**Institution: Loughborough University**

**Unit of Assessment: B12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering**

**Title of case study: A 60% reduction in diesel use: the impact of optical diagnostics on dual-fuel engines**

**1. Summary of the impact** (indicative maximum 100 words)

Loughborough University's (LU) research collaboration with The Hardstaff Group has resulted in a commercial Oil-Ignition-Gas-Injection system (OIGI®), which substitutes natural gas for Diesel oil in heavy goods vehicles. Using optical diagnostics OIGI® was redesigned, increasing average substitution rates from 45% to 60%. The economic impact for Hardstaff was a fuel saving of £406k per annum. The research allowed Hardstaff to create new business with Mercedes-Benz in the UK and Volvo in Sweden. OIGI® reduces $CO_2$ by up to 15%, harmful nitrogen oxides and particulate emissions by 30%. The research also demonstrated, for the first time, dual fuel technology in small, high-speed diesel engines, paving the way for its application in passenger cars.

**2. Underpinning research** (indicative maximum 500 words)

Dr Andrew Clarke and Professor Graham Hargrave (joined LU in 1999 and 1996 respectively) have made detailed studies of dual-fuel technology (natural gas and Diesel) and working with The Hardstaff Group, have developed a robust and flexible dual fuel technology.

In 2001 work on dual fuel technology was first addressed by Dr Andrew Clarke and became the subject of Dr Jill Stewart's PhD thesis "Combustion Diagnostics of a Dual Fuel Engine: An Experimental and Theoretical Study" (LU 2005) **[G3.1]**. This study concerned theoretical predictions and experimental measurements to find the performance/emissions characteristics for different gases. The work was published in the proceedings of SAE **[3.1]** and subsequently as an invited paper in a special issue on alternative fuels in the IMechE Journal of Automobile Engineering **[3.2]**. In a parallel effort, dual fuel technology was being investigated by the Nottingham based Hardstaff Group to retrofit to their fleet of 100 vehicles.

2006 saw the first consultancy project between Loughborough and the Hardstaff Group. Hargrave initiated a series of tests using optical diagnostics to investigate key process parameters. Particle image velocimetry (PIV), a technique pioneered by the Loughborough Optical Engineering Research Group, was used to characterise gas injectors to measure flow velocity and laser sheet imaging measured the degree of mixing prior to combustion. The short pulse Diesel injection (essential for dual fuel mode) was characterised using a novel liquid injection set-up and high-speed video analysis.

In 2008 this research, together with the theory developed by Stewart and Clarke, was exploited in a new Oil-Ignition-Gas-Injection (OIGI®) system that, by way of an innovative control system that worked alongside the vehicle's electronic control unit, could be exploited in a wider range of vehicles including Mercedes Benz Actros trucks that were then being introduced to the Hardstaff fleet. The Hardstaff Group funded a further PhD - "Modelling Compression Ignition Engines", Dr. Steve Johnson, Loughborough University (2008-2011) **[G3.2]** - to continue the application of optical diagnostics and to produce a multiple zone combustion model to forecast the performance over a range of operating conditions.

In 2009 East Midlands Development Agency (via its Transport iNet) awarded a development grant to the Hardstaff Group/Loughborough University to build a full-scale test facility for the production of dual fuel power systems **[G3.3]**. This joint facility has been used to establish phenomenological models of dual fuel combustion and to further optimise the process **[3.3, 3.4, 3.5]**. The new facility has three dedicated test engineers and this has dramatically speeded-up dual-fuel engine development.

From 2007 to 2010, the collaboration extended to the development of predictive models for flame propagation in premixed gaseous mixtures with varying gas composition, investigating methane from biogas sources containing hydrogen. Experimental measurement of flame propagation rates in turbulent premixed methane/hydrogen/air mixtures was conducted at Loughborough, providing data for reacting LES model development and validation in collaboration with Naples University **[3.6]**.

