Ricardo UK Ltd
Shoreham Technical Centre
Shoreham by Sea
West Sussex BN43 5FG
United Kingdom

Telephone: +44 (0) 1273 455611 • Fax: +44 (0) 1273 464124

THE BIOFUELS CONSORTIUM PROGRAMME

SUMMARY REPORT OF MODULE 1 - BIOFUEL EFFECTS ON DIESEL PERFORMANCE, EMISSIONS AND ECONOMY IN CONVENTIONAL AND ADVANCED TECHNOLOGIES

Q56058 **RD11/544501.1**
21st December 2011 **Client Confidential**

Author Jon Andersson

Contributors Justin Seabrook, Mark Braithwaite, Simon de Vries, Carmen O'Leary, Craig Charlton, Carl Jemma, Geoff Burchett, Phil Mortimer

Approved

Andrew de Vries
Project Director
Engines Product Group

Ricardo UK Ltd
Shoreham Technical Centre
Shoreham by Sea
West Sussex BN43 5FG
United Kingdom
Telephone: +44 (0) 1273 455611 • Fax: +44 (0) 1273 464124

CONTENTS

EXECUTIVE SUMMARY

A consortium of interested parties was formed in 2010 with a view to undertaking a series of modules of work on the impact of bio-fuels on engine operation. This work package, Module 1 of the programme, included the involvement of AGQM, DfT, OMV, PTT and Ricardo and was targeted at investigating the influence of bio-fuel FAME types and mixes on emissions in a standard, current production light duty diesel engine and a potential future advanced engine technology: in this case an engine running with the same hardware but simulating the inclusion of an adaptive calibration system (closed loop combustion control) that would optimise engine operation.

Different fuel properties will result in different ignition delays depending on the fuel 'combustion quality'. In a standard light-duty diesel engine, this effect leads to a change in engine performance which the calibration is unable to directly respond to. In this case, in order to maintain the same operating condition (speed and torque), the system requires a change in pedal demand, this change will then subsequently impact the operating point within the engine calibration (open-loop control).

With advanced engine control, sensor technologies such as the Beru Pressure Sensor Glow Plug (PSG) provide 'real-time' cylinder pressure measurements. From the output signals of these sensors types, parameters such as ignition delay (typically expressed as a crank angle for a percentage mass-fraction burn), may be used as an input to the engine calibration maps (closed-loop control). In so doing, an advanced engine system may be configured to respond to a change in fuel properties with an optimised calibration.

The fuel chemistry (dictated by the original source material of the bio-components) and blend concentrations was agreed by representatives of the consortium and resulted in 12 test fuels.

Nine of these fuels comprised a matrix that addressed RME, PME and SME at three different contribution levels (0%, 5% and 10%) blended into the mineral diesel reference fuel. Differing contributions of the 3 bio- and mineral diesel components within the 9 fuels enabled the production of several different blends: 1 x B0, 3 x B10, 1 x B15, 3 x B20 and 1 x B30.

The matrix was extended to evaluate 3 other fuels: CME, JME and HVO, all tested as 30% blends. However, CME was eventually omitted, due to difficulties encountered in preparing a suitable fuel sample and its relevance to the overall programme objectives, through agreement with the members and the requirement to minimise the commercial impact of the work.

Types of FAME used were Jatropha, Soy, Palm and Rapeseed. Sourcing of low- volume FAME material proved to be problematic for Ricardo, and as a consequence product was procured as raw oils and transesterified locally within the UK, except for RME which was procured as the methyl ester.

The approach taken to testing was based on the Design of Experiments (DoE) method. This is a system used for series production calibration development where a number of selected steady state results feed into simulated light-duty emissions cycle prediction routines (V-Sim; again used in the development of a series calibration) to estimate regulatory cycle emissions. Two DoE methods were employed: a 'global' DoE approach based on measurements taken over 200 speed and load sites that fall within the NEDC drive cycle speed and load envelope; and a more limited extended duration 'weighted' key-point DoE approach, a series of 6 measurement points that are within the NEDC operating envelope and that are fractionally weighted according to their estimated overall contribution to a NEDC

cycle result. This latter approach is necessary for collecting data for emissions where sample collection necessitates extended sampling periods (e.g. PM matter collection) and for unregulated emissions.

The results of the global DoE study found that when run on the optimal calibration derived for the type approval baseline RF06 fuel (the "Baseline Calibration"), all Biodiesel blends would pass NEDC NOx emission legislation. However due to the lower calorific value of FAME, there is a significant fuel consumption penalty above B10 blends (up to 2.81% with a RME10•SME10 blend). Fuel consumption from HVO30 was similar to, or lower than, RF06.

Optimisation of the engine calibration was able to achieve the engineering target of 0.200g/km NOx and 0.020g/km soot for all fuels excepting SME 10, where it was necessary to relax the engineering target to 0.225g/km. The SME10 NOx level was still within the NOx homologation limit for Euro 4 compliance. Engine-out emissions of CO and HC were consistently reduced from B10, B15, B20 and mixed B30 fuels relative to the baseline fuel by the calibration optimisation process. JME30 was an exception, showing increases in both CO and HC of >10%.

Engine-out emissions of CO and HC from HVO30 were similar to or lower than those from the base fuel.

Following calibration optimisation, fuelling was normalised to within a scatter of ±1% across most fuels, with the exception of RME10 and HVO30, where respective improvements of 3.67% and 1.93% were seen relative to operation on the baseline calibration. However, while the optimisation process had a universal positive effect on fuel consumption, it was unable to completely achieve the fuel consumption seen from the base fuel when testing all FAME blends.

Optimisation at full-load was able to normalise the torque for FAME blends to within +4% and -3% of that measured from the baseline fuel. Results of HVO were generally similar to the base fuel.

Weighted cycle DoE data indicated that there may be some synergistic and antagonistic effects between different FAME types, as seen in the blended FAME fuels. For example, increasing SME content by 5% was shown to have a significant effect of increasing NOx by 5%, but increasing both SME and PME simultaneously by 5%, led to a 5% reduction in NOx.

Also from the weighted cycle DoE, for the unregulated emissions:

There were few significant effects that strongly correlated with FAME type although total lubricant volatility HC was apparently increased by the presence of SME. This may be the consequence of fuel dilution admitting additional oil into the combustion chamber and its survival in the sump to associate with soot in the PM.

Though levels were generally low, emissions of nitrous oxide (N_2O) appeared elevated by increases in the level of SME in the fuel, although further in-depth work would be required to verify this finding. As a greenhouse gas, this is likely subject to future regulation. Nitric oxide emissions showed an upward trend with increases of RME, SME and PME, though only the PME effect was significant.

Comparisons of the levels of unregulated emissions emitted from FAME blends indicated significant increases in emissions levels from the base fuel in a number of unregulated components: in particular the N_2O and NO species, while other components were emitted at similar levels. Formaldehyde emissions were generally reduced with FAME blends.

Linearity of blend effects from the weighted cycle DoE:

Results from three fuels at 3 different FAME levels on the baseline calibration: B0 [RF06], B15 [PME5•RME5•SME5] and B30 [PME10•RME10•SME10] suggested that soot emissions were linear - decreasing with increased FAME at high loads and from the NEDC, but increasing with increased FAME at low loads. Additionally CO and HC results were potentially linear, showing reduced CO and HC with increased FAME at all conditions.

No clear evidence of linearity was apparent with NOx, noise, Pmax or the various mass fractions burned.

B30 effects from the weighted cycle DoE:

Three different B30 fuels were compared directly with each other, and with the base fuel, on the baseline calibration:

- An advanced 1st/2nd generation biofuel: HVO, at 30% in RF06 [HVO30]
- A non-edible 1st generation biofuel: JME, at 30% in RF06 [JME30]
- A Mixed FAME biofuel: PME10/RME10/SME10, at 30% in RF06 [Mixed B30]

The HVO30 typically showed similar fuel consumption and NOx emissions to the base fuel, but the lowest CO and HC emissions of all fuels. Soot levels were similar between all fuels.

Fuel consumption from the JME30 and mixed B30 fuels was similar, and from the NEDC around 2% higher than from the base fuel.

NOx emissions were highest of the 4 fuels from JME30.

CO and HC emissions were generally higher from the mixed B30 than from the JME30; both B30 fuels had lower or similar CO and HC emissions to the base fuel.

Of the B30 fuels, HVO proved to demonstrate potential fuel consumption benefits, lowered NOx and PM emissions and no obvious increases in unregulated emissions.

The mixed B30 and JME30 fuels showed similar fuel consumption levels, but the higher NOx emissions seen with JME30 may make this less desirable from a current regulatory perspective than the mixed B30, which had higher engine-out CO and HC emissions.

Biodiesel effects on diesel performance, emissions and economy in conventional and advanced technologies

The Ricardo Biofuels Consortium Module 1

Jon Andersson, Manager Chemistry and Aftertreatment, Ricardo UK
Dr. Juergen Fischer: AGQM
Annabel Kelly: UK Department for Transport
Nikolai-Josef Schubert: OMV
Somnuek Jaroonjitsathian and Somchai Siangsanorh: PTT

Agenda

- **Introduction**
- Objectives
- Engine and Testbed
- Fuels and Fuel Matrix
- Experimental Approach
- Measurements
- Results
- Conclusions

Introduction

- The ‘Biofuels Consortium’ was established to bring together parties with mutual interests in biofuels and their interactions with internal combustion engines
- Members were drawn from:
  - Government
  - Oil industry
  - Biofuels industry
  - Automotive industry
- Module 1 of the work was designed to study the impact of first-generation, FAME-based biofuels on the performance and emissions of a light-duty diesel engine in both conventional (Euro 4) and advanced (Euro 6 - type) modes of operation

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Objectives

- Operate light-duty diesel engine in conventional and simulated closed-loop control modes
- Use design of experiments (DoE) approaches to
  - Study the impact of first generation and advanced first generation biodiesel chemistry types and blend fractions in both control modes on:
    - Performance (full load optimisation)
    - Fuel consumption (NEDC)
    - Regulated emissions (NEDC)
- Assess ability of simulated closed-loop control strategies to address fuel consumption and emissions changes observed with biofuels use
  - Identify residual chemistry effects that resist normalisation by this calibration route
- Assess the linearity effect of biodiesel blend fraction on regulated emissions

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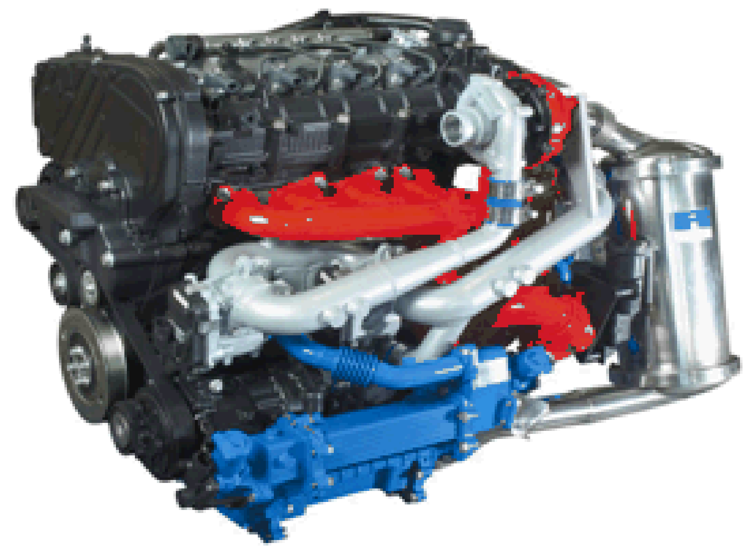
1.9 litre JTD test engine

Ricardo has experience in the development of CPEMS and closed-loop control systems for the FIAT JTD engine

- This strategy is included in the Ricardo Near Zero Emissions Demonstrator (NZED) vehicle
- Based upon the Saab 9-3

The JTD engine has:

- Common rail FIE
- 16-valve, 150PS (148hp/110kW)
- Oxidation catalyst
- EGR



Engine variants are used in a wide variety of vehicle applications

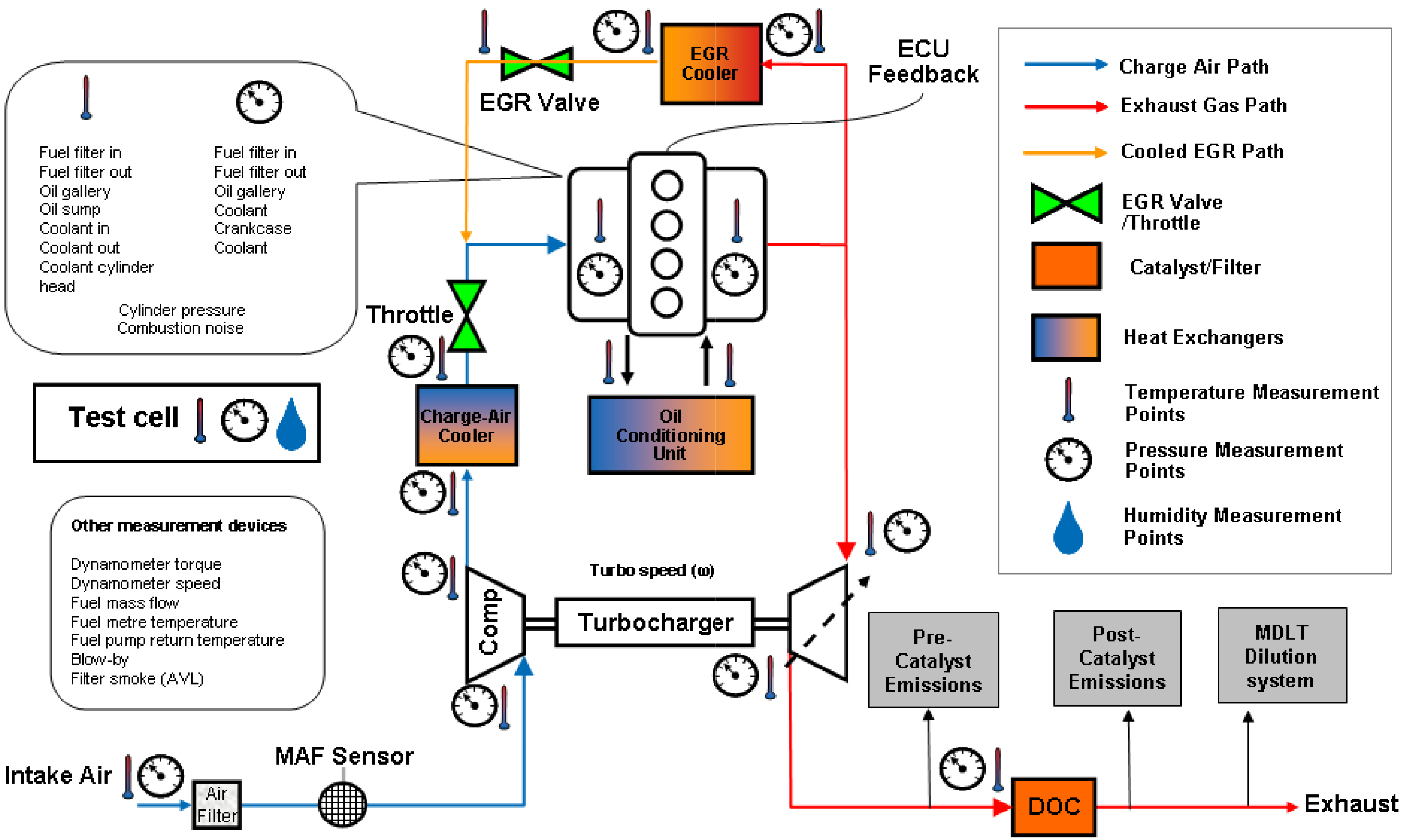
- Alfa Romeo 145, 146, 147, 156, 159, GT
- Fiat Bravo, Croma II, Doblò, Grande Punto, Marea, Multipla, Sedici, Stilo
- Lancia Strada, Lybra
- Opel Astra, Signum, Vectra C, Zafira
- Saab 9-3, 9-5

CPEMS – cylinder pressured-based engine-management system

Engine Installation and Testbed Hardware

1.9 litre JTD

Installed on a transient engine dynamometer, equipped with DOC (no DPF)



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Fuels and Fuel Matrices

Tested as part of the fuels DoE:

- RF06 (European diesel reference fuel)
- RME (Rapeseed methyl ester)
- PME (Palm methyl ester)
- SME (soy methyl ester)

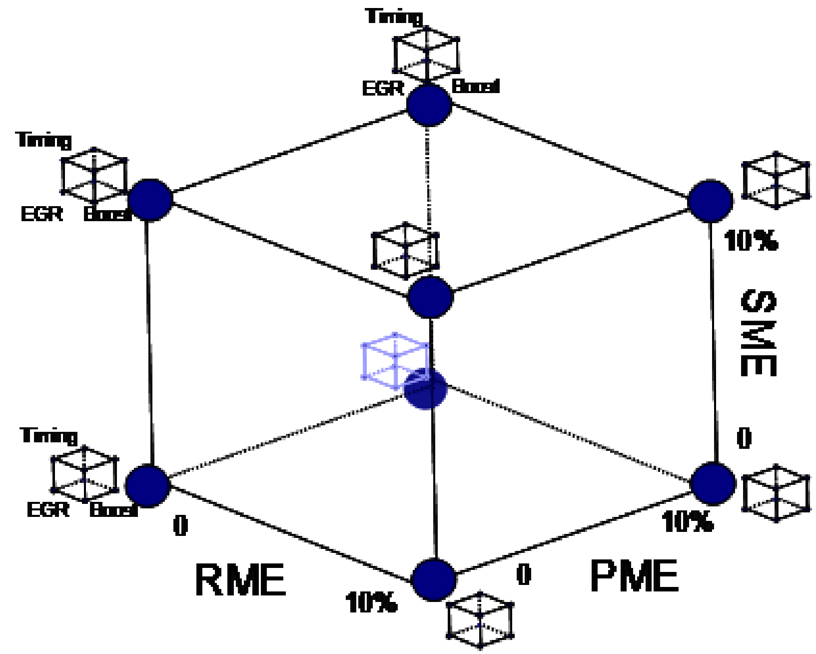
Additional comparison of B30 fuels:

- JME (Inedible oil; jatropha methyl ester)
- HVO (hydrogenated vegetable oil)
- Mixed B30 (RME10, PME10, SME10)

Linearity study by evaluation of 3 fuels from DoE matrix:

- B0 [RF06] (RME0, PME0, SME0)
- B15 (RME5, PME5, SME5)
- B30 (RME10, PME10, SME10)

Composite Experimental Design: Fuels and Calibration Variables



Fuel blends 0%, 5% and 10% in RF06 RME, PME, SME

Engine variables at each point in the matrix: Torque, speed, Rail pressure, MAF, VNT, main timing, pilot timing

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Experimental Approach: NEDC Simulations

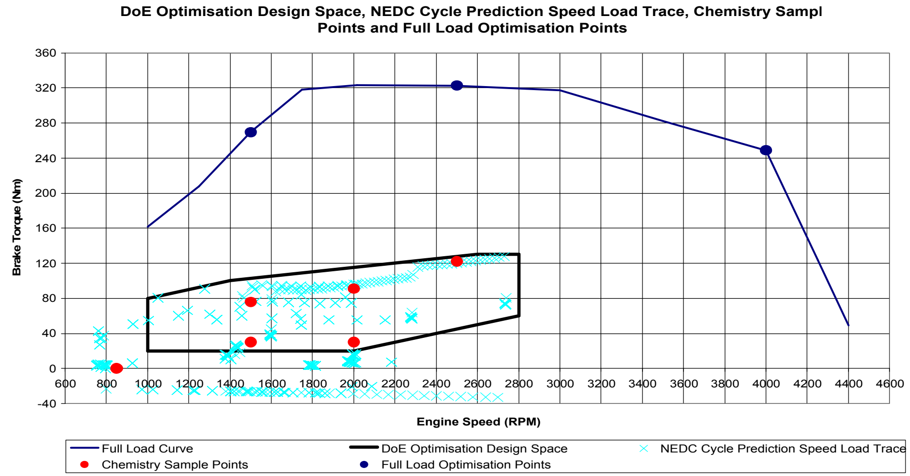
Two DoE approaches used for calibration and then simulating NEDC performance and emissions

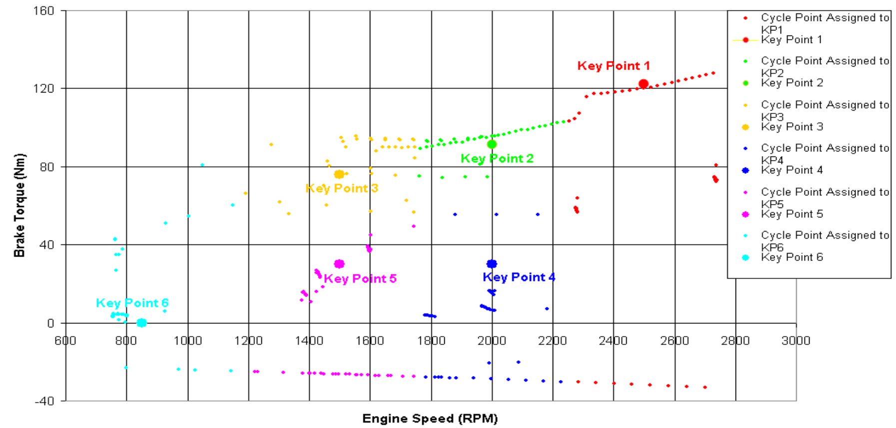
Global DoE

- Based upon multiple (200) steady states that encompass the whole operating region of the NEDC
  - Includes ‘centrepoint’ repeats
  - Fuel consumption and regulated emissions measured
  - Takes several hours

Weighted sum cycle estimation DoE (Weighted Cycle DoE)

- Based upon selected steady state keypoints: computes their respective contributions to the NEDC according to time the engine spends nearest to that keypoint through the cycle
  - Used to measure unregulated emissions and PM
  - Each keypoint run for ~30 minutes

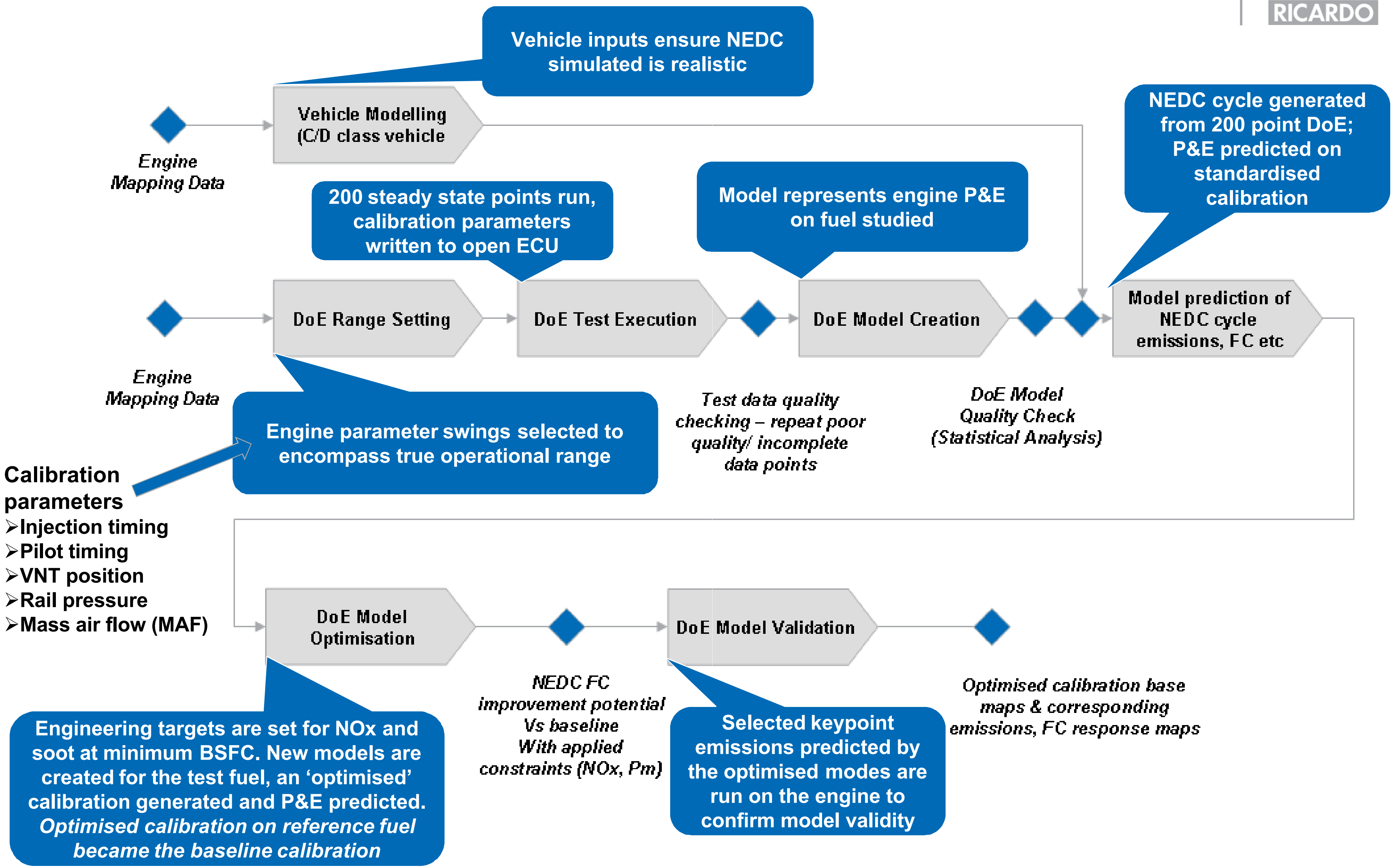




Kp	1	2	3	4	5	6
Factor (%)	34.09	24.81	9.38	22.25	7.58	1.89
Speed (rpm)	2500	2000	1500	2000	1500	850
Load (Nm)	122	91	76	30	30	idle

