Institution: University of Oxford

Unit of Assessment: 9 – Physics

Title of case study: Validating the design of the AJ133 engine

1. Summary of the impact

Improved measurement of fuel behaviour in automotive engines has contributed to the success of the AJ133 V8 engine, which powers over *[text removed for publication]* vehicles sold since 2009. The research, carried out at the University of Oxford in collaboration with Jaguar Land Rover (JLR), developed techniques to improve the understanding of combustion dynamics in engines and consequently enabled improvements to fuel consumption, emissions and engine reliability. Impacts include contributions to (1) JLR's improved engine design process and (2) improved fuel efficiency and thus lower emissions.

2. Underpinning research

The impacts arise from underpinning research carried out at the University of Oxford led by Professors Paul Ewart and Richard Stone. The research developed novel, laser-based diagnostics for measuring key combustion parameters, in collaboration with Shell and Jaguar Land Rover (JLR). Shell provided a synthetic fuel, which allowed fuel evaporation effects to be studied and JLR provided a prototype single cylinder engine with optical access, which enabled experimental testing.

Although the research described here is one part of a multi-university collaborative EPSRC grant, the Oxford research was distinctive in its specific focus on combustion diagnostics with lasers. The research undertaken at the University of Oxford improved the Planar Laser Induced Fluorescence (PLIF) method for optical diagnostics of combustion in engines.

The PLIF technique used a laser to produce fluorescence in a tracer molecule added to the fuel, which could then be imaged and tracked. While PLIF was a commonly used technique to understand combustion dynamics, it was not sufficiently accurate to monitor the complex combustion process in engines. The tracer could only follow one fuel fraction and the tracer molecule's behaviour would not necessarily reflect that of the fuel. There were also uncertainties in the fluorescence yield arising from unknown effects of collisional quenching.

To address these issues, the Oxford team made a series of improvements to the PLIF method [1].

- They devised and implemented a new method that took account of the different volatility of gasoline fractions by adding a tracer for each major fraction.
- They measured the effects of the exhaust gas residuals left over from the previous ignition, and found them to be a significant factor in fuel mixing diagnostics during engine firing.
- To account for collisional quenching, they implemented a new technique using a laser-induced grating that provided unprecedented precision of temperature and air/fuel ratio measurements.
- They used three-colour pyrometry and full-bore imaging with adapted optics to provide information on the generation of soot in the cylinder.

These improvements culminated in an improved method they named Quantitative Planar Laser Induced Fluorescence (QPLIF) [1]. Using QPLIF, they demonstrated:

- the effects of different injection strategies on fuel spray and mixture preparation;
- that accurate measurement of the air/fuel ratio could monitor the temporal evolution and distribution of air/fuel mixtures during the compression stroke of the engine;

- that cyclic variations (important for smoothness of acceleration and fuel economy) were correlated with engine operating conditions.

This research was led by Oxford researchers Professor Paul Ewart (1979 – present), Professor Richard Stone (1993 – present) with Benjamin Williams (DPhil student 2005 – 2008 then PDRA 2009 – present) and Xiaowei Wang (DPhil student 2004 – 2008).

3. References to the research (Oxford authors, * denotes best indicators of quality)

*[1] B Williams, P Ewart, X Wang, R Stone, H Ma, H Walmsley, R Cracknell, R Stevens, D Richardson, H Fu and S Wallace, (2010), Quantitative planar laser-induced fluorescence imaging of multi-component fuel/air mixing in a firing gasoline direct injection engine: effects of residual exhaust gas on quantitative PLIF, *Combustion and Flame,* 157, 1866-1878, doi: 10.1016/j.combustflame.2010.06.004, citations: 6 (Scopus). *This paper was winner of the 2010 Sugden Prize, an annual award for contributions to combustion research, awarded by The Combustion Institute. All non-Oxford authors were at Shell or JLR.*

4. Details of the impact

The Oxford research team used the new QPLIF technique to test, in Oxford, a prototype single cylinder engine for JLR's AJ133 V8 engine. QPLIF was used to confirm JLR's in-house computational fluid dynamics (CFD) predictions of fuel spray and mixture preparation in the cylinder, providing JLR with a validated model.

The purpose of the Oxford validation step was to improve the quality of the design process and ultimately the end product. JLR say: *"From a business perspective emphasis on putting the most reliable data, including CFD data supported by robust validation, into the early development process has contributed to the quality of the end product, in this case the production of the AJ133 engine."*

The validation provided by Oxford enabled JLR to exploit their model in the engine design process. JLR say that *"CFD is an important stage in the development of new engines and all subsequent engine development programmes. The high quality data provided by the University of Oxford for CFD validation has allowed the CFD simulation data to be used with greater confidence. The quality and the confidence JLR place in the data was due to the expertise of Professors Ewart and Stone and the research facilities at the University of Oxford."*

In relation to the specific work described in this case study, JLR said *"when there were extreme pressures on the JLR research budgets, we prioritised the continuation of research with the Professors Ewart and Stone at the University of Oxford at times when many other projects were being cut."* JLR also identify the value of the work for subsequent R&D, explaining that it *"improves the quality of engineering and allows the Jaguar Land Rover engine experimental work to be more focused."*

JLR used their validated CFD model to make improvements to and complete the design of the AJ133 5-litre V8 engine, which was launched in 2009. The new engine included a new spray-guided, homogeneous direct injection combustion system that was tested in Oxford. The AJ133 engine is available as an option in Jaguar models (XFR, XJR, XKR-S, XKR, XJ, XK) and Land Rover models (Discovery, Range Rover, Range Rover Sport). The price range of these vehicles is from £45,000 to over £100,000 and *[text removed for publication]* vehicles containing an AJ133 engine have been sold between the launch in 2009 and 31st July 2013. From this, one can estimate sales of between *[text removed for publication]*.

JLR say that *"the vehicles have been well received by the customers, resulting in increased sales and profits for the group; the engine is a major influence on the customer appreciation of a* *vehicle".* This is reflected in reviews of the engine. *Autocar* described the power delivery system as *"silky smooth and linear"* and *"at motorway speeds, the engine is quiet and refined, yet can also deliver impressive in-gear acceleration"* [B]. *Top Gear* called it *"one of the world's great V8s"* [C].

Car manufacturers now have strong motivation for their engines to use the minimum fuel. They have to meet increasingly stringent emission regulations and customers are becoming very conscious of rising fuel costs. Car ignition requires a rich fuel mix near the spark but the rest of the mixture can be lean (less fuel, more air): by optimising the combustion process, it is therefore possible to reduce fuel consumption and hence emissions. *[text removed for publication]*. While this is difficult to quantify, even a small improvement in fuel efficiency will have had a significant environmental impact over so many vehicles. The previous engine model, the AJ33, met the EU4 European Emission Standard but the AJ133 meets the EU5 standard, which has more strict requirements on nitrogen oxides and atmospheric particulate matter.

5. Sources to corroborate the impact

[A] Letter from Manager of Powertrain Research at Jaguar Land Rover (held on file) confirming impact of the research on JLR, and sales figures.

[B] 'Jaguar XK 5.0 V8', *Autocar,* 30th July 2011,

http://www.autocar.co.uk/car-review/first-drives/jaguar-xk-50-v8

[C] 'First pic. Meet the new Jaguar XJR', *Top Gear*, 20th March 2013,

http://www.topgear.com/uk/car-news/new-jaguar-xjr-revealed-first-picture-2013-03-20