



THE UNIVERSITY OF WESTERN AUSTRALIA

**School of Mechanical Engineering
Submission to
The Department of the Environment and
Heritage
Discussion Paper April 2004**

**Measuring Cetane Number:
options for diesel and alternative fuels**



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1 Executive summary

The University of Western Australia's School of Mechanical Engineering operates a Ricardo E6 standard single cylinder, four-stroke cycle, variable compression ratio, indirect injected diesel engine. The author performed various tests comparing the performance of biodiesel made using various feedstocks with that of fossil diesel in late 2002. Examining the American Society for Testing and Materials (ASTM) standard D613-03b, *Standard Test Method for Cetane Number of Diesel Fuel Oil*, those familiar with this engine are confident that the school can perform tests very similar to this standard at a superior cost-benefit result for Australian industry and government to the current testing regime. The technical arguments follow at the end of this submission. This submission specifically addresses the issues surrounding biodiesel engine testing and ASTM D613 although the engine can test cetane number of a wide variety of fuels.

It is in the national interest to establish an indigenous research base into diesel alternative fuels to assist industry and meet government targets for renewable energy use. In addition to possessing existing facilities requested by the discussion paper, The University of Western Australia has deep research capabilities in a broad range of related disciplines:

- Significant engine research by the Formula SAE racing car team
- Petroleum industry expertise and contacts in the School of Oil and Gas Engineering
- A School of Biomedical and Chemical Sciences that has recently performed biodiesel analytical tests
- Expertise in Australian oil crop feedstocks in the Faculty of Natural & Agricultural Sciences
- Community education via public biodiesel workshops delivered in the chemistry department of the School of Biomedical and Chemical Sciences

Importantly the School of Mechanical Engineering has the experience and technical support to operate the facility properly and consistently. Organisational structures to manage outside consultancy work are well established in the Engineering Design and Consultancy Centre. Postgraduate research funding is obtainable via many channels. Research reliant on specialised instrumentation can be performed cheaper and in a more timely manner than many alternatives due to an on-site mechanical and electrical workshop employing full time technicians familiar with the equipment.

In summary cetane number testing should be performed in Australia to develop the alternative diesel fuel industry. Direct cetane number testing appears more widely accepted than alternative methods. The cost of testing can be reduced by utilizing fit-for-purpose equipment and leveraging existing expertise. This proposal offers the minimum cost, maximum research and development value for the Australian alternative diesel fuel industry. The wider issue at hand is whether Australia wishes to be an importer of alternative diesel fuel technology or an exporter.



Request for use of the school's facilities may be directed to the Dean of the Faculty of Engineering, Computing and Mathematics, Prof. Mark Bush:

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2 Comment on discussion paper issues

2.1 Cetane number test background

The cetane number test is an indirect measure of ignition delay in compression ignition internal combustion engines. It varies the compression ratio of a specialist diesel engine to achieve an ignition delay of a specified crank angle rotation after top dead centre. The test methodology and principle has not changed since it was developed in the 1930's¹. The general theory behind the test is widely known in engineering circles, as outlined in discussion paper 6. However the detail of the test is not widely known as it is rarely used, the cheaper cetane index test is used by industry². A technical summary of the relationship between theory and test method is outlined in section 3.1.

2.2 Discussion paper number 6

The thrust of many submissions³ to the *National Standard for Biodiesel - Discussion Paper* number 6⁴ issued March 2003 was that there is a lack of research data and experience in Australia on alternative diesel fuel quality and engine operability tests. The general argument submitted by several established players in the petroleum and road transport industries, that biodiesel blends should be limited to only 5 vol% or 'B5' because further research validating this blend would not be necessary, implied disinterest in gathering research data to support higher percentage biodiesel blends. This attitude is contradictory to the recommendations of the Transport Energy Strategy Committee's report to the Western Australian government, that the Commonwealth should "facilitate the introduction of cleaner and locally produced fuels such as LPG, natural gas, biofuels (including biodiesel etc.) where there is a clear benefit"⁵. It is also an unjustifiable position given that the consensus of these same submissions was that there existed insufficient and sometimes contradictory information on biodiesel in the public domain regarding

1. The emissions impact of various blends, specifically if NOx increased or decreased
2. Engine performance, whether the approximately 10% lower calorific value of biodiesel compared with petro diesel actually manifested itself in appreciable reduction in engine power output. The author performed engine performance tests in 2002 and found little difference in engine power output over a wide range of operating conditions, although fuel economy was reduced.