Global DoE high similar to approach typically used in diesel engine transient cycle calibration programmes

Experimental Approach: Global DoE process schematic



Statistical analyses and discrimination

Results from fuels testing were compared following statistical analyses

- Baseline calibration NEDC model predictions
- Optimised calibration NEDC model predictions
- Optimised calibration 6 steady state point NEDC predictions

Statistical software "JMP" used to analyse data from the DoE

→ Repeatability for global DoE established from repeat visits to 'centrepoint' conditions during the 200 point mapping

→ Repeatability for weighted cycle DoE determined from 3 repeat tests / analyses at each of the 6 steady state conditions

2-sigma / 90% CI used to discriminate differences between fuels

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Measurements

Performance parameters

- Engine load / speed/ torque
- Fuel flow
- Temperatures
- Pressures
- Combustion parameters
  - 10%, 50%, 90% mass fraction burned
  - Rail pressure
  - MAF
  - VNT position
  - Main timing
  - Pilot timing

Emissions and measurement methods

- Regulated gaseous emissions
- Soot (AVL 415S)
- *PM (partial flow)*
- *Unregulated gases (FTIR)*
- *Particle size distributions (DMS)*
- *Solid particle number (Horiba SPCS)*
- *Aldehydes and ketones (HPLC-UV)*
- *PM filter analyses*
  - *Anions (IC)*
  - *Carbon / volatiles (TGA)*
  - *Fuel and Oil HC (GC-FID)*
  - *PAH (HPLC-UV)*

Analytes in italics sampled from 6 KPs only

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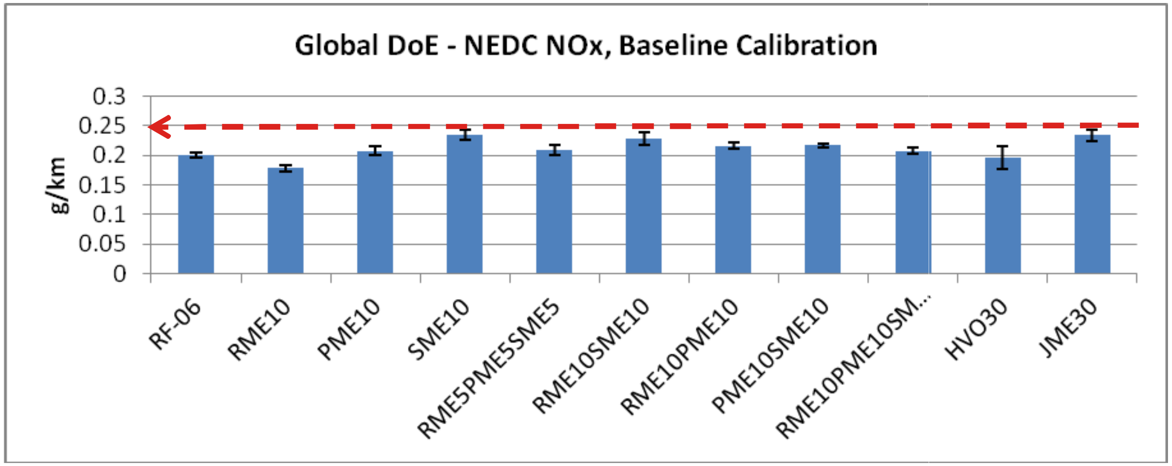
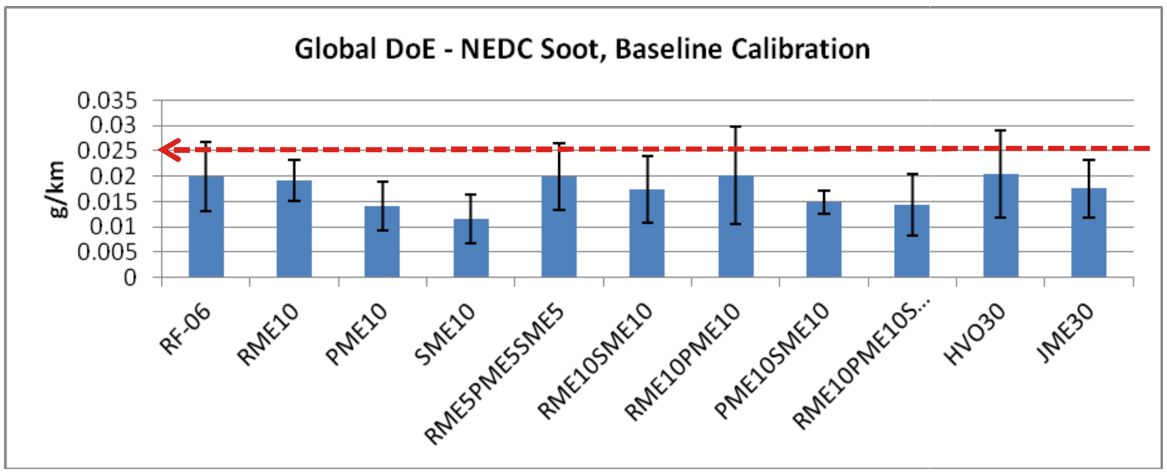
Results (1)

Biofuel effects on emissions: baseline "open loop" calibration

Baseline calibration: operation on FAME blends and HVO30 did not impact engine's ability to meet Euro 4 legislative targets





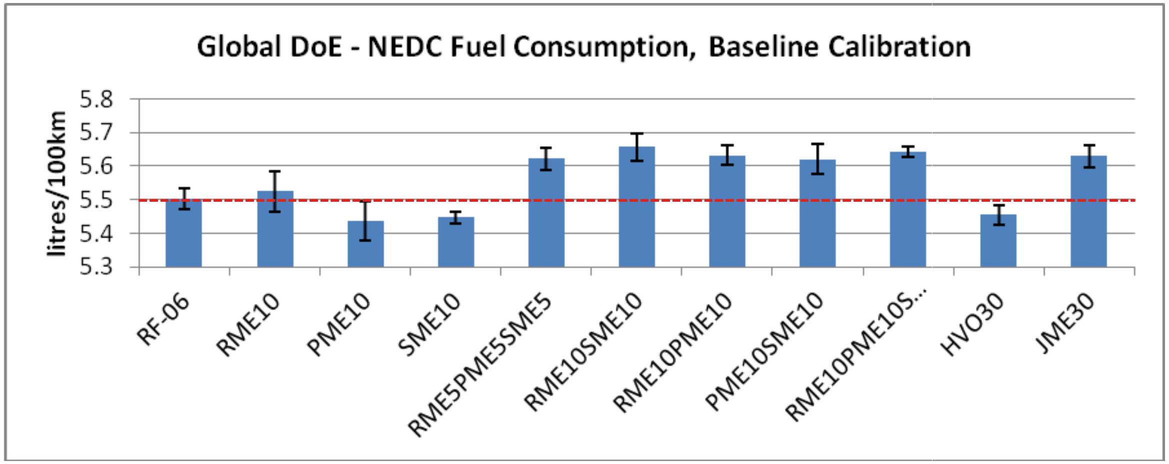
NOx

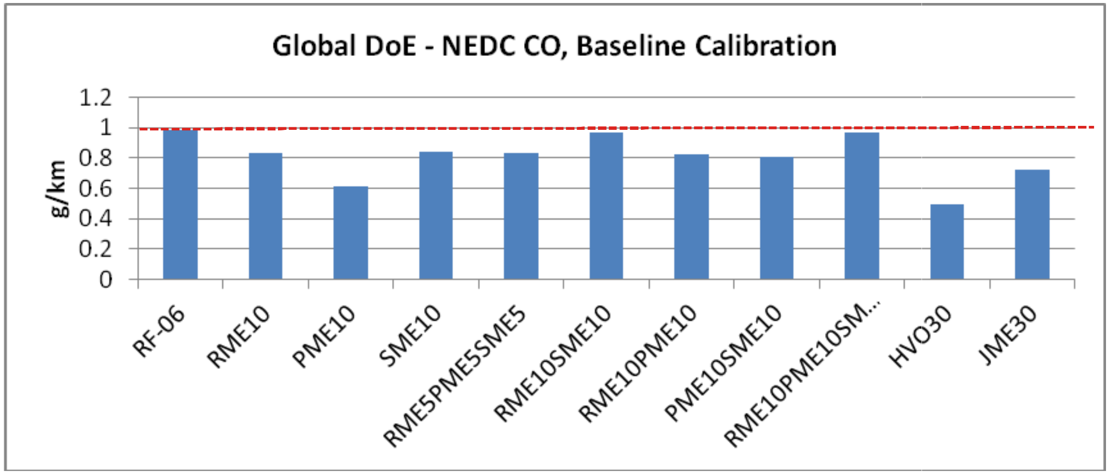
- >10% FAME leads to emissions increase
- All fuels' emissions were still below homologation target of 0.25g/km
- HVO emissions = RF06

Soot

- General reduction in soot with addition of FAME
- Consistent with localised introduction of oxygen to rich areas of combustion
- No negative impact of HVO

Baseline calibration: operation on FAME blends & HVO30 showed impacts on fuel consumption; no obvious effects on CO/HC





Fuel consumption*

- General increase with FAME content (up to 3%)
  - Likely due to lower calorific content of FAME
- Improved (~1%) FC with HVO30, possibly SME10 & PME10

CO and HC

- Engine-out measurements
- No obvious trends, but emissions not increased relative to base fuel
- Post-DOC HC and CO similar all fuels

All fuels met Euro 4 emissions levels

** All FC data are corrected for density effects*

Results (2)

Effects of calibration optimisation on FC and emissions – "closed loop control"

Optimised Calibration Constraints

Calibration optimised for simulated NEDC within 3 constraints

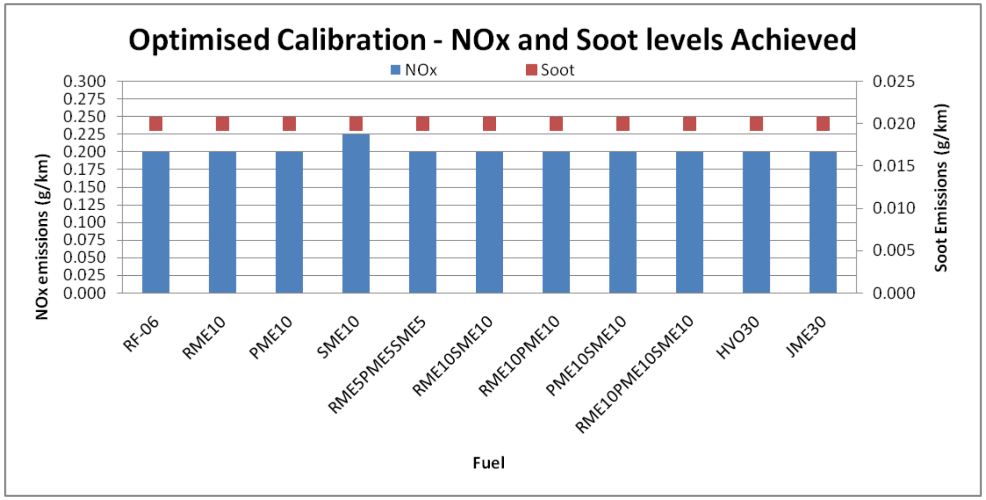
- NOx at 0.2g/km; Soot at 0.02g/km; MINIMIZED fuel consumption
- NOx and soot figures are realistic development targets

Optimisation able to achieve NOx and Soot targets

- By trading-off NOx, Soot and fuel consumption

Exception was NOx for SME10

- NOx target relaxed to 0.225g/km in order for optimisation to meet NOx, soot and FC objectives
- Relaxed level still within the homologation limit of 0.250g/km for NOx emissions over the NEDC



Optimised Calibration Improved Fuel Consumption Compared to Baseline calibration with almost all fuels