**3. References to the research** (indicative maximum of six references)


3.1 Patterson, J., Clarke, A. and Chen, R., "Experimental study of the performance and emissions characteristics of a small diesel gen-set operating in dual-fuel mode with three different primary fuels", SAE Paper No 2006-01-0050, *New Diesel Engines and Components and CI Engine Performance for Use with Alternative Fuels, SP-2014*, Society of Automotive Engineers, Inc., USA, Proceedings of the SAE 2006 World Congress & Exposition, Detroit, Michigan, USA, April 2006, pp 1-11, ISBN 0-7680-1749-1. DOI: 10.4271/2006-01-0050, **Peer-reviewed international conference.**

**3.2 Stewart, J., Clarke, A. and Chen, R., "An experimental study of the dual-fuel performance of a small compression ignition Diesel engine operating with three gaseous fuels", *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 221(8), 2007, pp 943-956, ISSN 0954-4070. DOI: 10.1243/09544070JAUTO458, Impact factor 0.583.**

3.3 Clarke, A. and Hargrave, G.K., "Measurements of laminar premixed methane-air flame thickness at ambient conditions", *Proceedings of the Institution of Mechanical Engineers, Part C Journal of Mechanical Engineering Science*, 223(C8), 2009, pp 1969-1973, ISSN 0954-4062. DOI: 10.1243/09544062JMES1259, **Impact factor 0.633.**

**3.4 Stewart, J. and Clarke, A., "A three-zone heat-release rate model for dual-fuel combustion", *Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science*, 224(11), 2010, pp 2423-2434, ISSN 0954-4062. DOI: 10.1243/09544062JMES1955, Impact factor 0.633.**

3.5 Johnson S., Clarke A., Fletcher T., and Hyland D., "A phenomenological approach to dual fuel combustion modelling" Proceedings of the ASME 2012 Internal Combustion Engine Division Fall Technical Conference ICEF 2012 September 2012, Vancouver, BC, Canada.Peer-reviewed international conference.

**3.6 Di Sarli, V., Di Benedetto, A., Long, E.J. and Hargrave, G. K., "Time-resolved particle image velocimetry of dynamic interactions between hydrogen-enriched methane/air premixed flames and toroidal vortex structures," Int. J of Hydrogen Energy, 2012, 37, pp16201-16213, ISSN: 0360-3199, Impact factor 3.548.**


**Grants and contracts:**

G3.1 2001-04: Studentship (Jill Stewart) "Combustion Diagnostics of a Dual Fuel Engine: An Experimental and Theoretical Study" EPSRC/Lister-Petter, £47k Dr Andrew Clarke (PI).

G3.2 2008-10: Studentship (Steve Johnson) "Modelling of Duel Fuel Compression Ignition Engines" £90k, The Hardstaff Group, Dr Andrew Clarke (PI).

G3.3 2009-10: Development Grant "Demonstration Project Force – Future On-Road CI Engines" £694k Project EMX06157 East Midlands Development Agency, Dr Andrew Clarke (PI), Prof. Graham Hargrave

G3.4 2010-12: Research Grant "High Speed Dual Fuel Direct Injection Engines with Advanced EGR and Injection Strategies to Reduce Carbon Dioxide Emissions" £148k TSB/EPSRC, Dr Andrew Clarke (PI), Prof. Graham Hargrave.

The turbulent flame propagation research, providing the under-pinning validation data for LES model development for gas engine combustion prediction [3.6], led to on-going collaborations with Dr. V. Di Sarli at Naples University and Prof. H. Kawanabe at Kyoto University **[L1]**. The research provided a unique data-set for methane and methane/hydrogen combustion that has been used for fundamental model development **[L2]**.

L1. Invited Lecture, Prof. G. K. Hargrave – University of Kyoto, "Optical diagnostics for natural gas

engine research," 2010.
L2. Dr. E. Long, "Turbulent premixed flame propagation in methane/air mixtures," won best paper in Institute of Physics Young Researchers meeting, 2010.