¹ Van Gerpen, J., 1996, Cetane Number Testing of Biodiesel, Available: http://www.biodiesel.org/resources/reportsdatabase/reports/gen/19960901_gen-187.pdf

² Chevron, 1998, Diesel Fuels Specification and Testing, Available: http://www.chevron.com/prod_serv/fuels/bulletin/diesel/L2_5_fs.htm

³ Department of the Environment and Heritage, 2004, Establishing a Fuel Standard for Biodiesel - Discussion Paper Submissions, Available: <http://www.deh.gov.au/atmosphere/biodiesel/submissions/>

⁴ Environment Australia, 2003, National Standard for Biodiesel - Discussion Paper, Available: <http://www.deh.gov.au/atmosphere/biodiesel/paper.html>

⁵ Transport Energy Strategy Committee Interim Report June 2003, Available: <http://www.dpi.wa.gov.au/sustain/tescinterimreport.pdf>

The opposing views on whether to adopt European or US biodiesel standards and the discussion on feedstocks highlight the national character of diesel alternative fuels. The discussion paper states in section 6.6 “the cetane number of biodiesel depends on the distribution of fatty acids in the original oil or fat from which it was produced.” It is highly likely Australian feedstocks would differ from European and US feedstocks sufficiently to warrant verification of some overseas literature quoted in the discussion paper. It would be beneficial to the industry to research cetane number in an institution that integrates chemistry, agricultural science and engineering capability. The University of Western Australia offers this expertise.

The concentration on European and US developments in alternative diesel fuels and the wish to harmonise with these standards with minimal Australian empirical research data to support the local relevance of various parameters is regrettable. Thinking that international only means US and Europe ignores the potential upside to developing Australian intellectual property to export to the Asian market. Many rapidly growing Asian nations do not have significant crude oil reserves and are facing increasing air pollution concerns. Australia may still capitalize on its reputation for region-leading technology but other nations will soon overtake Australia in biodiesel research without targeted funding to build a research base applicable to regional climate and feedstocks. This will compromise future export earnings from biofuel feedstocks, intellectual property and produced biofuels.

2.3 Automotive diesel issue for comment

Are you aware of any equipment available in Australia that may be used to test diesel to ASTM D613 (Standard Test Method for Cetane Number of Diesel Fuel Oil)

The oil industry’s accepted practice is to use cetane index and presumably internally gained experience as to the effect of various cetane enhancers. The head of UWA’s School of Oil & Gas Engineering has worked in BP’s Sunbury research centre in England. This single facility performed engine and fuel tests for BP’s worldwide operations. Although cetane improvers are likely to be increasingly deployed in Australia to meet more stringent emissions standards based on the Euro 2/3/4 timetable it appears unlikely these additives will be developed in Australia. It is perhaps likely the Australian operations of international oil refiners would continue using offshore testing facilities similar to the research centre mentioned above. For the purposes of independent compliance verification performed by government it may be advantageous to have a test laboratory under local jurisdiction however.

