EXECUTIVE SUMMARY

The recent interest in the use of non-transesterified vegetable oils as a diesel substitute has highlighted the need for the Department for Transport (DfT) to further the understanding of the emissions effects of such fuels, in order to enable informed policy decisions for the future.

This programme undertook testing of two vehicles, representative of the current UK fleet mix, over the current European legislative drive cycle with the aim of identifying emissions effects of pure vegetable oil (VVO100) compared to a baseline UK marketplace Ultra Low Sulphur (ULSD) diesel fuel. A splash blend of 5% rapeseed methyl ester in ULSD (RME5) was also evaluated.

This work was undertaken for the Department for Transport (DfT) under the terms of the Framework Agreement for provision of Scientific & Technical Support (S0217/VC).

The vehicles sourced for this programme were a VW Passat 1.9l and a Peugeot 106 1.5l. Both vehicles were at least Euro II compliant. In order to enable the vehicles to run on VVO100, conversion kits were supplied and fitted. The conversion kits consisted primarily of a heated line to maintain the fuel at 80°C, an auxiliary tank, and a manual switch to enable switching between diesel and VVO100. No operational problems associated with the kits were experienced during the programme.

Regulated emissions: hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO) and particulate mass (PM) were measured throughout, as well as carbon dioxide (CO\textsubscript{2}) and selected unregulated pollutants. These included nitrogen species (NO, NO\textsubscript{2}, N\textsubscript{2}O, NH\textsubscript{3}) and some hydrocarbon species including 1,3-butadiene, methane and formaldehyde, measured by FTIR, as well as mass weighted particle size distribution measurements via a micro orifice uniform deposit Impactor (MOUDI). Vapour-phase and particulate-bound Polycyclic Aromatic Hydrocarbons (PAHs) were also analysed as one sample to give a total PAH value. Duplicate and sometimes triplicate hot-start NEDC tests were undertaken; this ensured some degree of confidence in the dataset and the opportunity to undertake repeat tests should repeatability criteria not be met.

The main conclusions of the programme were as follows:

Fuel Effects:

- The conversion kit, fitted to enable the vehicle to run on VVO100, had a negligible effect on the emissions performance of baseline ULSD. Therefore it is considered valid to compare directly emissions results from VVO100, delivered via the conversion kit, to baseline ULSD running from the main tank.
- The effects of RME5 on emissions compared to baseline ULSD were small and within the error bands of the ULSD dataset in most cases.
- There was some evidence of carry-over effects on HC emissions on post-VVO100 tests in the VW Passat. Therefore, the post-VVO100 tests were not included in the discussion and graphs for fuel comparisons of HC emissions
- VVO100 showed increases in HC emissions of \textasciitilde250\% and CO emissions of \textasciitilde420\% in the VW Passat and increases in HC and CO emissions of 170\% and 60\% respectively in the Peugeot 106, compared to baseline ULSD.
- VVO100 also gave increases in PM of \textasciitilde100\% in the VW Passat and 8\% reduction in NOx compared to baseline ULSD. These effects were not seen in the Peugeot 106 vehicle.
• The rise in HC emissions on VVO100 in the VW Passat was mirrored by a rise in small combustion products, such as methane and ethane, and partial oxidation products, such as formaldehyde. The reduction in NOx was shown to be primarily due to a reduction in NO.

• The effects of RME5 on unregulated pollutants were unclear; for example, no discernible effects on aldehyde emissions were seen.

• VVO100 gave clear increases in PAH emissions compared to baseline ULSD in the VW Passat; for example, benzo(a)pyrene increased by nearly 20 times. Such effects on PAH emissions were not identifiable on the Peugeot 106.

• It is likely, from emissions evidence and published studies, that many of the emission effects seen on VVO100 fuel were associated primarily with poor atomisation due to the high viscosity and/or molecular weight of the fuel. However, the magnitude of these effects was engine-specific.

