Institution: Cardiff University, School of Engineering
Unit of Assessment: UoA 15
Title of case study: Low-Carbon Engine Design Through Integrated Simulation-Validation
1. Summary of the Impact

Cardiff University's research has provided quantitative characterisation of transient fuel sprays under engine condition for the first time. This has enabled integrated design optimisation of Gasoline Direct injection (GDi) engines, through computer simulation validated by Cardiff's experimental measurements. The method has been developed and used in collaboration with Ricardo, a world-leading engine design consultancy, and has resulted in:

Economic impact

- Ten contracts, generating Ricardo revenue of over £20M from major OEMs worldwide (including Ford, GM, SAIC, Proton and Chrysler);
- An additional $7M Ricardo contract secured with a major US manufacturer (2013);
- Increased licence sales (over £1M/year sales worldwide) for commercial software 'VECTIS';
- A novel tri-fuel Spray-Guided Direct Injection (SGDI) production engine designed and developed on behalf of PETRONAS (Malaysia).

Environmental impact

There have been substantial reductions in global CO_2 emissions. Prior to 2012, GDi engine production had resulted in over 20M tonnes CO_2 reduction globally, including 10M tonnes across Europe. A global reduction of 10M tonnes/year is predicted by 2020. Gasoline engines designed or developed by Ricardo in collaboration with Cardiff have provided a considerable contribution to this reduction. Cardiff's measurement techniques provided an essential step in designing these engines. For example, the PETRONAS engine uses 20% less fuel and produces 80% less NOx.

Improved Professional Engineering Practice

Cardiff's experimental validation methodology has enabled Ricardo to design engines through simulation rather than step-wise empirical development, significantly reducing lead time.

2. Underpinning Research

Cardiff's Innovations in Optical Diagnostics for Industrial Applications

Cardiff's expertise in this field dates back over 30 years to the development of bespoke laser velocimetry systems for the UK-AEA. Subsequently, Cardiff was first to develop and publish *phase-resolved* laser-Doppler anemometry for the *transient* fluid-dynamic 'precessing vortex core' phenomenon in industrial burners and cyclone-separators. This research was undertaken by Syred (then Professor) and O'Doherty (then Lecturer), between 1993-95. This resulted in the prestigious 'Combustion Institute' Sugden award for best UK paper (1997) and a Dyson contract for characterising dust separator prototypes (O'Doherty, 1998). Syred was Dyson's invited expert witness (1998-2000) in their successful 'Dyson versus Hoover' legal case, utilising Cardiff's pedigree and knowledge of transient swirling flows. Cardiff also won the 'NATO award for best international Collaboration' (with Russia and Ukraine) for its related work on gas turbines (2002).

Cardiff's Temporally-Resolved Spray Characterisation Breakthrough

Bowen (then Lecturer, 1995-97) and Bates (Reader, 1995-97) developed Cardiff's 'phase-resolved' methodology to *Phase* Doppler Anemometry (PDA), enabling enlightening time-resolved characterisation, *for the first time*, of 2-phase/droplet, swirling, transient flows (e.g. sprays). Traversing this methodology over a fine grid also enhanced the 3D spatial resolution [3.1], as shown in Figure 1. This breakthrough found application in the automotive sector, as these are precisely the type of flows found within automotive engine fuel sprays, where conditions are extremely challenging, namely: millisecond injection time-scales, 1-100 micron diameter droplets, 3D swirling flows with velocity magnitudes over 100 m/s, coupled with the extreme in-cylinder environments of high pressures and temperatures.

Cardiff-Ricardo Research Development, Communication and Strategic Partnership

Ricardo offers globally-leading innovation in the automotive industry. Through an EPSRC/Ricardo funded PhD studentship (Comer 1996-99), Ricardo sponsored Cardiff's proposition to prove and develop *phase-resolved PDA* for automotive injectors, and to develop its applicability to engine conditions. The research enabled Ricardo to validate for the first time its *transient*, 3-dimensional, 2-phase commercial spray models (within its commercial code VECTIS). Moreover, this was done under controlled, simulated engine conditions (with high pressures and temperatures), enabled by a new optical spray-cell which was designed and commissioned in Cardiff's laboratories.