The Australian Institute of Petroleum’s assertion that there is no cetane engine in Australia⁶ is no doubt true if the cetane number test is ASTM D613 to the letter. The engine specified by this American standard is Waukesha Engine Division’s model CFR F-5 manufactured by a division of Dresser Industries Inc. The current standard version D613-03b section 7.1 note 10 states “The sole source of supply of this engine equipment and instrumentation known to the committee at this time is Waukesha Engine, Dresser Inc., 1000 West St. Paul Avenue, Waukesha, WI 53188.” However there are alternative manufacturers of single cylinder, four-stroke cycle, variable

⁶ AIP submission, 2003, Available:
<http://www.deh.gov.au/atmosphere/biodiesel/submissions/pubs/aip.pdf>

compression ratio, indirect injected diesel engines. The University of Western Australia has such an engine, a British made Ricardo E6 fuel research engine, which has considerable technical and research support. The manufacturer parent company may be contacted at the following address:

Ricardo Consulting Engineers
Bridge Works
Shoreham-by-Sea
West Sussex BN43 5FG
United Kingdom

To determine the Ricardo engine's suitability for producing data of similar quality to D613 would require funding to conduct a research project. Pending a more detailed feasibility study, perhaps modest capital expenditure to purchase or produce specialised instrumentation will be required. This would occur in a response for a request for proposals.

2.4 Biodiesel issue for comment

Are you aware of any equipment available in Australia that may be used to test the Cetane Number of biodiesel to ASTM D613 (Standard Test Method for Cetane Number of Diesel Fuel Oil) or EN ISO 5156 (Petroleum products- Determination of the ignition quality of diesel fuels- cetane engine method)?

The author has not examined EN ISO 5156 and so cannot comment on the engine specified by this test however the argument regarding the substitution of a very similar engine, already installed with significant accumulated experience and supporting resources, holds.

2.5 Options for determining cetane number issue for comment

What is the appropriate means of determining the cetane number of Australian diesel and alternative diesel fuels or a surrogate in place of the direct measurement of cetane number?

The engineering community tends to be conservative and observe long established precedent in matters concerning engineering standards. A direct measurement of cetane number is more likely to convince engine manufacturers to extend warranties to cover diesel alternative fuels. Warranty cover is essential to the market adoption of alternative fuels. Engine manufacturers will often not pay for significant research into alternative fuel development. The cetane number testing issue is part of a wider issue; that more stringent standards seem to be applied to alternative diesel fuels as new market entrants because there is less experience in using them. This can be a market entry barrier.

The research required to validate another model engine for ASTM D613 is much less than the research required to establish acceptance of a different test principle. However development in the field of ignition delay is progressing. There exists an ASTM standard D6890-03a *Standard Test Method for Determination of Ignition*

Delay and Derived Cetane Number (DCN) of Diesel Fuel Oils by Combustion in a Constant Volume Chamber. This standard was published in 2003 in response to a product developed by Advanced Engine Technology of Ontario, Canada⁷. There also exists an alternative engine based German standard DIN 51773 (1996). However industry acceptance of these test methods is indicated by a 2003 European survey of cetane number testing laboratories for the purpose of quality assurance. Of the 22 laboratories that responded all but 2 used the ASTM D613 test method. Further details in section 2.6.

Although it may be argued different testing principles e.g. constant volume method are less dependent on combustion chamber geometry and therefore more representative of changing diesel engine technology, it seems unlikely engine manufacturers will adopt a predictive engine performance parameter that does not derive from an engine based test. The appropriate means for determining the cetane number of Australian diesel and alternative diesel fuels is engine testing by means of a single cylinder, four-stroke cycle, variable compression ratio, indirect injected diesel engine

2.6 Worldwide availability of cetane number test labs

The Institute for Interlaboratory Studies⁸ Spijkenisse, the Netherlands organizes an annual proficiency testing program of cetane number as part of *Proficiency testing schemes for Petroleum and Petrochemical Products: Fuels*. The latest round was performed in October 2003⁹ and included 27 laboratories worldwide, most in Europe and 5 in the USA.