• From both vehicles, the RME5 fuel provided a reduction in particulate mass measured by the MOUDI relative to the ULSD baseline. For PM10, this was ~4% for the Passat and ~20% for the Peugeot 106.

Vehicle Effects:

• The net effect of the base engine technology (i.e. IDI vs DI) in terms of emissions was difficult to discern since both technologies are converging in terms of emissions capability

• The Peugeot 106 showed poorer repeatability than the VW Passat, although it should be borne in mind that absolute emission levels were lower from the Peugeot

• Generally fuel effects on emissions were much more easily identifiable on the VW Passat than the Peugeot 106. It is possible that the higher combustion chamber temperatures which would be evident in the smaller, lower powered Peugeot, especially over the highest speed points of the NEDC cycle, may well lead to improved fuel dispersal upon injection, and/or better fuel burn out, and explain some of the differences in the response of the two vehicles to operation on VVO100.

• With operation in the Passat, the VVO100 generated PM10 emissions levels over twice as high as those from the reference ULSD. Alternatively, PM10 emissions from the Peugeot 106 running on VVO100 were similar to those from ULSD.

• While the addition of RME5 appears beneficial for PM10 emissions in both vehicle types – probably since it enhances in-cylinder oxidation and reduces carbon generation, the low volatility of the VVO100 may mean that larger engines when running at cooler combustion and exhaust temperatures may produce higher levels of particulate mass.
Recommendations:

- The conclusions from this study are based on a limited dataset from two vehicles only. Greater emissions understanding would be gained from expanding the fuels/vehicles test matrix.

- This study does not consider the long term effects on engine durability as a result of running on VVO100. The accompanying literature study (RD 03/305301.1) suggest that durability issues with VVO100 may be significant, and hence this would warrant further investigation in this area.
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1. INTRODUCTION

Owing to recent interest in the use of non-transesterified vegetable oil as a diesel substitute, the Department for Transport (DfT) wished to further their understanding with regard to the emissions effects of this fuel compared to conventional diesel or biodiesel. The work undertaken in this programme aims to provide emissions data which will contribute towards the ability to make future policy decisions for non-transesterified fuels, based on performance in vehicle tests.

A kick-off meeting was held at Shoreham on 19 August 2003, at which aspects of the programme were discussed and agreed with DfT.

This work was undertaken for the Department for Transport (DfT) under the terms of the Framework Agreement for provision of Scientific & Technical Support (S0217/VC).

2. OBJECTIVE

The objective of this programme was:

- To assess the emissions performance of virgin vegetable oil (VVO100) compared to current Ultra-Low Sulphur Diesel (ULSD) in 2 Euro II+ light duty vehicles representative of types common in the UK market

3. TEST PROGRAMME

3.1 Vehicle Selection and Check

Ricardo sourced and purchased two vehicles, meeting at least Euro II emission standards, on behalf of the programme. Care was taken over choice of vehicles to minimise effects of VVO100 on the fuel injection system; Ricardo were advised that Lucas/Cav pumps may suffer delivery problems. Hence vehicles were sought with Bosch or Nippon Denso fuel systems.

The vehicles finally sourced were agreed with DfT and were as follows:

- **Vehicle 1** – VW Passat 1.9l DI (100PS). Fitted with oxidation catalyst. Year of registration: 01/01/99 Mileage on receipt: 52,221

- **Vehicle 2** – Peugeot 106 1.5l IDI (58BHP). Fitted with oxidation catalyst. Year of registration: 01/03/01 Mileage on receipt: 21,000

The net effect of the two base engine technologies (i.e. DI vs IDI) on the emissions profiles of the vehicles is difficult to determine, since both vehicles were calibrated to
meet at least Euro II levels, and also DI and IDI technology has converged in recent years in terms of emission performance. Some background information on DI vs IDI is provided in Appendix 1, and net emissions effects are further discussed in Section 5 of this report. Although IDI numbers are dwindling in terms of sales/year (see Appendix 1), Ricardo considers that this technology is still representative since about 50%* of diesel passenger vehicles in the UK on-road fleet are still IDI.