	NEDC Fuel Consumption Prediction - Baseline Calibration [L/100km]	NEDC Fuel Consumption Prediction - Optimised Calibration [L/100km]	Difference between Baseline and Optimised Calibrations [%]
RF-06	5.50	5.50	0.00%
RME10	5.52	5.32	-3.67%
PME10	5.44	5.42	-0.25%
SME10	5.45	5.49	0.70%
RME5PME5SME5	5.62	5.60	-0.40%
RME10SME10	5.66	5.66	0.06%
RME10PME10	5.63	5.61	-0.45%
PME10SME10	5.62	5.61	-0.11%
RME10PME10SME10	5.64	5.62	-0.37%
HVO30	5.46	5.35	-1.93%
JME30	5.63	5.69	1.15%

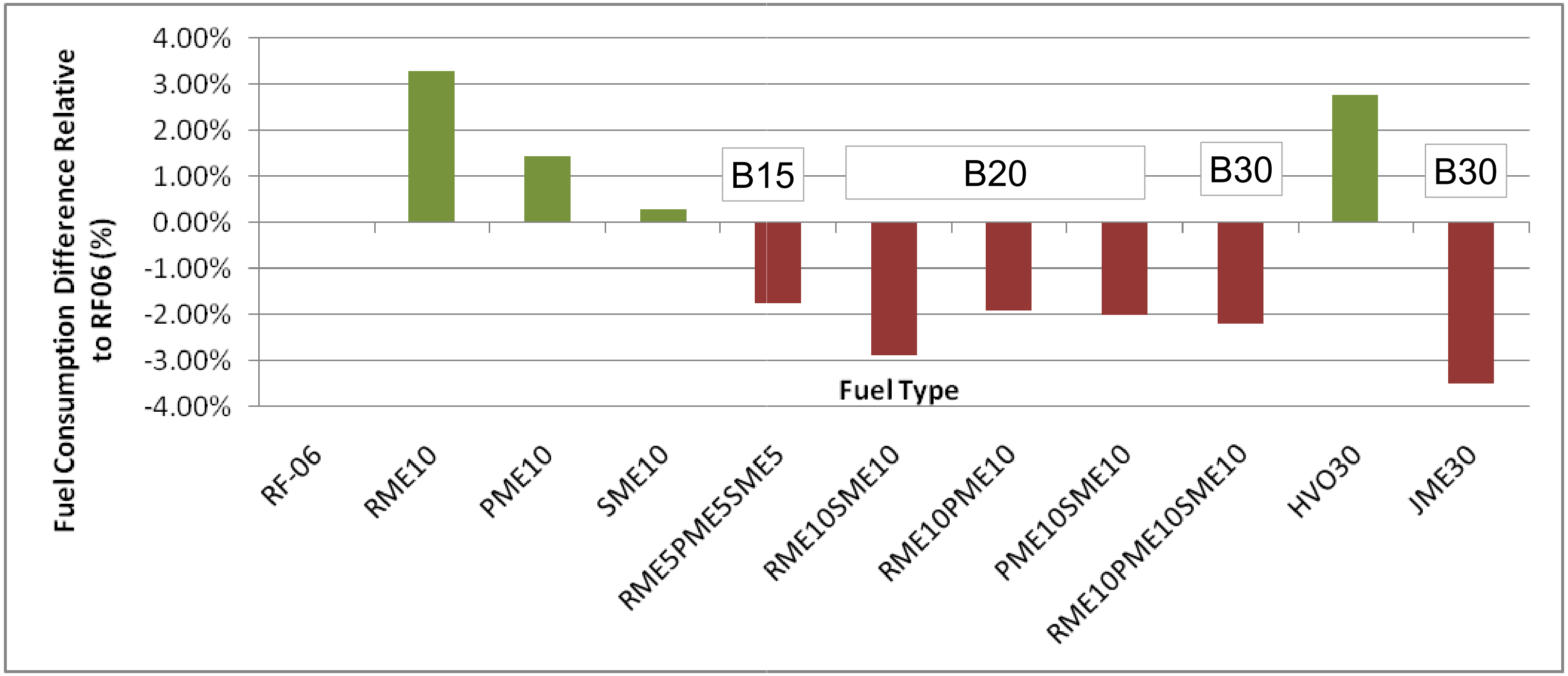
Optimised fuel consumption better than baseline calibration for 7/10 fuels

- 0.1% to >3.5%
- Best results RME10 and HVO30

Optimised fuel consumption poorer on 2/10 fuels

- 0.7%, 1.1%
- SME10 and JME30

For Fuels Above B10, the Optimised Fuel Consumption was not able to recover the level seen from the base fuel

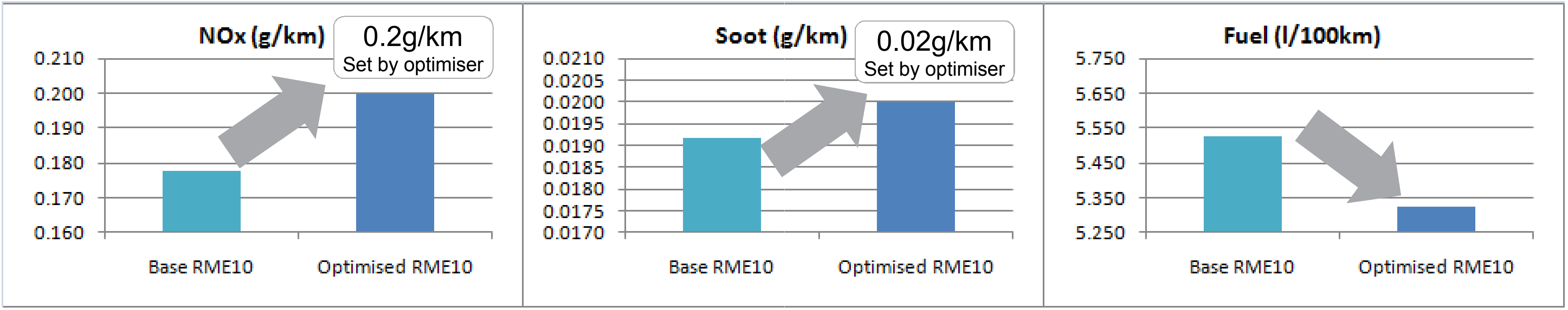


Typical fuel penalties were 2-3% relative to RF06 for B20 and above

Optimised calibration approach eliminated the fuel penalty seen from B10 FAME

Fuel consumption savings seen from HVO30 were increased by optimisation process

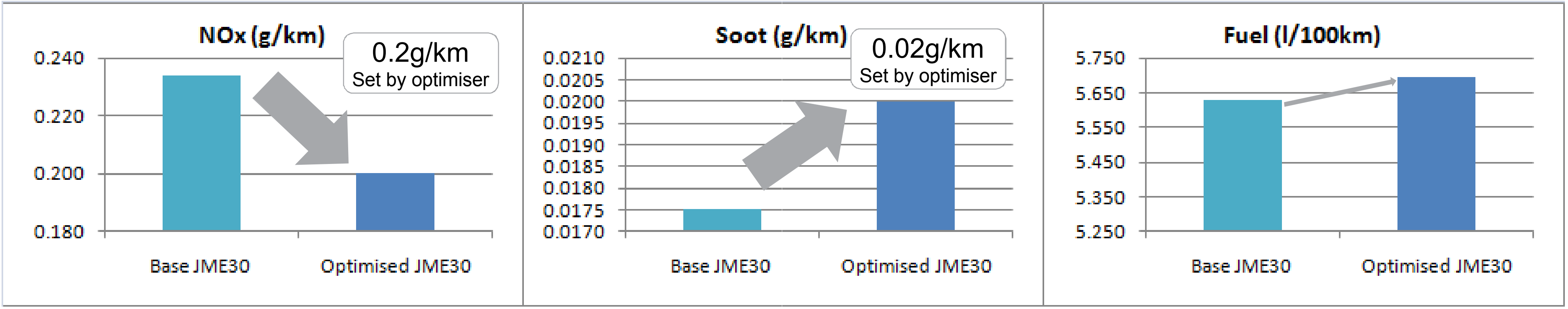
Optimisation process – RME10
(~3% Fuel Consumption reduction relative to RF06)



Low NOx and soot levels on the baseline calibration for RME10 enabled a low FC solution to be found by the optimiser

- Main emissions trade-off was mid to high speed, mid load NOx increase
  - Achieved via timing advance
- Fuel consumption gains came from the same timing advance
- High load NOx control was enabled by timing retard
  - Small increases in soot were implemented in this map region

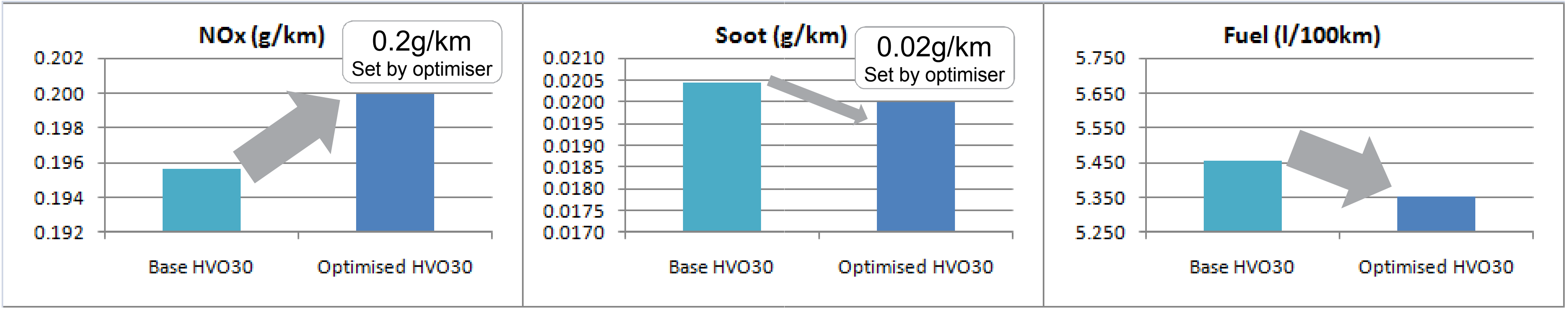
Optimisation process – JME30 (~3% Fuel Consumption penalty relative to RF06)



Baseline calibration emissions on JME30 were characterised by relatively high NOx and low soot

- Optimised calibration used a straightforward trade-off of soot vs NOx through retarded timing
- At target NOx and soot a small fuel consumption penalty resulted

Optimisation process – HVO30
(~3% Fuel Consumption benefit relative to RF06)



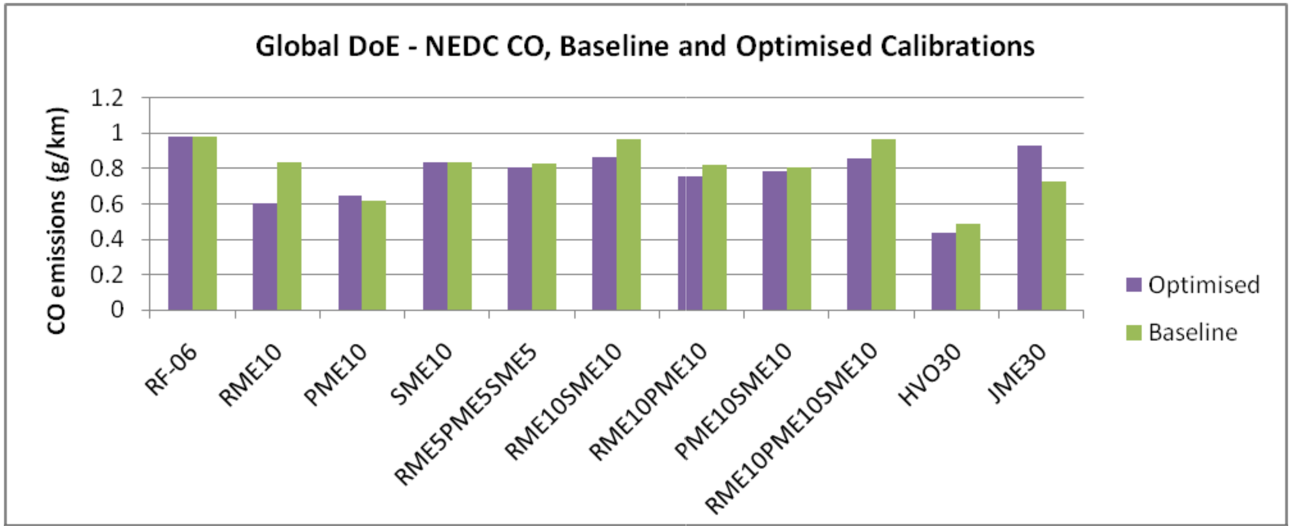
With HVO30, the main emissions trade-off was NOx/FC in the mid speed and low load region

