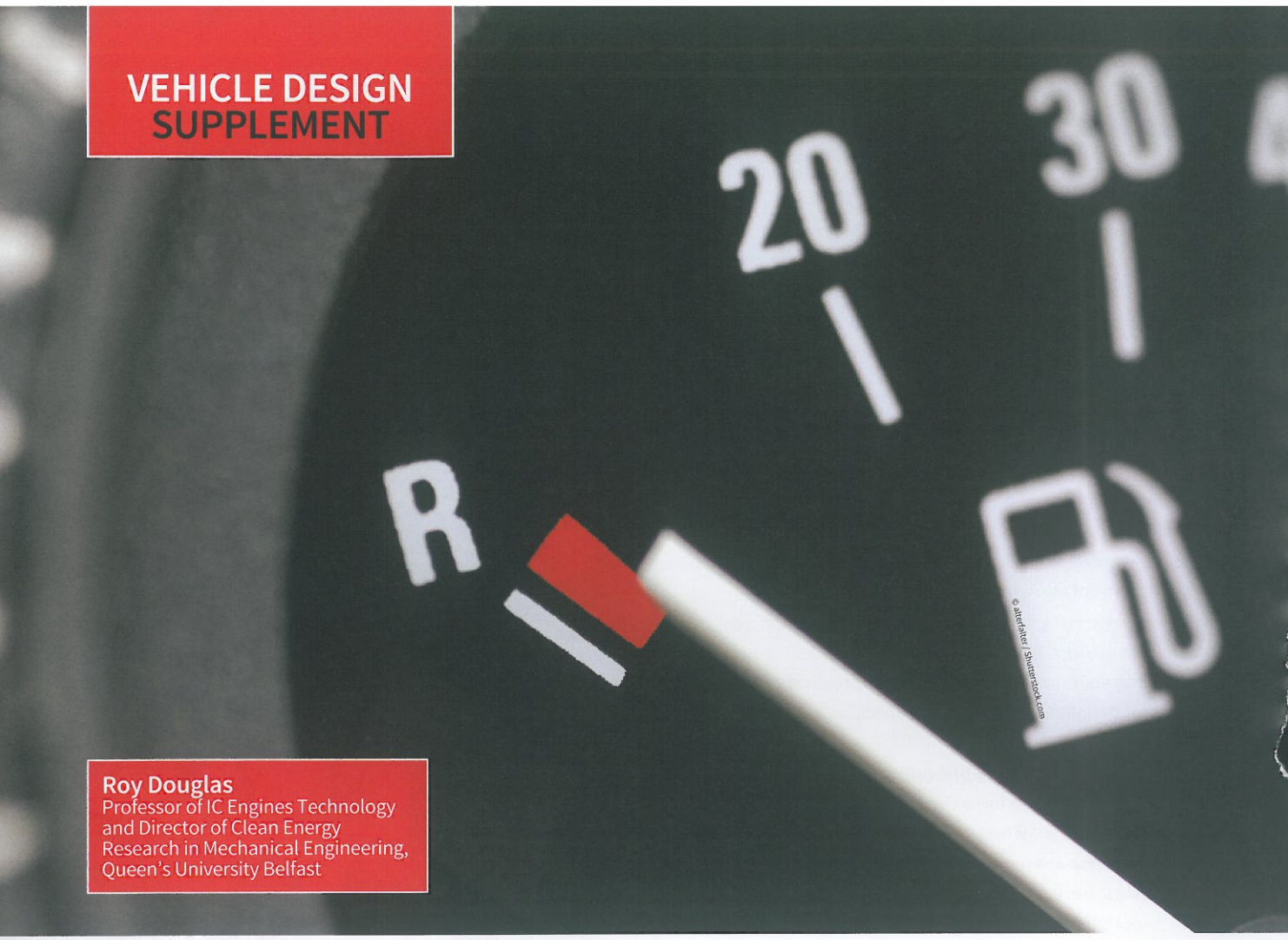


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Designing city bus engines to improve fuel consumption

TERS (Thermal Energy Recovery System) is a three-year collaborative project funded by the Technology Strategy Board (TSB) and Invest Northern Ireland with the aim of reducing CO_2 emissions and improving fuel consumption in city buses through capture and reuse of waste heat, or thermal energy recovery, from the bus engine.

TERS integrates pioneering thermal management and control concepts into a hybrid diesel-electric double-deck bus. Heat lost in the exhaust of a modern diesel engine can represent up to 40% of the available chemical energy content of the fuel used with a further 20-30% lost to the engine coolant system. The TERS project has focused on capturing this heat energy that would normally be wasted and converting it into useful power. The challenges in this project were huge but the potential for fuel economy improvement was also very significant.