*estimate based on data from UK Society of Motor Manufacturers (SMMT) and Ricardo knowledge.

The oxidation catalyst will typically convert between 80-95% of engine-out HC and CO, depending on conditions, and as such may “mask” some fuel effects on emissions. The oxidation catalyst will also convert a proportion (typically <40%) of the soluble organic fraction (SOF) portion of particulate, if the catalyst temperature is >~320°C.

Before commencement of testing, an MOT emissions check was undertaken to ensure compliance. Results are shown in Table 1 below:

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>CO ppm</th>
<th>HC ppm</th>
<th>Smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>VW Passat</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>1.17 m⁻¹</td>
</tr>
<tr>
<td>Peugeot 106</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>1.66 m⁻¹</td>
</tr>
<tr>
<td>MOT pass limit</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>2.5 m⁻¹ (NA) 3.0 m⁻¹ (Turbo)</td>
</tr>
</tbody>
</table>

3.2 Conversion Kits

Conversion kits to enable the vehicles to operate on VVO100 were sourced and fitted. A Ricardo employee was present when the kits were fitted to both vehicles and made the following observations:

The work was professionally carried out to a high standard although this was slightly compromised due to the requirement that the conversion would need to be removed at a later date, when the testing was complete, leaving no trace of the installation. Therefore no hole drilling was allowed. This meant that pieces of the kit were cable tied to a nearby point, rather than a permanent fixing being used. Accompanying photographs show the installation. The nylon fuel hose running from the extra tank in the boot, through to the inline fuel heater/solenoid switching block, situated near the Bosch fuel pump attached to the engine, was simply cable tied alongside the original fuel lines.
The conversion was completed to a high standard, with attention paid to cleanliness of components fitted.

3.3 Fuels

A UK supply of ULSD (S content <50ppm) was used as base fuel. The fuel analysis is shown in Appendix 2.

Rapeseed Methyl Ester (RME) component was sourced from a major oil company. This was blended into the ULSD at 5% to provide the second test fuel. Analytical results for
RME5 fuel are shown in Appendix 2. It is expected that the oxygen content of the RME in this fuel blend would be a key influence on emissions.

VVO100 originated from a retail supply. The VVO100 was of rapeseed origin (Canola) and was of food grade standard; hence no fuel specification sheet was available. However, the German Rapeseed Fuel Standard is enclosed for reference in Appendix 3. This can be compared with the analytical results for VVO100 in Appendix 2, showing that the test VVO100 fuel is within the German specification for density, kinematic viscosity @40°C and sulphur content. The differences in density and viscosity between VVO and ULSD base fuel would be expected to account for the major differences in emissions profiles from these two fuels. Other parameters which are included in the German specification were not requested for analysis; but it is not expected that these parameters would have a major influence on emissions.

3.4 Repeatability Criteria

Vehicles were tested over repeat hot start New European Drive Cycles (NEDC) (98/69/EC). For each vehicle/fuel combination, at least duplicate, and sometimes triplicate, tests were undertaken. Since testing was hot start, it was possible to complete testing on each fuel within a single day. Duplicate testing enables some degree of confidence in the data set, and triplicate tests allow for an additional data point should duplicate back-to-back test exceed the values stipulated by DfT, shown in Table 2 below:

<table>
<thead>
<tr>
<th>Light Duty Diesel</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-to-back</td>
<td>1.40</td>
<td>1.32</td>
<td>1.09</td>
<td>1.28</td>
</tr>
</tbody>
</table>

(Expressed as the ratio higher/lower result)

3.5 Preconditioning

Prior to commencement of tests on each fuel, the main fuel tank was flushed and filled with the new fuel. Running on the test fuel, the vehicle was then driven on the road under normal service conditions for 200 miles. For the VVO100 fuel, for the last 5 miles the vehicle was switched to run on ULSD in order to flush the lines of VVO100 and enable start up the next day. The vehicle was then left to soak at ambient temperature (20 –30°C) for at least 12 hours.