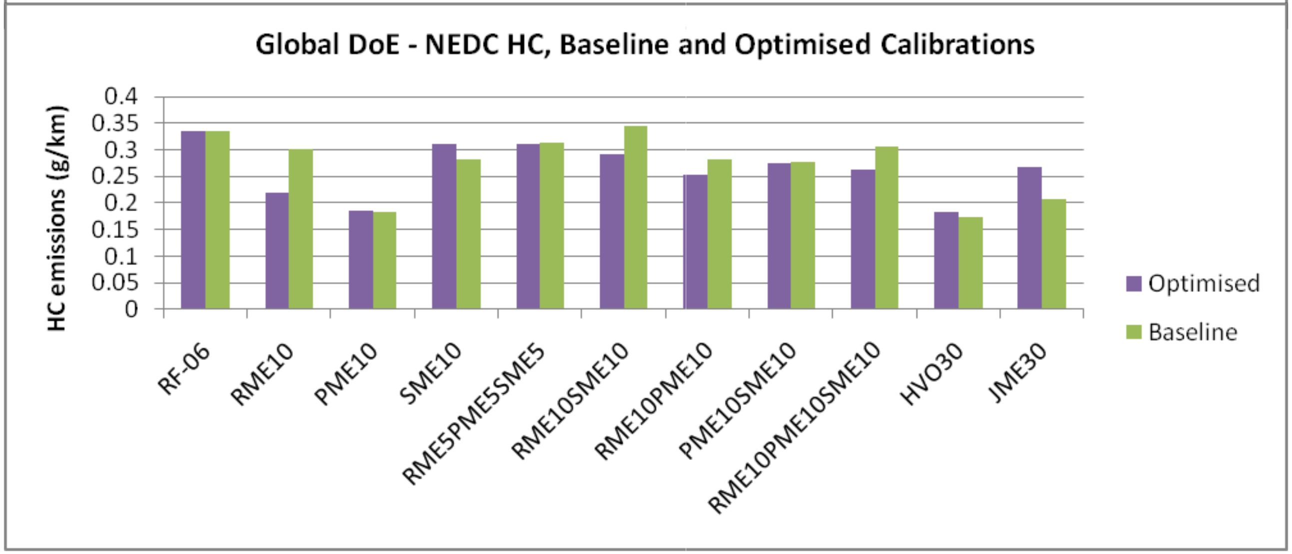
- localised gains of up to 7% for fuel consumption were observed
- Little scope for soot optimisation

The biggest gains in fuel consumption were from

- increasing rail pressure at mid to high engine speed and low to mid engine load
- advancing timing in this region

Optimised calibration led to general reductions in CO and HC relative to baseline calibration





No consistent negative impact of optimisation on engine-out CO and HC – except JME30?

Results (3)

Full load optimisation (baseline calibration)

Full load Optimisation

Five selected ECU parameters were optimised to produce maximum power whilst adhering to 3 constraints imposed on the engine

- **Parameters:** Injection timing, Pilot timing, VNT position, Rail pressure, Mass air flow (MAF)
- **Constraints:** Pmax = 160bar, Smoke = 2.5FSN and pre-turbine exhaust temperature = 780 °C

Three full load optimisation points were selected:

- Maximum power (4000 rpm, 266 Nm)
- Max torque at minimum FC (2500 rpm, 336 Nm)
- Low speed, rated torque (1500 rpm, 260 Nm)

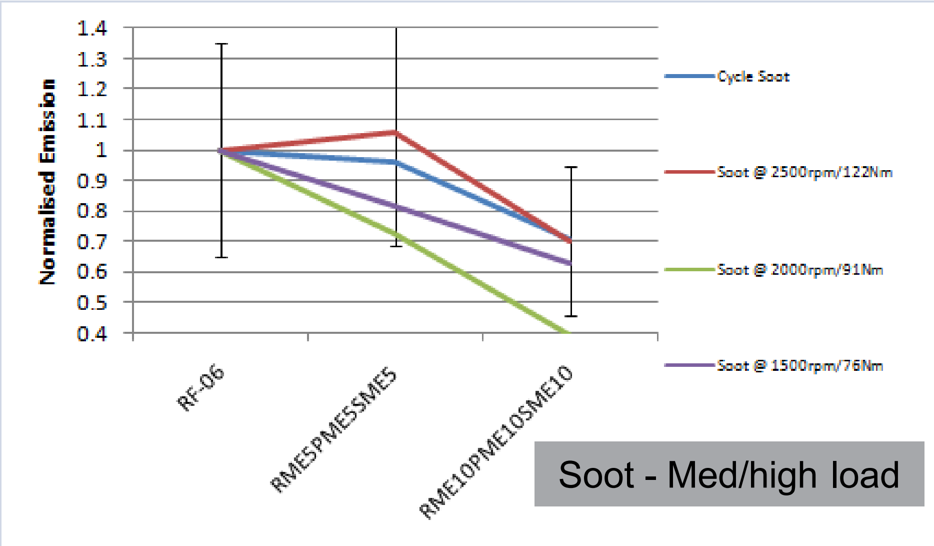
5 fuels showed higher peak torque/power than the base fuel: suggesting BSFC gains are possible

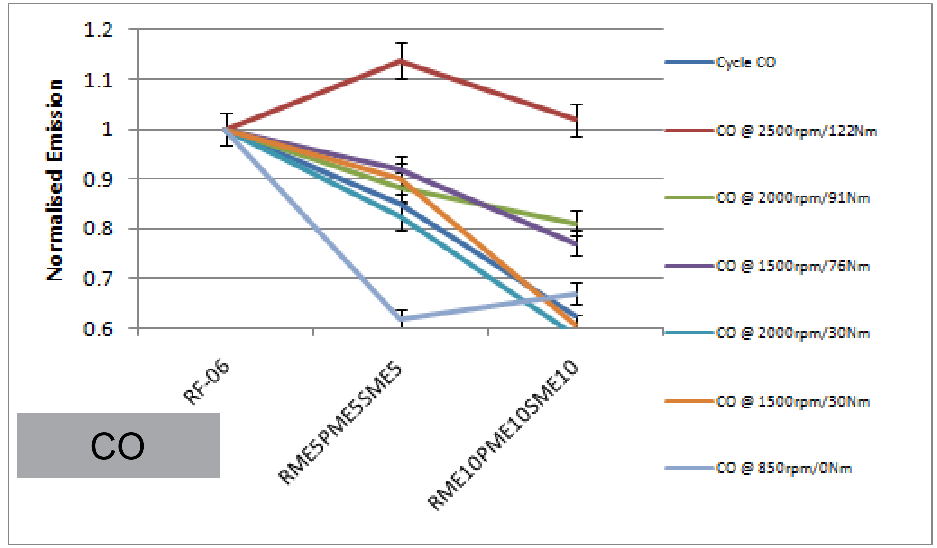
- **RME10, PME10, PME10SME10, RME10PME10SME10 & HVO30**
- These 5 fuels can give an increased fuel efficiency by
  - Allowing lower max fuelling ,and so lower BSFC ,at full load (maintaining peak torque/power at RF06 levels)
  - Alternatively, for an equivalent BSFC, power and torque would be higher in these fuels

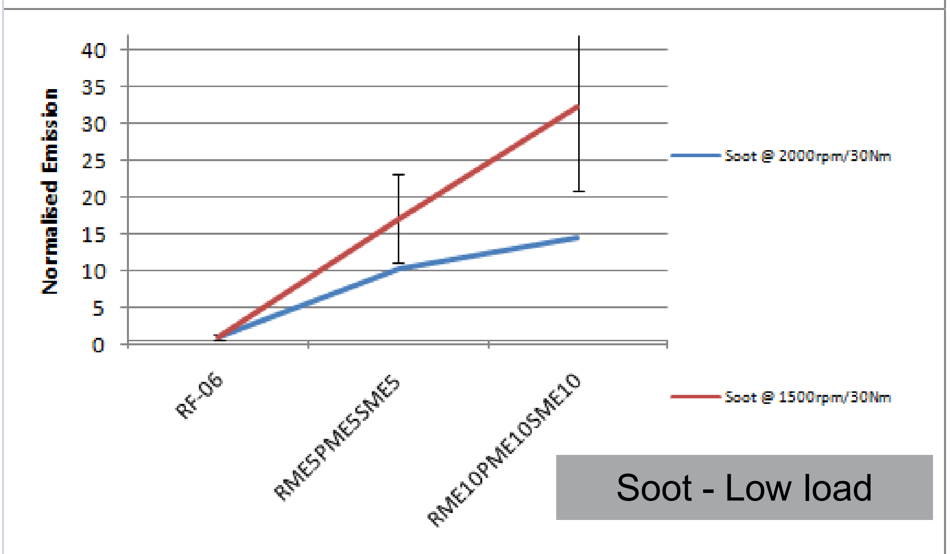
Results (4)

Linearity Effects (On Baseline Calibration)

Soot, CO and HC show evidence of linearity when B0 (RF06), B15 and B30 are compared







Soot

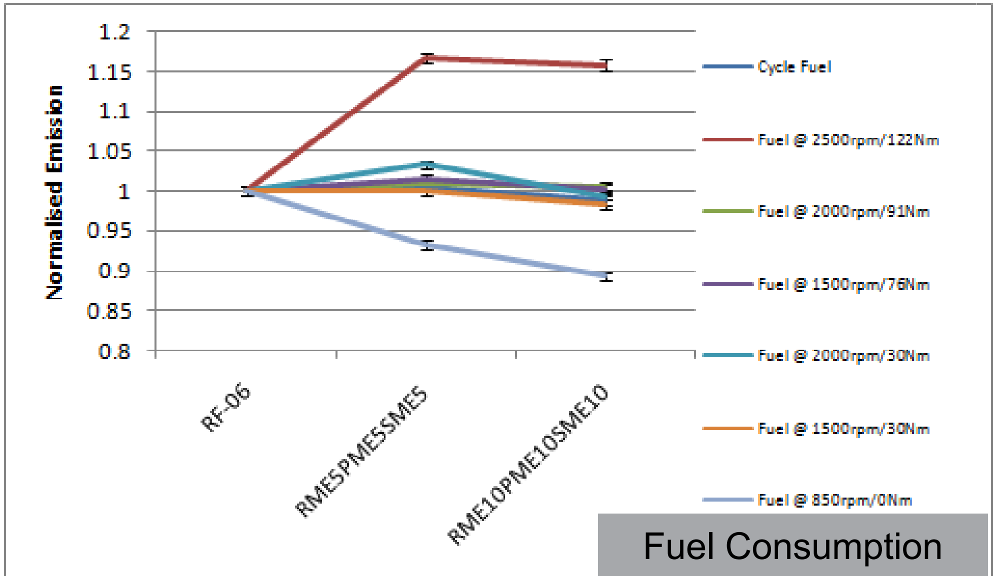
- Low load soot shows linear effect
- Directional trend opposite for medium and high load

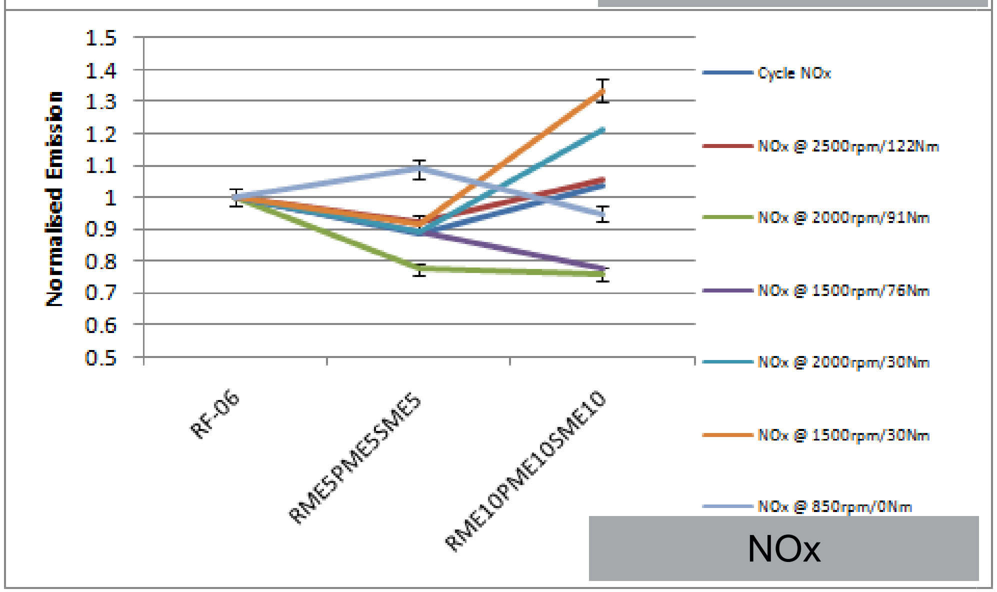
CO

- General linear downward trend in CO with increasing FAME
- High load and idle inconsistent