Incidentally the organization also collates tests on biodiesel samples, the latest being in May 2003¹⁰, it found the reproducibility of many of the parameters in Biodiesel standard prEN 14214 to be problematic. Quoting section 4.2 *Performance Evaluation for the Group of Laboratories* “without further statistical calculations it can be concluded that for many tests there is not a good compliance of the group of participating laboratories with the relevant standards.” This supports the argument put forward by Logical Systems Consulting¹¹ that many parameters in the *Environment Australia Discussion Paper No 6; National Fuel Quality Standards – Biodiesel* are unnecessary. Several submissions recommended the European standard EN14214 by speculating outside their area of expertise e.g. “as the European standards cover a wider range of parameters than the US standards, they appear to represent a more comprehensive approach”¹². If a group of 18 responding certified laboratories cannot produce results within professionally accepted statistical variation this indicates a problem with the parameters selected in the standard.

⁷ Company home page, Advanced Engine Technology, Available: <http://www.aet.ca/>

⁸ Organisation home page, Institute for Interlaboratory Studies, Available: <http://www.iisnl.com/>

⁹ Starink, R.J., 2003, Results of Proficiency Test Cetane Number of Diesel Fuel October 2003, Available <http://www.iisnl.com/pdf/IIS03G04x.PDF>

¹⁰ Starink, R.J., 2003, Results of Proficiency Test Biodiesel May 2003, Available <http://www.iisnl.com/pdf/IIS03G02.PDF>

¹¹ Logical Systems Consulting submission to National Standard for Biodiesel Discussion Paper no. 6 Available: <http://www.deh.gov.au/atmosphere/biodiesel/submissions/pubs/logical.pdf>

¹² EPA Victoria, 2003, Submission to National Standard for Biodiesel Discussion Paper no. 6 Available: <http://www.deh.gov.au/atmosphere/biodiesel/submissions/pubs/epa-vic.pdf>

The ASTM standard D613 mentions a *Diesel National Exchange Group* that performs interlaboratory repeatability tests. However the ASTM web page *Interlaboratory Crosscheck and Proficiency Testing Programs: Petroleum*¹³ does not reveal any program to test cetane number in 2004.

2.7 Options for determining cetane number advantages and disadvantages comment

Quoting from the discussion paper section 4

1. Send samples overseas for cetane number analysis

Likely advantages:

- *Suitable short term solution whilst production and supply levels are low.*
- *Assurance that diesel and diesel alternatives meet cetane specifications.*

Likely disadvantages:

- *Not feasible in the long term due to cost.*
- *Expensive, especially for smaller alternative diesel producers.*
- *Lengthy reporting timeframe on results.*
- *Delays in releasing fuel to market.*

→ Will not develop Australian expertise

A neglected likely disadvantage is that sending samples overseas forgoes developing indigenous expertise in fuel quality parameters relevant to the Australian environment and market conditions.

2. Buy cetane engine

Likely advantages:

- *Long term solution.*
- *Comparable to overseas analysis.*
- *Allows local analysis of cetane number with cost and time savings.* → issue

→ Perform cetane testing for overseas customers

It is not necessarily the case that local testing will reduce the cost or turn around time of cetane number tests. There may be issues of economies of scale that mean an overseas laboratory can perform tests more cheaply than an Australian laboratory. It may be commercially attractive for an Australian cetane number testing laboratory to compete in analysing samples from the Asian region.

Likely disadvantages:

- *Cost (approx. \$500,000), ongoing maintenance and operating costs.*
- *Requires trained staff with high-level expertise.*
- *Reliability and accuracy of results.* → issue
- *Ownership arrangements.*
- *Expertise for operation.*

¹³ <http://www.astm.org/cgi-bin/SoftCart.exe/STATQA/petroleum.htm?L+mystore+qwxo6715+1083248806>



- Lead time to purchase, install, commission and certify engine
- Risk that engine type cetane test will become defunct in future

It is unlikely given the specialist nature and the single source of supply for ASTM D613 certified equipment that the order can be filled before the September 2004 date of effect for cetane number parameter.