Since the NEDC test cycles were hot start, preconditioning took place on the morning of the tests themselves. Since vehicles are unable to start up on VVO100, the preconditioning procedure was designed to ensure maximum similarity between tests. The preconditioning procedure was as follows:

- Vehicle drove two consecutive ECE cycles followed by an EUDC cycle.
- The first ECE was driven on ULSD with a change to the test fuel during the short idle at the end of that cycle.
- The second ECE and EUDC were then driven on the test fuel.
A dilution system conditioning protocol was also employed to minimise contamination of the dilution system by low volatility materials associated with the VVO100 and biodiesel fuels. This is briefly described below:

Following the last emissions test of the day, a vehicle (NOT the test vehicle) was driven at 120km/h for 30 minutes in order to purge the exhaust system, dilution system and transfer line of residual materials. This vehicle was fuelled with ULSD from the same batch as the test fuel. In this way, the tunnel and transfer line were both purged and standardised by a vehicle operating on the programme ULSD.

### 3.6 Test Protocol

Preconditioning took place immediately prior to the emissions test themselves, since the NEDC test was hot start. Therefore each set of tests per fuel followed this procedure:

- (1) Preconditioning (Section 3.5) consisting of one ECE on ULSD, followed by one complete hot start NEDC on test fuel
- (2) Idle vehicle for 5 minutes, switch off
- (3) one hot start ECE on ULSD, hot start NEDC emissions test #1 on test fuel
- (4) Idle vehicle for 5 minutes, switch off
- (5) one hot start ECE on ULSD, hot start NEDC emissions test #2 on test fuel
- (6) Idle vehicle for 5 minutes, switch off
- (7) one hot start ECE on ULSD, hot start NEDC emissions test #3 on test fuel

The complete test protocol for each vehicle in this programme is shown in Table 3 below:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fuel</th>
<th>Tank</th>
<th>Repeat Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ULSD</td>
<td>Main</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>RME5</td>
<td>Main</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>ULSD</td>
<td>Main</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td><em>ULSD</em></td>
<td>Auxiliary Tank 1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>VVO100</td>
<td>Auxiliary Tank 2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td><em>ULSD</em></td>
<td>Auxiliary Tank 1</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>ULSD</td>
<td>Main</td>
<td>2</td>
</tr>
</tbody>
</table>

The protocol was designed so that an A-B-A test order was provided for each alternative fuel. In addition, the protocol allowed for the effects of the conversion kit on “base” fuel to be ascertained (Stages 4 and 6 – tests on ULSD from auxiliary tank and heated line system). Repeat tests on ULSD from the main tank at Stages 1,3 and 7 allowed any baseline drift through the programme to be identified.

It should be noted that the VVO100 was run from a dedicated auxiliary tank which was used for both vehicles. This eliminated the possibility of cross-contamination between VVO100 and ULSD in the auxiliary tanks.

The total number of tests conducted in this programme, according to the protocol above, was as follows:
2 vehicles x 18 tests = 36 tests total

In practice it proved necessary to undertake additional tests, for example, when the MOUDI measurements failed. Extra tests undertaken are detailed in the Results Section (Section 4).

3.7 Regulated and Unregulated Emissions Measurement

For each test, regulated emissions (CO, NOx, HC and PM) were measured throughout. These were collected as bagged samples over each phase of the cycle and expressed as g/km. CO₂ emissions were also recorded. In addition, tailpipe raw emissions were collected on a second-by-second basis. Raw emissions are expressed as ppm and presented as cumulative mass over time.

MOUDI samples were collected over every test. Results are expressed as 11 size discriminated stages which represent mass fractions ranging from > 10 µm to < 56 nm.

FTIR analyses were undertaken on \( \frac{2}{3} \) of tests on ULSD, and on every test undertaken on the VVO100 or biofuel blends. Thus the total number of FTIR tests undertaken in this programme was 28.