HC results similar to CO (not shown)

Little evidence of linearity for NOx and Fuel consumption when B0 (RF06), B15 and B30 are compared





Lack of linearity suggests chemical interactions within the blended FAME

- Properties of the fuels or aspects of the fuel chemistry may have synergistic or antagonistic effects on combustion at different blend levels
- Can only be studied by comparing pure chemistries
  - Pure fatty acid methyl ester DoE

Results (5)

Effects of B30 Fuels on the Baseline

Comparison of B30 fuels with Base Fuel on Baseline Calibration

Change in fuel / emissions value relative to RF-06

	RF-06 values	RF-06	HVO30	RME10PME10SME10	JME30
Cycle Fuel l/100km	5.502	0.0%	0.8%	-2.6%	-2.3%
Cycle NOx g/km	0.200	0.0%	2.2%	-3.8%	-17.1%
Cycle Soot g/km	0.020	0.0%	-2.2%	27.9%	12.4%
Cycle CO g/km	0.983	0.0%	50.1%	2.0%	26.1%
Cycle HC g/km	0.336	0.0%	48.6%	8.9%	38.0%

Significant negative

Significant positive

Not Significant

Clear separation between HVO30, JME30 and 'Mixed FAME' B30

- HVO30 similar to, or lower, emissions and fuel consumption than base fuel
- Mixed FAME and JME30 show higher FC and NOx
- JME30 shows lower HC and CO than Mixed FAME, but highest NOx

Results (6)

Unregulated Emissions – Optimised Calibration

Few Significant Effects were observed with Unregulated emissions

↑ = significant effect

↑ = directional indication

	Increasing PME	Increasing RME	Increasing SME
Elemental Carbon Emissions	=	=	=
Fuel Derived HC (from PM analyses)	=	=	=
Oil Derived HC (from PM analyses)	=	=	↑
Nitrate (from PM analyses)	=	=	=
Sulphate (from PM analyses)	=	=	=
Accumulation Mode Particle Number	↑	↓	↑
Total Particle Number	↑	↓	↑
PMP Solid Particle Number	↑	↓	=
Total Aldehydes	=	=	=
Total Particle Phase PAH	↑	↑	=
Nitrous oxide	↑	=	↑
Nitrogen oxide	↑	↑	↑
Nitrogen dioxide	↓	=	=

Particle effects may be true reflection of fuel impacts on soot

Possible increase in N_2O with increasing FAME, but effect small

General increase in NO with increasing FAME

NO_2 may decrease with increasing FAME, possibly due to reduced catalyst function

Agenda

- *Introduction*
- *Objectives*
- *Engine and Testbed*
- *Fuels and Fuel Matrix*
- *Experimental Approach*
- *Measurements*
- *Results*
- **Conclusions**

Conclusions

Headline Conclusions

No fuel tested compromised the engine's ability to meet Euro 4 on the baseline calibration

No negative FC or emissions impacts were experienced when running B10 fuels

FAME levels of greater than B10 on the baseline calibration showed some +ve & -ve effects:

- **Fuel consumption penalties of up to 3.5%**
- **General increases in NOx**
- **General reductions in soot**

The optimised calibrations:

- **Improved FC from almost all fuels relative to the baseline calibration**
  - **B10 FAME fuels and HVO30: FC was superior to that seen from RF06**
  - **B15 FAME and above: FC was unable to achieve parity with RF06**

Full load optimisation showed scope for capping peak torque and power, reducing max fuelling and realising BSFC benefits when several fuels showed superior performance to RF06

Linearity effect observed with soot; possible with CO and HC; unlikely with NOx and FC

No obvious negative effects of FAME & HVO on unregulated emissions following optimisation

…and finally

- From this study it appears that closed-loop combustion control is a possible enabler for the use of 1st generation, FAME-based biofuels with reduced fleet average fuel consumption penalties …
  - … BUT work performed is based upon simulated NEDC results, so further work that includes the impacts of cold start and transient operation is necessary

OMV

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RICARDO

Department for Transport

ARBEITSGEMEINSCHAFT QUALITÄTSMANAGEMENT BIODIESEL E.V.

1. DISCUSSION

1.1 Non-compliance of Water Content and Oxidation Stability of FAME with ISO14214

The levels of water in several FAMEs were above the permitted levels for commercially marketed biofuel. Elevated levels of water may have negative impacts on the long term storage of FAME, and could lead to engine corrosion issues. However, for this programme, where fuels were blended into diesel base fuel at relatively low levels and tested for a short duration, negligible impact on observed emissions would be expected.

Since the tests were designed to determine the impact of fuel compositional effects on instantaneous performance, fuel consumption and emissions, it is unlikely that the water content of the FAME components had a material impact on the results. The most likely impact of high water content in the fuels would be associated more with long term storage, corrosion, further degradation and microbial growth. These aspects were not targeted within the consortium.

The main impacts of high water content on instantaneous operations will be a second order effect on calorific value (hence fuel consumption). The effect of calorific value will be proportional to the water content which in all cases was <0.2% m/m before blending into diesel, and therefore likely to be lost within test repeatability.

Similarly, poor oxidation stability sometimes observed with FAME would suggest issues concerned with storage, deposits and long-term fuel stability, with minimal impact on short-term combustion characteristics and emissions.

1.2 Representative Nature of Test-Bed and NEDC Cycle Testing With Regard To On-Road Performance

On light duty diesel development programmes, engine dynamometer results are used as part of the standard process to predict emissions and fuel economy for a vehicle operating over the NEDC. For key point based calculation, a relatively large number of points are required to give reliably accurate predictions of vehicle emissions; however for comparative purposes, e.g., to understand broad percentage changes in emissions, 6 keypoints are considered to be a minimum requirement.

Global modelling has significant advantages compared to keypoint based methods. Perhaps the most significant advantage of the global-modelling approach, is the beneficial ability to predict emissions from transient cycles on a second-by-second basis, rather than relying on interpolation between a few discrete points.

For either method, where only data from the hot engine is used, it should be recognised that emissions and fuel economy predictions for cold start cycles (such as the NEDC) will be slightly compromised as the influence of engine warm-up factors cannot be considered.

The approaches used in this study are representative of those used during engine development to identify broad trends when assigning hardware or fuel effects. It is expected that the predicted NEDC results from the global mapping approach would be ‘closer’ to a real driven cycles values, but that both global and keypoint approaches would successfully identify broad trends related to hardware and fuel changes.

1.3 The 1.9 litre turbo-diesel Engine's Configuration as Representative of the Current and Future European Light-duty Diesel Vehicle Fleet

The engine used for this project was a Euro 4 specification engine equipped with a high pressure common rail system, externally cooled EGR and a variable geometry turbocharger. This engine is used in conjunction with a Diesel Oxidation Catalyst (DOC) and DPF aftertreatment to achieve Euro 4 emissions levels in the various vehicle applications in which it is used. Fundamentally, the level of technology for the Euro 4 engine is that same as the vast majority of Euro 5 engines within the same class. Upgrades from Euro 4 to Euro 5 have generally ranged from no updates (Euro 4 technology capable, minor calibration changes only), to changes in specification of individual components for improved emissions control. These changes are manufacturer and application specific, but may include EGR cooler heat rejection capacity, combustion chamber geometry, injector nozzle specification or turbocharger match.

At Euro 6, light-duty diesel engines will be equipped with both particulate (DPF) and NOx emissions control systems. The use of SCR or LNT in combination with DPF may result in some manufacturers moving to higher engine-out PM calibrations with lower engine-out NOx, or to high efficiency NOx control systems with smaller, longer regeneration period, DPF systems. The results from this engine best reflect the trends likely to be seen from the high-efficiencyNOx control approach.

1.4 Can the results from this study be used to indicate effects in other vehicles in the light-duty diesel parc?

The engine used for the study is representative of Euro 4/5 technologies and hence of the current and near future diesel vehicle parc. Effects seen on the engine are expected to be representative but, depending on the engine combustion characteristics and calibration settings, may vary in magnitude for particular engines and vehicles.

1.5 How relevant are the closed-loop optimisation results for current and future vehicles?

Closed loop combustion technologies are in production in a small number of production Euro 5 applications including the Opel Insignia. The engine in this application uses combustion feedback from pressure sensing glow-plugs to adjust fuel injection quantity and timing to account for engine to engine variability; engine and fuel injection system wear and fuel quality. There are likely to be increased numbers of vehicle using this technology at Euro 6, so the optimised results are more likely to be relevant to the future Euro 6 parc than to the current/future Euro 5 parc.

1.6 Implications for in-use Emissions Robustness with Biofuels

From the global DoE, all FAME-based fuels tested with both baseline and optimised calibrations were able to achieve regulated emissions targets for NOx and soot. Consideration of soot emissions rather than PM (PM cannot be accurately measured in real-time) ignores the fact that there is a significant volatile contribution to PM and this may increase as levels of FAME in the fuel are increased. Post-DOC this could potentially lead to in-use compliance (IuC) failures of the 0.025g/km PM limit in Euro 4 vehicle applications if NOx was reduced by trading-up elemental soot levels. However, closed-loop combustion control will not become widely applied until Euro 6, and at this stage all light-duty vehicles will be equipped with DPFs to meet particle number legislation. Current post-DPF emissions levels from vehicles emitting engine-out soot levels of 50mg/km are <1mg/km compared with the Euro 6 limit of 4.5mg/km.

At Euro 6 the concern will primarily be with the fuel consumption impact of increased PM – related to an increase in the rate of DPF fill and regeneration periodicity – and the probability of emissions failures due to elevated PM during IuC is negligible.

1.7 Biofuels Benefitting from Calibration Changes

From the global DoE, in terms of fuel consumption, all the FAME-based biofuels and HVO30 benefitted from calibration optimisation. HVO and RME10 also appeared to demonstrate fuel consumption levels that were better than the level seen from RF06.

Most fuels also benefitted from calibration with reduced NOx traded for increased soot over the NEDC.

1.8 Which Biofuels impact P&E and FC the most?

HVO30 is the stand-out fuel tested in this project. From the global DoE there were no substantive negative impacts of this fuel and the potential for reductions in fuel consumption, NOx and PM. Similarly, the weighted cycle DoE showed reductions in almost all unregulated emissions.

There appeared to be a significant fuel consumption benefit of RME10, higher than seen on other fuels. Both HVO30 and RME10 showed optimised calibrations that were substantially different to the base fuel and each were optimised very close to the soot and NOx limits.

HVO30 seems to give the best results for the smallest calibration changes and while it does not demonstrate the lowest FC, due to its near-mineral nature it would respond better to a near base calibration than the FAME-based fuels.

RME10 gave by far the highest fuel consumption gains with the optimised calibration leading to increased PM at lower speeds/loads through a quite large timing advance and separation of the pilot injection. RME 10 would not give as great a FC benefit when running on a calibration similar to RF06.

SME10 proved to be challenging for the calibration optimisation, with the initial NOx target of 0.2g/km relaxed to 0.225g/km. This may be the result of the high degree of unsaturation in the fuel.

Almost all of the FAME-based fuels responded similarly to the calibration optimisation process, giving broadly similar calibration maps.

RME10PME10SME10 seemed most unresponsive to moderate calibration changes and hit the optimisation limits of NOx and Soot before the calibration could be optimised for good fuel consumption reduction.

1.9 The Results of this Project in the Context of Other Studies Testing FAME in Light-duty Diesel Engines

The biofuels directive in Europe is a way to encourage the introduction of bio-derived components into automotive fuels. The current EN228 and EN 590 fuel standards allow only 5% by volume content of biocomponent.

The latest issue (May/ June 2011) published by International Fuel Quality Centre (IFQC) highlights the fact that any amendment made in fuel specification for Euro 5 is based and driven by CO_2 emission reduction. At Euro 6 FAME blend level in diesel will increase from 5 to 7 vol%.

At present there is a need to understand the impact of higher levels of biodiesel on fuel specification, vehicle performance and emissions. Bio-diesel FAME (Fatty Acid Methyl Ester), which is largely derived from Rapeseed in Europe, is a renewable resource produced from crops and its density and cetane number are suitable for diesel engines and therefore used for diesel blends. There are many studies in the literature that address the impact of adding FAME to baseline diesel fuel. However for relevance to the biofuels consortium study, the majority of these, that address heavy-duty applications and/or US fuels, or earlier engine technologies (Euro 3 or earlier), have to be discounted.