"TERS integrates pioneering thermal management and control concepts into a hybrid diesel-electric double-deck bus"

The project commenced in 2010, with a UK consortium led by Wrightbus and including Queen's University Belfast (QUB), Revolve Technologies and Ricardo Plc and is now approaching completion with the new system fitted in a hybrid bus for testing and demonstration. A Wrightbus Gemini 2 Hybrid double-deck bus, on loan from FirstGroup plc, was chosen as the powertrain to allow ease of integration of the TERS design into the demonstrator. This bus has a full, series-hybrid, diesel-electric powertrain with a 2.4L Ford Puma

turbo-diesel engine. The project was carried out in five stages of development: modelling and specification; design and build; system testing and calibration; systems installation in the bus; and vehicle testing and demonstration.

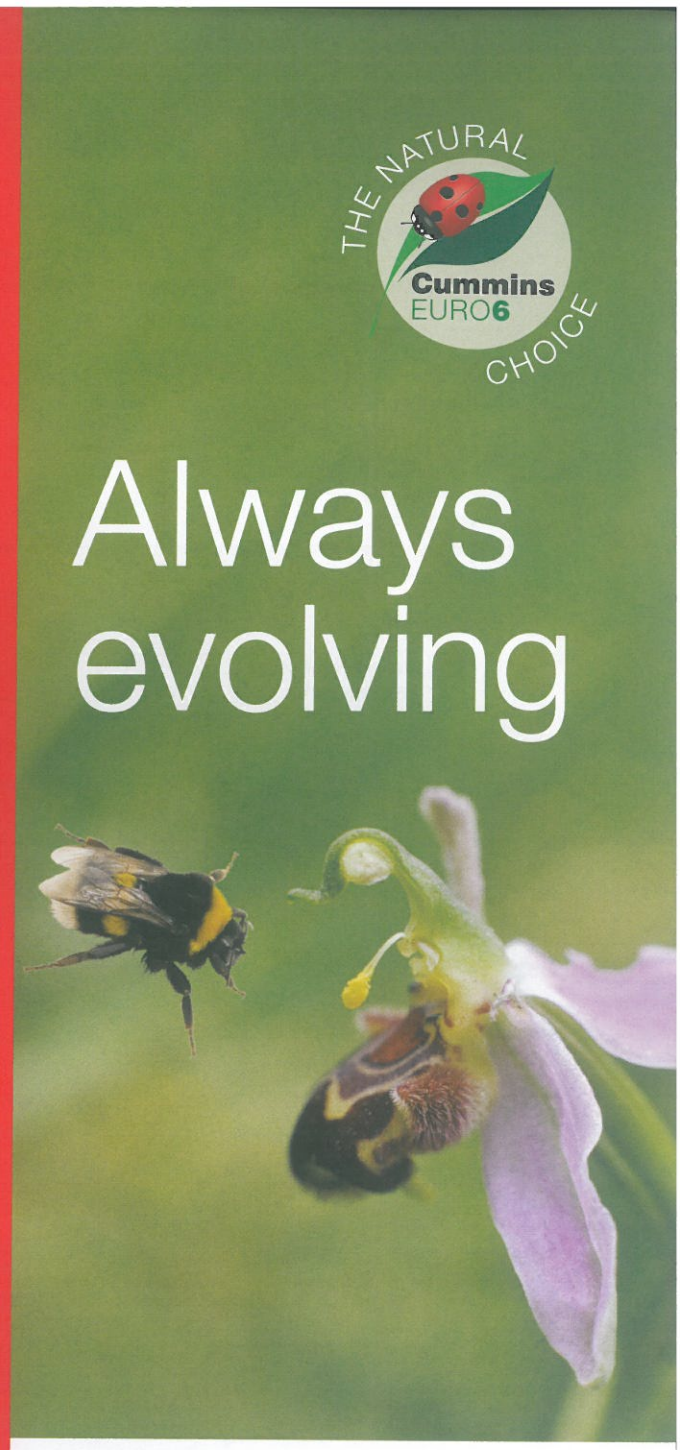
The Organic Rankine Cycle (ORC) was chosen as the appropriate technology at an early stage in the project for optimisation but was limited by component availability. In an ORC, a low-boiling-point, organic fluid is pumped at high pressure around the power circuit, as shown in **Figure 1** (page 50). Heat is added in a boiler/heat-exchanger to boil the liquid producing a high-temperature, high-pressure vapour. This vapour is then passed through an expander to extract energy and produce useful power. The final process in the cycle is to condense the vapour back to a liquid in preparation for pumping. In the example (see **Figure 1**), the engine coolant and exhaust heat exchangers act as the boiler to deliver the vapour to the power expander. The key components are the expander and the heat exchangers as the design and performance of these components determines the overall performance of the ORC.