The following compounds were measured:

- Ammonia (NH₃)
- Nitrous Oxide (N₂O)
- Nitric Oxide (NO)
- Nitrogen Dioxide (NO₂)
- Methane
- Formaldehyde
- Acetaldehyde
- 1,3-butadiene

Analyses of Polycyclic Aromatic Hydrocarbons (PAH) were undertaken on \( \frac{1}{3} \) of tests on ULSD, and \( \frac{2}{3} \) of tests on every biofuel. Thus the total number of PAH tests in this programme was 16.

Particulate-bound and vapour phase samples were taken; these were combined and analysed as one sample to give a “total PAH” value.

4. RESULTS

For the purposes of this report, fuels are referred to throughout as follows:

- ULSD = Ultra Low Sulphur Diesel running from main tank
- *ULSD* = Ultra Low Sulphur Diesel running from auxiliary tank and through heated line
- RME5 = 5% Rapeseed Methyl Ester and 95% ULSD blend
- VVO100 = 100% Virgin Vegetable Oil
4.1 VW Passat – Regulated Emissions

Table 4 shows all regulated emissions and CO₂ results for the VW Passat

<table>
<thead>
<tr>
<th>Date</th>
<th>Fuel Name</th>
<th>Total CO (g/km)</th>
<th>Total THC (g/km)</th>
<th>Total NOx (g/km)</th>
<th>Total PM (g/km)</th>
<th>Total CO₂ (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 2, 2003</td>
<td>ULSD</td>
<td>0.129</td>
<td>0.066</td>
<td>0.715</td>
<td>0.071</td>
<td>140.2</td>
</tr>
<tr>
<td>Sept 2, 2003</td>
<td>ULSD</td>
<td>0.129</td>
<td>0.060</td>
<td>0.730</td>
<td>0.072</td>
<td>138.8</td>
</tr>
<tr>
<td>Sept 2, 2003</td>
<td>ULSD</td>
<td>0.125</td>
<td>0.060</td>
<td>0.729</td>
<td>0.075</td>
<td>137.4</td>
</tr>
<tr>
<td>Sept 3, 2003</td>
<td>RMES</td>
<td>0.122</td>
<td>0.054</td>
<td>0.714</td>
<td>0.068</td>
<td>142.4</td>
</tr>
<tr>
<td>Sept 3, 2003</td>
<td>RMES</td>
<td>0.130</td>
<td>0.059</td>
<td>0.704</td>
<td>0.069</td>
<td>139.6</td>
</tr>
<tr>
<td>Sept 3, 2003</td>
<td>RMES</td>
<td>0.125</td>
<td>0.058</td>
<td>0.711</td>
<td>0.070</td>
<td>139.3</td>
</tr>
<tr>
<td>Sept 4, 2003</td>
<td>ULSD</td>
<td>0.123</td>
<td>0.057</td>
<td>0.700</td>
<td>0.069</td>
<td>139.1</td>
</tr>
<tr>
<td>Sept 4, 2003</td>
<td>ULSD</td>
<td>0.120</td>
<td>0.057</td>
<td>0.711</td>
<td>0.069</td>
<td>138.3</td>
</tr>
<tr>
<td>Sept 4, 2003</td>
<td>ULSD</td>
<td>0.125</td>
<td>0.061</td>
<td>0.717</td>
<td>0.073</td>
<td>139.3</td>
</tr>
<tr>
<td>Sept 5, 2003</td>
<td>ULSD*</td>
<td>0.114</td>
<td>0.056</td>
<td>0.725</td>
<td>0.072</td>
<td>140.8</td>
</tr>
<tr>
<td>Sept 5, 2003</td>
<td>ULSD*</td>
<td>0.119</td>
<td>0.059</td>
<td>0.735</td>
<td>0.074</td>
<td>137.4</td>
</tr>
<tr>
<td>Sept 8, 2003</td>
<td>VVO</td>
<td>0.654</td>
<td>0.191</td>
<td>0.667</td>
<td>0.137</td>
<td>152.2</td>
</tr>
<tr>
<td>Sept 8, 2003</td>
<td>VVO</td>
<td>0.657</td>
<td>0.206</td>
<td>0.687</td>
<td>0.152</td>
<td>150.4</td>
</tr>
<tr>
<td>Sept 8, 2003</td>
<td>VVO</td>
<td>0.686</td>
<td>0.223</td>
<td>0.667</td>
<td>0.173</td>
<td>152.6</td>
</tr>
<tr>
<td>Sept 9, 2003</td>
<td>ULSD*</td>
<td>0.147</td>
<td>0.113</td>
<td>0.735</td>
<td>0.076</td>
<td>140.9</td>
</tr>
<tr>
<td>Sept 9, 2003</td>
<td>ULSD*</td>
<td>0.145</td>
<td>0.107</td>
<td>0.747</td>
<td>0.082</td>
<td>139.4</td>
</tr>
<tr>
<td>Sept 9, 2003</td>
<td>ULSD*</td>
<td>0.135</td>
<td>0.102</td>
<td>0.763</td>
<td>0.087</td>
<td>142.7</td>
</tr>
<tr>
<td>Sept 10, 2003</td>
<td>VVO</td>
<td>0.128</td>
<td>0.089</td>
<td>0.763</td>
<td>0.077</td>
<td>140.3</td>
</tr>
<tr>
<td>Sept 10, 2003</td>
<td>ULSD</td>
<td>0.124</td>
<td>0.089</td>
<td>0.754</td>
<td>0.078</td>
<td>140.5</td>
</tr>
</tbody>
</table>