The findings of a brief literature review on light-duty vehicles clearly demonstrates that diesel fuel containing biocomponents typically reduces HC, CO and PM emissions and had a neutral effect or caused an increase in NOx in conventional diesel engines meeting current (Euro 4/5) legislative emissions standards:

An investigation was carried out to study the effect of FAME-blend levels on the state of art Euro 4 compliant Avensis 2.2L D4-D vehicle[i]. Surprisingly, the experimental results showed that the B20 RME gave the highest HC emissions of 0.04g/km and then these emissions dropped considerably for the B40-B60 blends. NOx emissions were at ~0.18g/km, typically, higher than the ~0.15g/km for non-bio fuels. The PM emissions (post-DPF) were around 3 mg/km levels. The CO_2 emission for B20 RME was ~175g/km which was consistent with that seen from current EN 590 diesel fuel. The CO emissions for B20 at ~0.22g/km were comparable to the regular European diesel but significantly increase with RME content (B30-B100).

Further research was conducted to verify the impact of emissions in the presence of biodiesel blends (RME at 30% and higher) in a Euro 4 light duty DI engine[ii]. The experimental results suggested that both the CO and the NOx emissions increased by 6% for B30 blend during the NEDC cycle. However the HC emissions were decreased by 3% for B30 but increased with higher blends. With no DPF present, the PM emissions decreased by 21% for the B30 blend, and by 11% for the B50 blend.

Another study was conducted to monitor the effect of biodiesel blend on the gaseous emissions on a light duty engine Euro 4 engine with and without a DPF[iii]. A detailed examination of the regulated emissions for a DPF engine demonstrated that B20 FAME had ~5mg/km HC emission which was lower than the reference EN 590 diesel (10mg/km). The CO exhaust emission for a DOC engine for B20 FAME showed reduced levels of 0.11g/kWh compared to reference diesel (0.18g/kWh). The NOx emissions for a DOC engine using B20 FAME increased to 7.86g/kWh compared to the reference diesel (7.18g/kWh) whereas for a DPF engine the reference diesel and B20 blend demonstrated no change in NOx.

The effect of using a blend (30%vol) of 2 different FAME (RME, JME) in a Euro 5 small displacement passenger car was examined for various engine loads[iv]. At a medium load operating condition (5 bar BMEP) an increase in the EGR rate caused an increase in soot emission, and there was a small change in the NOx emission which was comparable to the standard diesel fuel. However at a low load (2 bar) there was an increase in the CO and HC emissions with FAME which could be attributed to a change in the combustion process, but at medium loads the HC emissions were comparable to the standard diesel emissions. The CO_2 emissions at medium load were lower than the standard diesel fuel which was attributed to the lower carbon content of the RME and JME.

An investigation was conducted on a Euro 4 compliant DI-Diesel Fiat 1.9 JTD to observe the effect of biodiesel blending (FAME). The findings strongly laid emphasis on the NOx and soot formation[v]. The soot formation decreased with increased amounts of biodiesel (B20, B30) because the oxygen present in the fuel improved soot oxidation. The NOx emission decreased with increase in blending levels because in the presence of FAME: the local combustion temperature decreased and this in turn reduced NO formation.

In this biofuels consortium study, the regulated emissions effects observed when testing FAME on the baseline calibration were consistent with literature findings: increased levels of FAME tended to reduce soot (carbon) and result in increased fuel consumption and CO_2 emissions. Emissions of NOx, CO and HC also tended to be higher with the addition of FAME to the baseline fuel.

Little data exists in the literature regarding the testing of different FAME types, other than RME, with optimised closed-loop calibrations on light-duty applications. In addition, little is known about the effects these different fuels have on unregulated emissions. However, as stated in Sections 1.1 to 1.5, the engine tested is of a technology level, and includes representative components, of the Euro 4/5 vehicle fleets and the data from this project should prove a valuable addition to the knowledge-base on 1st generation biofuels.

1.10 Do Some Unregulated Emissions Resist Normalisation During Calibration?

Following calibration optimisation, and considering data from the weighted cycle DoE, there were few unregulated emissions that showed significant generic increases in emissions.

Emissions of nitrous oxide (N_2O) were elevated or similar to base fuel levels from all the FAME containing fuels, but actual levels (at <10mg/km) were low compared with total NOx. N_2O is a partially oxidised form of nitrogen and is known to be a greenhouse gas of high potency, and from diesel engines its formation is usually associated with the oxidation of ammonia downstream of SCR systems. In this case, where production is most likely to be in-cylinder, the N_2O may be formed from partial oxidation of nitrogen at the boundaries of localised regions of fuel survival during low temperature combustion. In this study, emissions levels of N_2O were 3mg/km, or less, higher than observed from the base fuel, which equates to a <1g/km of CO_2 global warming potential GWP equivalent compared to baseline.

The fuel fraction of PM was also elevated from a majority of FAME-containing fuels. This is consistent with the addition of FAME reducing the back-end volatility of the fuel and the heavier fractions surviving to incorporate within the PM. Though this acts to increase PM, it is not necessarily a negative finding as once incorporated in the PM these oxygenated semi-volatiles may assist in light-off of soot during DPF regeneration.

Post-DOC elemental carbon and solid particle numbers were elevated with some FAME containing fuels – as a consequence of the optimisation exploiting the NOx/Soot trade-off. Particle-phase PAH may also have been increased. However, diesel engines running closed-loop calibration optimisation, such as that in this study, would be equipped with particle filters and increases would not directly challenge in-use emissions levels.

1.11 Utilisation of Closed-loop Control on Biofuels

The main method of controlling for closed loop combustion is to use a cylinder pressure sensor mounted in the glow-plug. In this approach, the full cylinder pressure trace is 'inspected' by the ECU to calculate start of combustion relative to ECU main timing. This start of combustion timing is then compared with a 'look-up' table of ideal values for engine speed/load and the main timing is corrected from the base map to give the ideal start of combustion and peak cylinder pressure.

Different fuels will give different ignition delays depending on the fuel 'combustion quality' and these can be used to characterise the fuel and for timing/other variable corrections to be applied to the baseline, diesel-based, maps to give best performance / emissions.

Normally main timing alone is varied in this way, but sometimes pilot separation and injection quantity will also be varied in order to give an ideal cylinder pressure curve for each operating point and a more robust calibration.

It is conceivable, if a fuel can be characterised using its combustion trace, that other variables such as EGR, boost etc can be adjusted using a similar offset method based on an ideal value.

References

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2. CONCLUSIONS

2.1 Results of the Global DoE

2.1.1 Baseline Calibration – Operation on Biofuels

With the baseline calibration, soot emissions generally reduced or were unchanged from the FAME-containing fuels, while NOx emissions increased beyond the NEDC development target of 0.20g/km. However, the levels observed did not exceed the Euro 4 homologation target of 0.25g/km. This suggests that even if a B30 Biodiesel blend is used, the test vehicle simulated would still pass NEDC NOx emission legislation.

Engine-out CO and HC emissions were generally lower from FAME blends than from the baseline fuel.

Trends seen when increasing the level of individual FAME in the base fuel and running on the baseline calibration are summarised in Table 1 below, though none of these were statistically significant and should be considered indicative only.

Table 1: Summarised FAME Effects – Global DoE, Baseline Calibration

	Increasing PME	Increasing RME	Increasing SME
Fuel Consumption	↑	↑	↑
NOx emissions	=	=	↑
Soot emissions	↑	=	↓
CO emissions	↑	↓	↑
HC emissions	↑	↓	↑

2.1.2 Calibration Optimisation – Biofuel blends

Following optimisation, the biofuel blends were able to achieve NEDC development target emissions of 0.020g/km Soot and 0.200g/km NOx with the exception of SME10, where it was necessary to relax the NOx target to 0.225g/km in order to achieve an optimisation. This however, was still with the 0.250g/km homologation limit for Euro 4 compliance.

Engine-out emissions of CO and HC were consistently reduced from B10, B15, B20 and mixed B30 fuels by the calibration optimisation process, excepting JME30 which showed increases in both CO and HC of >10%.

Engine-out emissions of CO and HC from HVO30 were similar to or lower than those from the base fuel.

2.1.3 Baseline Calibration – Fuel Consumption Penalty

Due to the lower calorific value of FAME, with baseline calibrations a fuel consumption penalty was observed with Biofuel blends above B10. The highest penalty was with RME10•SME10 at 2.81%. Fuel consumption from HVO30 was similar to, or lower than, RF06.

2.1.4 Optimised Calibration – Fuel Consumption Penalty

Following optimisation, fuelling was normalised to within a scatter of ~1% across most fuels, with the exception of RME10 and HVO30 where respective improvements of 3.67% and 1.93% were seen relative to operation on the baseline calibration.

However, the optimisation process was unable to completely achieve the fuel consumption on all FAME blends to that seen from the base fuel.

2.1.5 Optimised Calibration – NOx / soot trade-off

For FAME containing fuels, the elevated levels of NOx seen when running on the baseline calibration were reduced in the optimisation process by exploiting the NOx / soot trade-off and increasing the soot fraction of PM.

2.1.6 Full load Optimisation

Overall, the optimisation process was able to normalise the torque for FAME blends to within +4 and -3% of that measured from the baseline fuel. Results of HVO were generally similar to the base fuel.

Five fuels (RME10, PME10, PME10•SME10, RME10•PME10•SME10 and HVO30) showed higher peak torque/power: these could give an increased fuel efficiency 'bonus' on top of any which is gained simply from switching to the fuel, by allowing a lower max fuelling and so lower BSFC at full load (at the expense of keeping peak torque/power at RF06 levels). Alternatively, for an equivalent BSFC, power and torque would be higher in these fuels. Smoke would not be a limiting factor between RF06 and biofuels at full load. Higher turbine in temps for those fuels that give higher power/torque could indicate a NOx penalty at full load, but this is outside NEDC and would not be regulated. If fuelling was decreased to lower power and BSFC, then the temperature would drop to RF06 levels.

2.1.7 General Comments on Calibration and Optimisation

The majority of observed fuel consumption reductions came through increased rail pressure and advanced main timing.

Almost all fuels showed an increase in NOx when run on the baseline calibration (optimised RF06 calibration). This NOx increase led to the requirement for areas of the optimised calibrations to include retarded timing and more EGR to lower the NOx.

For fuels SME10•PME10, SME10•PME10•RME10, SME5•PME5•RME5, RME10•SME10, RME10•PME10 and JME30, the optimiser was not able to find a solution to reduce fuel consumption below the levels of RF06. Optimised calibrations still gave reduced fuel consumption over baseline calibration for each fuel. NOx was greatly reduced for each of these calibrations over RF06 with soot staying at a similar level to baseline

For all the other fuels' calibrations, both fuel consumption and NOx were reduced compared to RF06 with soot staying generally the same as baseline.

2.1.8 Summary of Main Fuel Consumption and Emissions Effects- Relative to RF06

Table 2 shows a comparison of absolute fuel consumption and emissions levels and percentage differences between RF06 and the biofuels tested on the baseline calibration. Table 3 shows a similar comparison, with all fuels run on their optimised calibrations.

In the percentage columns, above 102% of the RF06 result are highlighted in red, with results below 98% of that from RF06 highlighted in green. Results in the range 98% to 102% are shown in yellow.

All data are drawn from the global DoE.