VECTIS is an international, industry-standard software product, focused on in-cylinder processes in the automotive sector, which is used by leading international engine manufacturers such as [text removed for publication]. The Cardiff technique established confidence in the VECTIS spray modelling, provided by like-for-like validation (rather than time/spatial integration), hence attracting a wide range of international clients and delivering *validated* spray modelling for engine design. The technique was presented first at a British Combustion Institute meeting (Bowen, 1997). A Cardiff-Ricardo strategic partnership was established to consolidate this on-going research and technology breakthrough, and facilitate the application of the phase-resolved technique to a wide range of global automotive clients. Cardiff has effectively industrialised the spray characterisation process to the extent of ***now carrying out all of Ricardo's spray characterisation work for use in both research and customer programmes*** [5.1]. Complementary to this, Brighton University undertake Ricardo's reciprocating optical engine R&D.

A continuous sequence of five EPSRC/Ricardo funded PhD studentships at Cardiff over the past 15 years has enabled development of the spray characterisation methodology (see Figure 1) for: fuel injection parameter studies [3.2]; critical analysis of optical techniques [3.3]; Computational Fluid Dynamic (CFD) model validation [3.4]; injection into high pressures/temperatures and impingement [3.5]; and novel injector designs involving alternative fuels. The integrated simulation/validation methodology now routinely practiced by the Cardiff-Ricardo partnership has proven invaluable for optimal design of GDi engines. Cardiff's pipeline of innovative optical diagnostic techniques has continued, most recently with another new, laser-based technique which quantifies transient in-cylinder liquid fuel films, utilising laser-induced fluorescence principles [3.6].

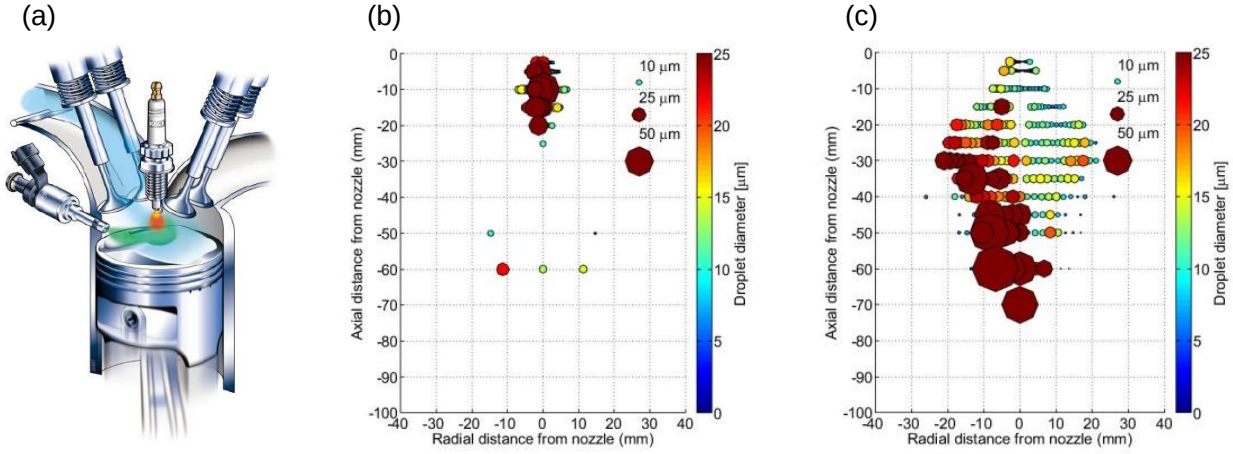

Figure 1. **Examples of 'instantaneous' characterisation of a Pressure-Swirl GDi Spray**
(a) 'Wall-Guided' GDi Operation. (b) Fuel droplet size 0.75-1.0 ms after injection. (c) Fuel droplet size 1.75-2.0 ms after injection.