4.1.1 Repeatability

Repeatability of emissions on this vehicle was generally good and typically well within acceptance criteria. Table 5 shows mean, standard deviations and coefficient of variance (COV) for Passat emissions for all results:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CO₂ (g/km)</th>
<th>CO (g/km)</th>
<th>THC (g/km)</th>
<th>NOx (g/km)</th>
<th>PM (g/km)</th>
<th>Fuel (km/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
<td>139.2</td>
<td>0.125</td>
<td>0.066</td>
<td>0.727</td>
<td>0.073</td>
<td>18.90</td>
</tr>
<tr>
<td>RMES</td>
<td>140.4</td>
<td>0.126</td>
<td>0.057</td>
<td>0.709</td>
<td>0.069</td>
<td>18.78</td>
</tr>
<tr>
<td>&quot;ULSD*&quot;</td>
<td>140.2</td>
<td>0.131</td>
<td>0.084</td>
<td>0.741</td>
<td>0.078</td>
<td>18.76</td>
</tr>
<tr>
<td>VVO100</td>
<td>151.7</td>
<td>0.665</td>
<td>0.206</td>
<td>0.673</td>
<td>0.153</td>
<td>19.04</td>
</tr>
<tr>
<td>ULSD -stddev</td>
<td>1.1</td>
<td>0.003</td>
<td>0.017</td>
<td>0.022</td>
<td>0.004</td>
<td>0.15</td>
</tr>
<tr>
<td>RMES - stddev</td>
<td>1.7</td>
<td>0.004</td>
<td>0.003</td>
<td>0.005</td>
<td>0.001</td>
<td>0.23</td>
</tr>
<tr>
<td>&quot;ULSD*&quot; - stddev</td>
<td>2.0</td>
<td>0.015</td>
<td>0.028</td>
<td>0.015</td>
<td>0.006</td>
<td>0.27</td>
</tr>
<tr>
<td>VVO100 -stddev</td>
<td>1.2</td>
<td>0.017</td>
<td>0.016</td>
<td>0.012</td>
<td>0.010</td>
<td>0.15</td>
</tr>
<tr>
<td>ULSD-CO₂</td>
<td>0.8</td>
<td>2.6</td>
<td>25.4</td>
<td>3.0</td>
<td>4.9</td>
<td>0.8</td>
</tr>
<tr>
<td>RMES - CO₂</td>
<td>1.2</td>
<td>3.2</td>
<td>4.5</td>
<td>0.7</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>&quot;ULSD*&quot; - CO₂</td>
<td>1.4</td>
<td>11.6</td>
<td>33.1</td>
<td>2.0</td>
<td>8.0</td>
<td>1.4</td>
</tr>
<tr>
<td>VVO100 - CO₂</td>
<td>0.8</td>
<td>2.6</td>
<td>7.7</td>
<td>1.7</td>
<td>11.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