**4. Details of the impact** (indicative maximum 750 words)

In this section we present evidence that the research cited in s2 and s3 has had the following three major impacts:

- economic benefit (reduced running costs) in the haulage industry
- environmental benefit (reduced emissions) nationally and internationally
- change in approach to new fuel systems in industrial production.

**Impact 1: Economic benefits to haulage sector**

The optical diagnostics applied by Hargrave in the period from 2006-2010 and the theory developed by Clarke from 2001 **[3.3, 3.4]** allowed Hardstaff to introduce their innovative new Oil-Ignition-Gas-Injection (OIGI®) system in 2008. The research allowed the average Diesel substitution rate (by energy) to be increased from about 45% to a natural gas content of about 60%. The immediate impact of this was reduced running costs for the Hardstaff haulage business that operates a fleet of more than 100 heavy goods vehicles in the UK. At current pricing the increased substitution rate offers a saving of £406k p.a. and compared to a similar sized fleet operating on 100% Diesel fuel a saving of £1.6M p.a. **[5.1]**.

The application of the theory developed by Clarke **[3.3, 3.4]** has allowed the OIGI® system to be reconfigured for other engines and has reduced the experimental time necessary to re-map the control system from around two weeks to one day **[5.1]**. This has created a further revenue stream. The Hardstaff Group is now an approved Mercedes-Benz Dealer that supplies the OIGI® system as an approved retro-fit or OEM system on all Axor and Actros long haul trucks in the UK. In 2012 this business was worth approximately £2.8M and with current orders is expected to double in 2013 **[5.1]**. In addition a Scandinavian subsidiary, Hardstaff AB, located in Göteborg Sweden, was opened in 2010 to provide OIGI® systems for Volvo FL and FE trucks. This business was worth approximately £1.3M in 2013 **[5.1]**.

**Impact 2: Environmental benefits**

The precise control that is afforded by the OIGI® system means that it can be optimised to reduce emissions and adjusted to run on carbon neutral biogas and other biofuels **[5.1, 5.2]**. The £694k Hardstaff/Loughborough University full scale test facility funded by East Midlands Development Agency was commissioned in 2009 and allowed the environmental impact of dual fuel technology to be assessed particularly under transient loads. Relative to a comparable Diesel engine, dual fuel offers a 15% reduction in carbon dioxide and at least 30% reduction in harmful nitrogen oxides, smoke and particulate emissions **[5.1]**. The environmental impact of dual fuel technology is considerable in the UK, Europe and beyond and resulted in Hardstaff and Loughborough University winning the prestigious Lord Stafford Award in 2010 for "Innovation for Sustainability" **[5.3]** and Hardstaff Group being runner-up in the industry's Low Carbon Champions Awards hosted by the Institute of Mechanical Engineers **[5.4]**.

**Impact 3: Changing approaches in industry**

As a result of the work of Johnson and Clarke and work conducted under the TSB/EPSRC Grant "High Speed Dual Fuel Direct Injection Engines with Advanced EGR and Injection Strategies to Reduce Carbon Dioxide Emissions" a state-of-the-art computer model of the dual fuel combustion process has been developed **[G3.4]**. It has been shown that with multiple Diesel injection events, it is possible to increase the substitution rates in small, high speed engines. This work paves the way for the exploitation of dual fuel systems in passenger cars and small/medium commercial vehicles.

**5. Sources to corroborate the impact** (indicative maximum of 10 references)

The following sources can be made available at request:

**Statements**

5.1 Letter from Hardstaff
5.2 The Hardstaff dual fuel technology is detailed in the company webpages: http://www.hardstaffgroup.co.uk/site/hardstaff-dual-fuel-technologies

**Awards**

5.3 Hardstaff Group and Loughborough University winner of the Lord Stafford Award 2010 for "Innovation for Sustainability", http://www.hardstaffgroup.co.uk/site/awards/lordstaffordaward
5.4 Hardstaff Group runner-up in the Low Carbon Heavy Duty Vehicle Manufacturer of the Year 2011, http://www.lowcvp.org.uk/lowcarbonchampions/results.asp