The first stage of development was modelling of the proposed system and of operation in the bus to assist in system specification and design. This work was carried out jointly between Ricardo Plc and QUB and managed by Wrightbus. Engineering Equation Solver (EES) was chosen as the tool for ORC system modelling to investigate fluid selection, operating conditions and component selection. Fluid properties were provided by REFPROP, a database of properties

"Heat lost in the exhaust of a modern diesel engine can represent up to 40% of the available chemical energy content of the fuel used with a further 20-30% lost to the engine coolant system"

supplied commercially by the US National Institute of Science & Technology (NIST). A specialised ORC fluid was chosen on the basis of performance, availability and cost so the main phase of modelling was to investigate system operation. Ideally, a high temperature around 300ºC and a high pressure around 50 bar would be chosen for best system efficiency and this was supported by the modelling study. However, operating pressure was limited by fluid selection and by design specification of both heat exchangers and expanders so a pressure limit of 20 bar was imposed. During this stage of development, the Wrightbus, hybrid-bus, drive-cycle model was also applied to determine engine operation and available waste heat for the ORC for subsequent engine testing.

The second stage was for the design and build of the ORC system to turn the potential into reality. The main part of the work was carried out at QUB with oversight and support by Wrightbus and Ricardo. The control system was developed by Wrightbus based on the current-generation of the hybrid bus control system. The modelling exercise had provided a series of specifications for typical systems and system layouts with indication of potential performance and efficiency. Some main components were relatively easy to source: compatible pumps are readily available, a plate heat exchanger is well suited for coolant engine heat and a condenser was selected from the standard range available for bus air-conditioning. However, exhaust heat exchangers and power expanders are in very limited supply with



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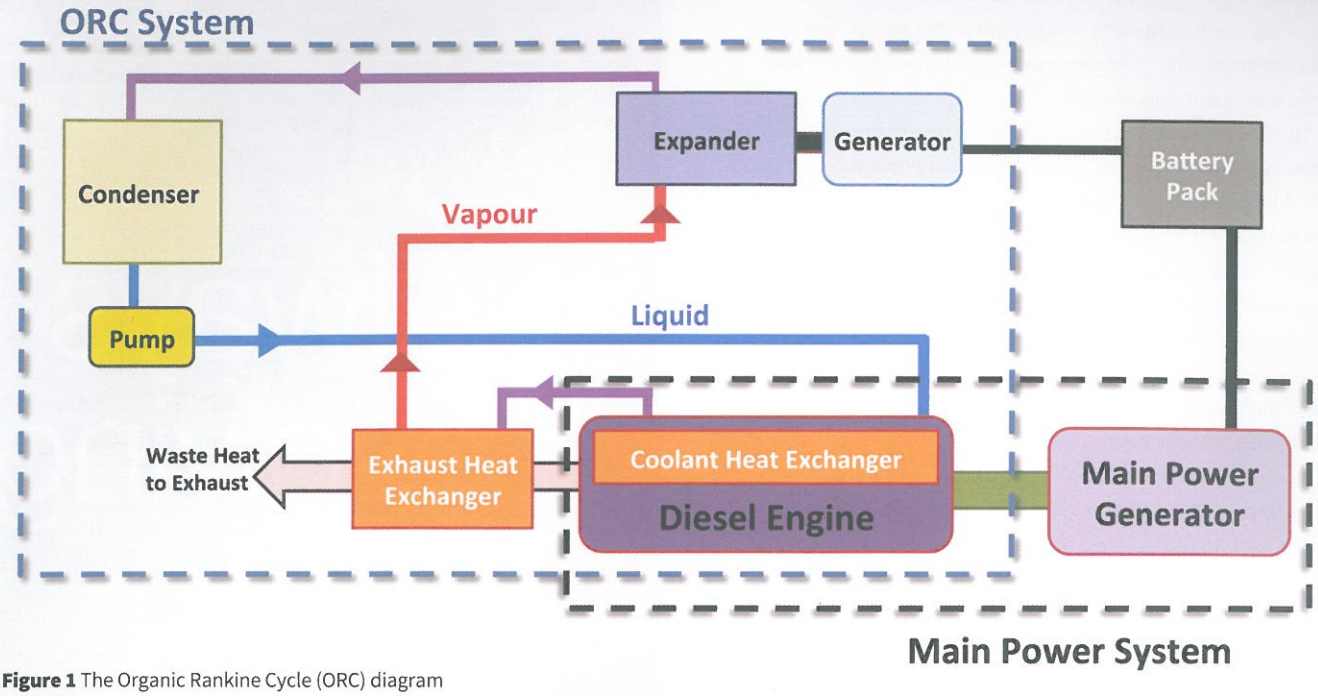


Figure 1 The Organic Rankine Cycle (ORC) diagram

limited performance. As a result, peak operating pressure was limited to 20 bar to match the specification of an exhaust heat exchanger supplied by a UK company, GEA Heat Exchangers Ltd. Choice of expanders was very limited, so a scroll design was selected and supplied by a US-based company, Air Squared Inc. Although a 5kW version was available, it was decided to use two 1kW units with separate circuits for both coolant and exhaust. This design was better matched to operating conditions for inner-city bus operation, whereas the more-powerful 5kW unit would be better suited to higher-speed operation such as trucks or coaches.