CO₂ and NOx emissions generally showed the best repeatability with COVs of <1.5 and 3.0 or less respectively. Higher COVs for other emissions were evident; especially for HCs on ULSD and "ULSD", CO on "ULSD", and PM on VVO100. Reasons for higher variability on these emissions are discussed later in this Section.

From Figure 3, it can be seen that repeatability within each set of fuel tests is generally good. For example, NOx emissions on the first set of ULSD tests vary from 0.715g/km to 0.730g/km. However, for HC emissions and possibly NOx emissions also, there are
clear differences in absolute levels between tests undertaken before VVO100 testing, and those undertaken after VVO100. HC emissions, for example, were ~0.06g/km for all fuels tested before VVO100. After VVO100, HC emissions on subsequent fuels were in the range ~0.08g/km - 0.11g/km. Similarly NOx emissions showed directional increases after VVO100 testing (range ~0.70g/km - 0.73g/km before VVO100; ~0.74g/km - 0.76g/km after VVO100).

These results indicate that, despite careful preconditioning and having a dedicated VVO100 tank to avoid cross contamination, some evidence of carry-over from VVO100 testing is apparent on HC emissions. This is further confirmed by the progressive decrease in HCs from the three tests on ULSD immediately following the VVO100 tests. Effects of VVO100 on NOx emissions are more unclear, although the progressive decrease in HC emissions is mirrored by a progressive increase in NOx.

Therefore, although repeatability on fuel sets undertaken before VVO100 testing is good, after VVO100, HC and possibly NOx results are influenced by carry over effects. These factors are taken into account when considering comparisons between fuels (Section 4.1.2) and also when considering possible drift on the baseline emissions of the vehicle through the programme.
Figure 3: VW Passat - Repeatability of Gaseous Regulated Emissions; All Fuels, Chronological Order

- **NEDC CO (g/km)**
- **NEDC T.HC (g/km)**
- **NEDC NOx (g/km)**
Figure 4: VW Passat - Repeatability of Particulate Mass

![Graph](image1)

Figure 4 shows that repeatability of measured particulate masses on most fuel sets was good. For example, emissions from RME5 were within the range of 0.068 g/km - 0.070 g/km. Particulate masses on ULSD also repeated well between fuel sets. Particulate masses on VVO100 repeated less well, with progressive increases in mass from the first to the third test on this fuel (0.137 g/km – 0.173 g/km. It is probable that this progressive increase is related to the relatively low volatility of VVO100; this is discussed further in Section 5, Discussion.

Figure 5: VW Passat - Repeatability of Carbon Dioxide Emissions

![Graph](image2)
Similarly (Figure 5), for the Passat vehicle, CO$_2$ emission repeatability within fuel sets and between fuel sets was good; this was reflected by the low COVs of 1.4 or less.

4.1.2 Comparison of Fuels

In addition to emissions values expressed in g/km, the following calculations were performed, with the agreement of DfT in order to be able to determine percentage change in emissions relative to baseline (ULSD) tests. It is assumed implicitly that the variations in emissions measurements follow the log-normal distribution and therefore geometric (logarithmic) means are used instead of arithmetic means.

Averages were determined for each fuel thus:

- $\text{EXP(AVERAGE(LN(data point1),LN(data point2),LN(data point 3)…etc))}$

To allow best discrimination between fuels each individual test was given equal weighting.