It is incorrect to list as a likely disadvantage “reliability and accuracy of results”. There is no reason to suspect that Australian institutions cannot perform tests that laboratories from former Eastern bloc countries with smaller economies and less prestigious scientific institutions than Australia have managed in the latest proficiency testing program outlined in section 2.6.

The standard cetane number test engine does not resemble modern light duty (car and truck) diesel engines. The ignition delay inside an engine is a function of the fuel’s interaction with the cylinder geometry, temperature and pressure conditions. As the pace of change of engine technology increases e.g. increasing popularity of common rail direct injection, it is possible the standard test will become no longer predictive of engine performance. Whether this comes to mean replacement of some Waukesha engine parts, complete abandonment, or steadfast adherence to traditional testing is up to ASTM committee *D02.01 Petroleum Products and Lubricants: Combustion Characteristics*. Committee research reports, unfortunately not in the public domain, do examine issues such as substitution of non-standard instrumentation. One of these is report *78:D-2 Evaluation of Non-Standard Instrumentation for the ASTM Cetane Method (Test for Ignition Quality of Diesel Fuels by the Cetane Method, D 613)*¹⁴ which suggests the committee could be interested in cetane number research performed on alternative engines.

The proposal by the School of Mechanical engineering addresses all the likely disadvantages of buying a cetane engine put forward by the discussion paper.

- Ongoing maintenance and operating costs are likely to be lower than a standalone test facility due to on site mechanical and electrical workshop
- Technical staff already trained in engine operation, academic staff have published research papers
- Ownership arrangements though established precedent of outside consulting and research through Engineering Design & Consultancy Centre
- Diesel alternative fuel tests performed as recently as late 2002

3. Buy new/alternative cetane testing technology

Likely advantages:

- *Cheaper and easier to use than cetane engine.*
- *Allows local analysis of cetane number with cost and time savings.*

Likely disadvantages:

- *Laboratory staff require training.*
- *Compatibility with established test methods.*

¹⁴ List of Committee D02.01 on Combustion Characteristics Research Reports on File with ASTM Available: <http://www.astm.org/COMMIT/R0056-00.pdf>



→ Not currently acceptable by engine manufacturers for warranty specification

The author is unfamiliar with the theoretical basis of alternative cetane testing technology so cannot comment on instruments sold by Advanced Engine Technology outlined in section 2.5. The issue with ignition quality testers is that they are developed by scientific instrument manufacturers as proprietary technology. Therefore the intellectual property developed in Australia using this method is limited to a trained technician. Research performed on the Ricardo engine of the School of Mechanical Engineering, in keeping the University's charter, is publishable in the public domain.

4. Develop cetane indices

Likely advantages:

- *Potentially cheaper in the long term than testing cetane number using combustion process.*

Likely disadvantages:

- *May not be achievable.*
- *If achievable may take a long time to develop.*
- *Specialist knowledge of fuel may be chemistry required.*
- *Limited expertise and experience in Australia on alternative diesel fuel quality chemistry and analysis.*

The author does not have the expertise to comment on this issue

3 Technical considerations

3.1 Cetane number test method and theory

The general cetane number test theory can be found in many engineering textbooks and public domain documents. The test procedure does not actually use n-cetane (hexadecane) or heptamethylnonane (HMN). These are primary reference fuels whose cetane numbers define the theoretical equation

Equation 1

$$\text{Cetane Number} = \text{vol\% n-cetane} + 0.15 \times \text{vol\% HMN} \quad 15.$$

The ASTM standard D613 actually uses a “bracketing by handwheel procedure” where a mixture of secondary reference fuels is formulated to closely bracket the test sample’s estimated cetane number. If this guess is close enough and the higher and lower blends of secondary fuels are within 5.5 the following equation is used to calculate cetane number.