Table 2: FC and Emissions Summary: RF06 and Biofuels (Baseline Calibration)

Baseline Calibration	Density Corrected Fuel Consumption (L/100km)		Nitrogen oxides g/km		Soot g/km		Carbon monoxide g/km		Total Hydrocarbons g/km	
RF-06	5.5022	100%	0.2000	100%	0.0200	100%	0.9827	100%	0.3361	100%
RME10	5.5248	100%	0.1778	89%	0.0192	96%	0.8342	85%	0.3013	90%
PME10	5.4376	99%	0.2074	104%	0.0141	71%	0.6144	63%	0.1839	55%
SME10	5.4481	99%	0.2341	117%	0.0116	58%	0.8377	85%	0.2815	84%
RME5PME5SME5	5.6213	102%	0.2094	105%	0.0198	99%	0.8297	84%	0.3125	93%
RME10SME10	5.6569	103%	0.2279	114%	0.0175	87%	0.9654	98%	0.3448	103%
RME10PME10	5.6321	102%	0.2157	108%	0.0201	100%	0.8211	84%	0.2810	84%
PME10SME10	5.6200	102%	0.2172	109%	0.0149	75%	0.8061	82%	0.2768	82%
RME10PME10SME10	5.6439	103%	0.2076	104%	0.0144	72%	0.9628	98%	0.3062	91%
HVO30	5.4554	99%	0.1957	98%	0.0204	102%	0.4901	50%	0.1728	51%
JME30	5.6291	102%	0.2342	117%	0.0175	88%	0.7259	74%	0.2084	62%

Table 3: FC and Emissions Summary: RF06 and Biofuels (Optimised Calibration)

Optimised Calibration	Density Corrected Fuel Consumption (L/100km)		Nitrogen oxides g/km		Soot g/km		Carbon monoxide g/km		Total Hydrocarbons g/km	
RF-06	5.5022	100%	0.2000	100%	0.0200	100%	0.9827	100%	0.3361	100%
RME10	5.3218	97%	0.2000	100%	0.0200	100%	0.6065	62%	0.2187	65%
PME10	5.4237	99%	0.2000	100%	0.0200	100%	0.6501	66%	0.1850	55%
SME10	5.4863	100%	0.2250	112%	0.0200	100%	0.8314	85%	0.3114	93%
RME5PME5SME5	5.5986	102%	0.2000	100%	0.0200	100%	0.8083	82%	0.3106	92%
RME10SME10	5.6605	103%	0.2000	100%	0.0200	100%	0.8651	88%	0.2925	87%
RME10PME10	5.6069	102%	0.2000	100%	0.0200	100%	0.7578	77%	0.2526	75%
PME10SME10	5.6136	102%	0.2000	100%	0.0200	100%	0.7863	80%	0.2758	82%
RME10PME10SME10	5.6228	102%	0.2000	100%	0.0200	100%	0.8585	87%	0.2618	78%
HVO30	5.3500	97%	0.2000	100%	0.0200	100%	0.4370	44%	0.1836	55%
JME30	5.6941	103%	0.2000	100%	0.0200	100%	0.9276	94%	0.2677	80%

2.2 Results of the Weighted Cycle DoE – Baseline Calibration

2.2.1 Regulated Emissions and Fuel Consumption

Results of the weighted cycle $NEDC_{si}$ were consistent with those seen from the global DoE. However, these data did indicate that there are some synergistic and antagonistic effects between different FAME types. For example, increasing SME by 5% was shown to have a significant effect of increasing NOx by 5%, but increasing both SME and PME simultaneously by 5% led to a 5% reduction in NOx.

Trends seen when increasing the level of individual FAME in the base fuel and running on the baseline calibration are summarised in Table 4 below. Those trends shown in bold were statistically significant. Despite being generated from 6 points these trends were very similar to those seen from the >150 point global DoE (Table 1).

Table 4: Weighted Cycle DoE, Baseline Calibration – Effects of Increasing Fuel FAME Content on Regulated Emissions

	Increasing PME	Increasing RME	Increasing SME
Fuel Consumption	↑	↑	↑
NOx emissions	=	↓	↑
Soot emissions	=	↑	↓
CO emissions	↓	↑	↑
HC emissions	↓	↑	↑

2.3 Weighted Cycle DoE Results – Optimised Calibration, FAME Effects

2.3.1 Regulated Emissions and Fuel Consumption

None of the results of the weighted cycle $NEDC_{si}$ contradicted those seen from the global DoE. Few significant effects were observed, though a ~1.1% increase in fuel consumption was observed to result from a 5% increase in SME.

Trends seen when increasing the level of individual FAME in the base fuel and running on the optimised calibration are summarised in Table 5 below.

Table 5: Weighted Cycle DoE, Optimised Calibration – Effects of Increasing Fuel FAME Content on Regulated Emissions

	Increasing PME	Increasing RME	Increasing SME
Fuel Consumption	↑	↑	↑
NOx emissions*	=	=	=
Soot emissions*	=	=	=
PM emissions	↑	↓	↑
CO emissions	↓	↓	↑
HC emissions	↓	↓	↑

2.3.2 Unregulated Emissions

There were few significant effects with unregulated emissions that strongly correlated with FAME type.

Analysis of PM filters from the $NEDC_{si}$ revealed no significant effects of the different FAME on elemental carbon or fuel volatility HC. However, total lubricant volatility HC was apparently increased by the presence of SME: a 5% increase in SME resulted in a 1.4mg/km increase in lubricant volatility HC. This may be the consequence of fuel dilution admitting additional oil into the combustion chamber and its survival to associate with soot in the PM.

Emissions of nitrous oxide (N_2O) were elevated by increases in the level of SME in the fuel: by ~0.7mg/km for a 5% increment in fuel SME content. As a greenhouse gas likely subject to future regulation, increases in nitrous oxide emissions may be of concern with the widespread use of SME if this observation is repeated in other studies.

Unsurprisingly, as regulated emissions analyses had indicated for NOx, and as a result of the soot/NOx trade-off, nitric oxide emissions directionally increased with increases of RME, SME and PME, though only the PME effect was significant: ~12 mg/km (~8% of NO) for a 5% increment in fuel PME content.

Trends in unregulated emissions seen when increasing the level of individual FAME in the base fuel and running on the optimised calibration are summarised in Table 6 below. Those trends shown in bold were statistically significant.

Table 6: Weighted Cycle DoE, Optimised Calibration – Effects of Increasing Fuel FAME Content on Unregulated Emissions

	Increasing PME	Increasing RME	Increasing SME
Elemental Carbon Emissions	=	=	=
Fuel Derived HC (from PM analyses)	=	=	=
Oil Derived HC (from PM analyses)	=	=	**↑**
Nitrate (from PM analyses)	=	=	=
Sulphate (from PM analyses)	=	=	=
Accumulation Mode Particle Number	↑	↓	↑
Total Particle Number	↑	↓	↑
PMP Solid Particle Number	↑	↓	=
Total Aldehydes	=	=	=
Total Particle Phase PAH	↑	↑	=
Nitrous oxide	↑	=	**↑**
Nitrogen oxide	**↑**	↑	↑
Nitrogen dioxide	↓	=	=

2.4 Weighted Cycle DoE Results – Optimised Calibration, Physical Effects

Contrary to the limited effects seen from FAME type, there appeared to be much stronger correlations identified within the statistical analyses for fuel chemistry properties. However, these findings require validation through a specific fuel property related DoE for two reasons: the fuels matrix was non-orthogonal for the properties under test, which throws doubt on the magnitude of effects observed; a number of fuel properties were cross-correlated with other fuel properties. Any validation work should seek to decouple effects and maximise fuel to fuel differences. In this study, many of the effects of unregulated emissions appeared to be related to two fuel properties: Fraction saturated FAME and Fraction <C16 FAME (which represents fuel front-end volatility).

In general, components of particulate matter were either reduced in response to increases in the Fraction saturated FAME (EC, Fuel HC, sulphate) or increased in response to increased Fraction <C16 FAME (Oil HC, nitrate). Particle number parameters, which were dominated by the solid particle mode showed the same trend as elemental carbon emissions.

Aldehydes also decreased with an increase in the Fraction of saturated FAME, this may indicate an increased tendency of unsaturated FAME to result in partially oxidised carbonyl species. An increase in methane was also related to an increase in iodine number and therefore unsaturation.

N_2O and NO_2 were reduced by increases in the Fraction saturated FAME, while NO (like NO_3) was increased by increases in Fraction <C16 FAME.

2.5 Weighted Cycle DoE Results Optimised Calibration – Fuel Effects on Unregulated Emissions

Following optimisation on each of the fuels, comparisons of the levels of unregulated emissions were made. Significant increases in emissions levels from the base fuel have been interpreted to indicate that changes made to the calibration have resulted in negative impacts in species not currently subject to legislation. Reductions in emissions levels indicate that those species are reduced by the calibration.

2.5.1 Species Increased by Calibration Optimisation

Tests on all fuels produced similar, or elevated, N_2O levels to the base fuel. Highest overall levels (~9mg/km) were observed from the B20 fuels, with SME 10 also producing high emissions levels. Lowest levels were seen from the base fuel and RME10 at ~6mg/km. As a greenhouse gas, emissions of N_2O are of future concern. According to the International Panel on Climate Change (IPCC)[1], N_2O has a global warming potential (GWP) 298 times greater than CO_2. On this basis, the N_2O GWP effect of moving from the base fuel to FAME-based fuels would be equivalent to 0.003*298 = 0.9g/km CO_2.

Emissions of NO, the major part of engine-out NOx, were increased with increasing FAME level, in response to the calibration optimisation exploiting lower soot levels seen in the baseline calibration from FAME containing fuels.

At ~5mg/km, methane emissions were higher from SME10 and JME30 than from the base fuel, while other fuels emissions were similar to those of the base fuel (3mg/km). Methane is also a greenhouse gas and has a global warming potential (GWP) 25 times greater than CO_2. On this basis, the CH_4 GWP effect of moving from the base fuel to FAME-based fuels would be minimal (equivalent to 0.002*25 = 0.05g/km CO_2 or less).

Solid particle number emissions were higher from the SME10•PME10•RME10 B30 fuel (by ~50%) and SME10 (by ~75%) than from the base fuel. Accumulation mode PN from the DMS showed similar effects. Increases in solid particles were shown to be closely related to increases in the elemental carbon fraction of PM. Black carbon from fossil fuel is now considered to have a GWP of ~1000 based upon mass[2], though the influences of particle number/surface are being explored.

Total (solid plus volatile) particle numbers were elevated from SME10•PME10•RME10 B30 fuel relative to the base fuel by ~10%: indicating that the base fuel has a larger volatile particle fraction than the SME10•PME10•RME10.

Analyses of PM Chemistry indicated several fuel-to-fuel differences:

Elemental carbon levels were highest from the B30 fuels and exceptionally, at 30mg/km, highest from SME10.

Unburned Fuel HC (including FAME) generally increased with FAME level, with one or more fuels in B10, B15, B20 and B30 categories showing higher emissions than the base fuel.

Lubricant HC were higher from the two B30 fuels than from the base fuel, and also higher from SME10 and SME5•PME5•RME5 B15 fuel.

Sulphate levels were higher from some FAME-based fuels than from the base fuel, however levels were extremely low (20 – 80µg/km) in-line with low fuel and lubricant sulphur levels.

Nitrate levels were up to 0.5mg/km higher from some FAME containing fuels (SME10, SME5•PME5•RME5, JME10) than from the baseline fuel (emissions of ~2mg/km). However, there were no obvious trends on emissions.

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[1] http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf
[2] http://en.wikipedia.org/wiki/Black_carbon#cite_ref-39

There was an overall trend of increased particle-phase PAH with FAME containing fuels. However, levels of these PAH were very low (typically <5µg/km). There was an indication that PME may have a greater tendency to increase PAH than other FAME: this may be linked to elevated levels of elemental carbon seen from PME10.

It should be noted that PM chemistry effects are of limited concern, other than their contribution to particulate mass, as most species are efficiently collected and retained by the diesel particulate filters (DPFs) which will be mandatory in Europe from the end of 2011.

2.5.2 Species Reduced by Calibration Optimisation

Many unregulated emissions constituents showed similar levels of emissions to the base fuel, but only formaldehyde showed consistent reductions with all FAME-based fuels. Emissions of acetaldehyde and total aldehydes (excluding acetone) were also generally reduced, excepting JME30 which showed a 30% increase in total aldehydes and a small increase in acetaldehyde.

2.6 Weighted Cycle DoE Results: Linearity Effects from Baseline Calibration Tests on 3 Fuels

From the analysis of regulated emissions results and engine parameters from three fuels at 3 different FAME levels: B0 [RF06], B15 [PME5•RME5•SME5] and B30 [PME10•RME10•SME10], linearity effects were studied.

Results suggest that soot emissions were linear - decreasing with increased FAME at high loads and from the NEDC, but increasing with increased FAME at low loads. CO and HC results were probably linear, showing reduced CO and HC with increased FAME at all conditions.

There was no clear evidence of linearity with the following emissions and engine parameters: NOx, noise, Pmax, 10%, 50% and 90% mass fractions burned.

2.7 Weighted Cycle DoE Results: Effects of Different FAME types – Comparison of B30 Fuels

Three different B30 fuels were compared directly with each other, and with the base fuel, on the baseline calibration:

- An advanced 1st/2nd generation biofuel: HVO, at 30% in RF06 [HVO30]
- A non-edible 1st generation biofuel: JME, at 30% in RF06 [JME30]
- A Mixed FAME biofuel: PME10•RME10•SME10, at 30% in RF06 [Mixed B30]

The HVO30 typically showed similar fuel consumption and NOx emissions to the base fuel, but the lowest CO and HC emissions of all fuels. Soot levels were similar between all fuels.

Fuel consumption from the JME30 and mixed B30 fuels was similar, and from the NEDC around 2% higher than from the base fuel.

NOx emissions were highest of the 4 fuels from JME30.

CO and HC emissions were generally higher from the mixed B30 than from the JME30; both B30 fuels had lower or similar CO and HC emissions to the base fuel.