3. References to the Research

3.1 **Comer M. A**., **Bowen P.J**., **Bates C.J**., Sapsford S.M. and Johns R.J.R. (1999) Transient 3D analysis of a DI gasoline engine injector spray, *Atomisation and Sprays*, Vol. 9 No. 5 pp. 467-482, ISSN 1044-5110

3.2 **Comer M.A.**, **Bowen P.J**., Sapsford S.M. and Johns, R.J.R. (1998) The transient effects of line pressure for pressure-swirl gasoline injectors, *ILASS-EUROPE '98*, Proceedings of the

14th International Conference on Liquid Atomisation and Spray Systems, July 1998, UMIST, Manchester, pp. 364-370

3.3 **Comer M.A.**, **Bowen P.J**., **Bates C.J.** and Sapsford S.M. (2001) Critical appraisal of current laser diagnostic techniques for GDi Spray kinematics quantification, *Journal of Optical Diagnostics in Engineering*, Vol 5. No. 1, ISSN 1364-4173 (online journal)

3.4 **Comer M.A.**, **Bowen P. J.**, Sapsford S.M. and Kwon S.I. (2004) A parametric sensitivity study of GDI spray characteristics using a 3-D transient model, *International Journal of Automotive Technology*, Vol. 5 No. 3 pp. 145-153, ISSN 1229 9138

3.5 **Kay P.J., Bowen P.J.**, Gold M.R. and Sapsford S.M. (2012) Transient fuel spray impingement at atmospheric and elevated ambient conditions, *Experiments in Fluids*, Vol. 53 No. 4 pp. 873-890, ISSN 0723-4864, 10.1007/s00348-012-1334-0

3.6 **Alonso M., Kay P.J., Bowen P.J.**, Gilchrist R. and Sapsford S.M. (2010) A laser induced fluorescence technique for quantifying transient liquid fuel films utilising total internal reflection, *Experiments in Fluids*, Vol. 48 No. 1 pp. 133-142, ISSN 0732-4864 10.1007/s00348-009-0720-8

4. Details of the Impact

The crucial importance of Cardiff's research breakthrough to the success of the new GDi engine designs is highlighted by Ricardo's Computer Aided Engineering (CAE) Manager James Mullineux in 'Ricardo Quarterly' [5.2]: *'**Validating a detailed VECTIS spray model** of the selected injector is the first step in being able to simulate the operation of a new form of combustion system'.* He continues in [5.3]: ***'a significant aspect of the achievement of the T-SGDI research project has been the ability to produce validated VECTIS models of the combustion system that can be used to provide a truly predictive assessment of the engine under operation**.* Although the approach used on the research project included a CFD correlation exercise both with the (Cardiff) spray rig and an optically accessed engine, the latter would, *as Mullineux concludes, not be necessary as part of a production CAE process.'* Details of the major, wide-ranging impacts achieved as a result of the spray characterisation methodology developed at Cardiff University are described below.

Economic impact

Significant international business has been secured for Ricardo, the industrial sponsor and global leader in automotive engine design. The Cardiff-Ricardo methodology has been applied and disseminated through Ricardo and their international clients. Ricardo have, for example, used this integrated modelling-validation methodology, in partnership with Cardiff, to develop bespoke gasoline engine designs and fuel-injection operational strategies on behalf of a ***broad range of international clients such as*** [text removed for publication]. These ***contracts have generated over £20M revenue for Ricardo*** [5.1], and significantly more revenue for Ricardo's OEM clients through revolutionary performance improvements and resultant sales.

Recently [5.2] the Ricardo/Cardiff partnership used its methodology in the ***design of a fuel-flexible SGDI engine for Malaysian-based multi-national PETRONAS*** (a *Fortune 100* global company). This engine was designed to run efficiently and flexibly on ethanol, methanol and gasoline fuel. Hence, not only does this engine offer the ***efficiency gain associated with SGDI, but also the significant additional environmental benefit of utilising sustainable fuels***. Cardiff worked very closely with both Ricardo and PETRONAS, including regular PETRONAS research staff visits to Cardiff's laboratories [5.1], to ensure effective understanding and implementation of the integrated modelling/validation approach in the engine design process.