The third stage was the main testing phase both of the ORC systems and of the Ford engine. During the design and build phase of the ORC systems, the engine was installed on a dynamometer testbed at Revolve Technologies. A set of four test points were chosen based on the drive-cycle modelling study by Wrightbus. The engine was instrumented and a full energy balance carried out at each operating point to provide full thermal data for the ORC testing phase. The



A Gemini 2 double-deck bus was loaned from Wrightbus to help with the TERS project

coolant ORC system was tested first in the QUB labs with a boiler as the heat source for coolant heat. The expander was installed on a dynamometer and tested on air to check operation and to assess performance. The ORC was tested separately without the expander to evaluate system operation. Once well tested separately, the full ORC circuit was assembled and tested over a range of operating conditions and heat input. The same process was applied to the exhaust-heat ORC system using a high-temperature electrical furnace as the heat source.

"On completion of the laboratory testing, the full ORC systems were then integrated into the demonstrator bus by Wrightbus, converting it to a mobile laboratory"

Once separate system testing was complete, the ORC systems were fully assembled with the expanders and with AC generators as the power absorbers. The systems were then shipped to Revolve and installed in the engine test cell for evaluation of the complete TERS system: engine and ORC units. The engine was operated at the same set of test points with the engine acting as the heat source for both the coolant ORC system and the exhaust ORC system. It was at this point that the full system could be evaluated and the potential realised. Results showed that the original target of 10% improvement in fuel consumption and CO_2 emissions could be realised, with an optimised system and bespoke components.

On completion of the laboratory testing, the full ORC systems were then integrated into the demonstrator bus by Wrightbus, converting it to a mobile laboratory. This was a difficult process, due to the size and complexity of the ORC systems. The hybrid battery pack was relocated into the lower-deck passenger compartment to allow installation of the exhaust heat exchangers in the engine bay. The rest of the ORC systems, including the pumps, expanders and condensers, were also located in the passenger compartment. The systems were fully instrumented to laboratory standards and the new control strategy fully implemented.

The final stage was the vehicle testing: statically, on road and on a chassis dynamometer. The Wrightbus Gemini 2 double-deck used in the TERS project was provided by FirstGroup plc and was converted into an effective mobile laboratory. This allowed much of the testing to be carried out directly on the bus, with minimal additional equipment. The system was rigorously tested in static mode with an electrical load bank for power absorption. Road testing of the bus was also conducted to evaluate the full operational package. The vehicle is currently undergoing SORT 1-3 cycles (Standardised On-Road Testing Cycling), benchmarking performance against baseline SORT tests carried out earlier on the same vehicle before the TERS systems were fitted. Initial testing has already delivered some very encouraging results, both in terms of fuel economy and CO_2 emissions. Once the results are completed, the TERS team will be looking at the potential for introducing some of the technologies that have been developed in the project into future production vehicles and potential off road applications.



The Wrightbus vehicle on show at a recent low carbon industry event

"The new systems have been designed, built and tested; the potential of the TERS approach has been successfully demonstrated and, although testing has not yet been completed, we expect to meet the fuel economy target of 10% improvement"

This has been a very successful project meeting the original targets set at the outset. The new systems have been designed, built and tested; the potential of the TERS approach has been successfully demonstrated and, although testing has not yet been completed, we expect to meet the fuel economy target of 10% improvement.

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Roy Douglas is Professor of IC Engines Technology and Director of Clean Energy Research in Mechanical Engineering at Queen's University Belfast. He has over 35 years of experience in the areas of engine research and development, systems modelling and automotive after-treatment. For the past 10 years, Roy's research has concentrated on automotive after-treatment and energy management, with particular emphasis on catalyst ageing and applications such as waste heat recovery from engines using Organic Rankine Cycle technology. As an academic, Roy has an extensive list of publications in the area of automotive research with many awards and research grants. He is a Senior Member of the School of Mechanical Engineering and a Member of the Management Board. The School has received top research ratings in the last three UK Government Research Assessment Exercises and has been continually ranked in the top 10 Mechanical Engineering Schools in the UK since 1996.