Equation 2

$$\text{CN}_S = \text{CN}_{\text{LRF}} + (\text{HW}_S - \text{HW}_{\text{LRF}}) / (\text{HW}_{\text{HRF}} - \text{HW}_{\text{LRF}}) \times (\text{CN}_{\text{HRF}} - \text{CN}_{\text{LRF}}) \quad 16$$

Where

CN_S = cetane number of sample,

CN_{LRF} = cetane Number of low reference fuel,

CN_{HRF} = cetane number of high reference fuel,

HW_S = handwheel reading of sample,

HW_{LRF} = handwheel reading of low reference fuel, and

HW_{HRF} = handwheel reading of high reference fuel.

The handwheel reading is directly related to compression ratio. It is simply a matter of correlating compression ratios between the Ricardo and Waukesha engines¹⁷ and the respective handwheel readings to utilise the same bracketing procedure to determine cetane number on the Ricardo engine. The only significant difference to be investigated is the combustion chamber geometries outline in section 3.4.

3.2 Reproducibility limits

The cetane number data using the standard engine, when it is considered the range of values of typical diesel check fuels is between 38 and 55¹⁸, is surprisingly imprecise. The statistical terms of interest are: reproducibility, the expected tolerance in cetane number values between independent laboratories; and repeatability, the expected tolerance in cetane number values obtained at the same laboratory. The proposed Australian standard for biodiesel, the *Fuel Standards (Biodiesel) Determination 2003*, specifies a cetane number of 51 (min). If identical samples of nominal cetane number 51 were sent to two different laboratories the cetane number results could be 51 +/- 4.1 and still satisfy ASTM D613 as per Table 1 reproduced below¹⁹. The specification

¹⁵ ASTM D613-03b Equation 1

¹⁶ Ibid. Equation 4

¹⁷ Ibid. Equation X2.1

¹⁸ Ibid. *Reagents and Reference Materials* section 8.5.

¹⁹ Ibid. Table 2

of secondary reference fuels with established cetane numbers (designated T fuel and U fuel available from a specified supplier²⁰) used to ‘bracket’ the test sample limits the practical range of test sample CN_S numbers.

Table 1 Cetane Number Repeatability and Reproducibility Limits

Average Cetane Number Level*	Reproducibility Limits, Cetane Number	Reproducibility Limits Cetane Number
40	0.8	2.8
44	0.9	3.3
48	0.9	3.8
52	0.9	4.3
56	1.0	4.8

* Values for cetane numbers intermediate to those listed above, may be obtained by linear interpolation.

3.3 Engine qualification

The substitution of a Ricardo E6 engine for the ASTM specified engine is not different in kind to a Waukesha engine that is newly commissioned. Both must be qualified by testing reproducibility and repeatability given in D613 section 11 *Calibration and Engine Qualification*. Simply put engine performance is judged satisfactory if testing a check fuel sample is within the tolerance limits specified by the following equation

Equation 3

$$\text{Tolerance limits} = \text{CN}_{\text{ARV}} \pm 1.5 \times \text{S}_{\text{ARV}} \quad 21$$

Where

CN_{ARV} = the cetane number accepted reference value of the Check Fuel

1.5 = a selected tolerance limit factor (K) for normal distributions

S_{ARV} = the standard deviation of the Check Fuel data used to determine CN_{ARV}

This can be verified in a research project using existing human resources in the School of Mechanical Engineering.

3.4 Ricardo E6 vs Waukesha CFR F-5 engine

The standard D613 contains detailed plans for the Waukesha engine in addition to the operating conditions of the cetane number test. Typical indirect injection compression ignition engines operate by injecting diesel fuel into a smaller precombustion chamber where the fuel vapourises. This is connected to a main combustion chamber above the piston head. The total volume of the two chambers and the volume swept by the piston (bore x stroke) determines the compression ratio. The Waukesha engine varies the compression ratio by varying the volume of the precombustion chamber. The Ricardo engine has a constant volume precombustion chamber and varies compression ratio by raising and lowering the cylinder head which changes the volume of the main combustion chamber.

²⁰ Chevron Phillips Chemical Company LP., 1301 McKinney, Suite 2130, Houston, TX 77010–3030 USA

²¹ Ibid. Equation 3