This SGDI engine represents a step change in direct injection (DI) combustion system design, reaching levels of fuel consumption for diesel engines, but without the associated costs due to throttle-free operation. SGDI is even more dependent upon accurate temporal/spatial spray simulation than its predecessor, the 'wall guided' GDi design, thus further emphasising the crucial role of Cardiff's methodology. ***PETRONAS has recently entered into agreements with far-eastern OEMs that will see derivatives of this engine entering volume production from 2014, rising to in excess of 100,000 units per year [5.1].***

Ricardo's commercial code VECTIS, which Cardiff's research enabled Ricardo to validate and hence which contributes to its market lead, ***generates more than £1M in revenues per annum*** for this innovative, high-tech UK multi-national company. It is used by global companies such as [text removed for publication] for combustion system design and development.

The integrated Cardiff-Ricardo methodology has enabled the design of GDi engines more quickly and robustly, thereby gaining significant competitive advantage. Ricardo continues to use the integrated methodology to secure new orders in the growing GDi market. For example, it used the Cardiff-Ricardo methodology to ***secure a further $7M contract with a major US car manufacturer in 2013 [5.1].***

Environmental impact

Bosch [5.4] state that GDi engines have increased market penetration from 2% (in 2002) to 22% (in 2012). The global market for road vehicles in 2012 was around 84 million [5.5]. When coupled with downsizing and boosting (for which DI is a major enabler), GDi technology is estimated to reduce CO_2 emissions by over 20%. Hence, interpolating data between 1996-2012 shows that ***GDi engine technology has already been responsible for a reduction in new car emissions of over 20M tonnes globally, including 10M tonnes across Europe***. As Ricardo is the leading international consultancy in GDi engine design, having undertaken GDi design projects with many of the major global OEMs since 1996, the Cardiff-Ricardo partnership has provided a considerable contribution to this global CO_2 reduction.

Furthermore, it is projected that around 26 million cars with GDi engines will be produced per annum by 2020 [5.4]. This represents a reduction of CO_2 emissions from new cars of ***over 10M tonnes per annum (by 2020) through the adoption of GDi technology, and integration with usage of alternative fuels will result in further CO_2 savings.***

Impact on engineering practice

Ricardo claim that the ***PETRONAS project is one of their best examples of successful modelling-led engine designs [5.1, 5.3],*** where test-bed commissioning of the first prototype performed generally as predicted. *Validated* spray modelling and integrated design (enabled by Cardiff's research) is crucial to ensuring such a successful result [5.2] and for promotion of the elusive goal of truly simulation-led (rather than empirical) engine design and manufacture. Ricardo state, ***'The (Cardiff) fuel spray rig will always be a crucial part of the CAE tool chain ..... As such, we have a highly efficient and cost-effective CAE methodology that can now be applied in the development of production implementations of this type of advanced and highly fuel-efficient combustion technology'*** **[5.3].** Hence, it is clear that the Cardiff-Ricardo methodology provides additional impact through improving professional engineering practice.

In sum, Cardiff's research has revolutionised the design of modern gasoline engines worldwide, with global economic and environmental impacts of major significance.

5. Sources to Corroborate the Impact

5.1 Confirmation of economic benefits and impact of Cardiff-Ricardo partnership: Steve Sapsford, Ricardo Global Market Sector Director, (steve.sapsford@ricardo.com)

5.2 Cardiff's contribution to improved GDi engine designs : Ricardo Quarterly (pp. 19-22), 4th Quarter, 2012 http://www.ricardo.com/PageFiles/24669/RQ_Q4_2012.pdf

5.3 Cardiff validation of VECTIS spray model critical to computer-aided engine design: http://www.ricardo.com/PageFiles/24138/Software_CAE_issue_2_2012.pdf

5.4 Bosch data for GDi Market Penetration. http://www.bosch-presse.de/presseforum/details.htm?txtID=6406&tk_id=108

5.5 Data enabling evaluation of CO_2 reduction through GDi: International Organization of Motor Vehicle Manufacturers (OICA) http://www.oica.net/category/production-statistics/