Furthermore, since there was evidence of carry-over on HC emissions following VVO100 tests, the later tests on ULSD (conducted on 9 and 10 Sept) are excluded from the following results, and those data were not included in graphs. Since carry-over effects on NOx are more unclear, the results are included in graphs and comments include a consideration of potential carry-over.

Figure 6 shows a comparison of regulated gaseous emissions between the four fuel sets. Each figure also shows error bars +/- one standard deviation of each fuel’s mean value. The 1s error bars are equivalent to approximately 67% confidence interval, therefore care must be taken when drawing conclusions about the significance of differences between fuel sets based on these error bars.
Figure 6: VW Passat - Comparison of Fuels, Mean Gaseous Emissions

- **NEDC CO (g/km)**
  - ULSD
  - RME5
  - "ULSD"
  - VVO100

- **NEDC CO2 (g/km)**
  - ULSD
  - RME5
  - "ULSD"
  - VVO100

- **NEDC T.HC (g/km)**
  - ULSD
  - RME5
  - "ULSD"
  - VVO100

- **NEDC NOx (g/km)**
  - ULSD
  - RME5
  - "ULSD"
  - VVO100

*NB For HC Emissions, Post VVO100 results on ULSD and "ULSD" are excluded*
ULSD vs *ULSD* - There was very little evidence that the emissions were influenced by the effects of running the diesel fuel through the conversion kit (auxiliary tank + heated fuel line). Figures 3 – 6 show that emissions results on both an individual and a mean basis are very similar for ULSD and *ULSD*, and that scatter bands between the fuel sets overlap. For the purposes of percentage emissions comparisons, ULSD and *ULSD* are therefore taken as one dataset to give the “baseline”.

ULSD vs RME5 – Generally the emissions effects of RME5 on the Passat were small or indistinguishable from baseline ULSD results. Figure 8 also shows HC emissions on an expanded scale, showing that average HC emissions are similar and error bars overlap between RME5, ULSD and *ULSD*.
Figure 8: VW Passat - RME5 vs ULSD and *ULSD* (pre VVO100 tests only); HC and NOx Emissions

![Graph showing HC and NOx emissions comparisons between ULSD and RME5](image)

Figure 9: VW Passat - RME5 - Percentage Change from ULSD and *ULSD

![Graph showing percentage change in emissions](image)

Figure 9 presents percentage change in emissions taking the whole ULSD and *ULSD* dataset as the baseline. "Ph 2" and "Ph 3" labelling refer to the two phases of the European Drive Cycle; the ECE and the EUDC respectively. Percentage changes must be viewed with caution, as examination of Figures 6, 7 and 8 reveals that datasets for ULSD and RME5 are very similar.
VVO100 vs ULSD – Figures 6 and 7 show that VVO100 produced considerably higher levels of CO, HC, PM and CO\(_2\) and lower NOx compared to baseline fuel. For example, CO emissions were approximately 5.3 times higher from VVO100 at \(~0.66\text{g/km}\) compared to \(~0.12 - 0.13\text{g/km}\) on ULSD and "ULSD". NOx emissions were \(~0.67\text{g/km}\) from VVO100 compared to \(~0.71- 0.74\text{g/km}\) from ULSD and "ULSD".

It should be noted that there is the possibility of “double accounting” due to the way HCs and PM are captured and measured and therefore comparisons between conventional diesel and VVO100 may not always be on a like-for-like basis. This can be explained by the fact that the semi-volatile HCs trapped by the PM filter may not be effectively retained by the heated filter upstream of the flame ionisation detector (FID) and thus may also be measured as gaseous HCs.

Figure 10 presents percentage change in emissions with VVO100. This shows that, compared to baseline, VVO100 gives \(~420\%\) increase in CO, \(~250\%\) increase in HCs and just over \(100\%\) increase in PM. NOx, on the other hand, reduces by about \(8\%\). Figures 6 and 7 show that all of these changes are at a significant level.

The effects of fuels on regulated emissions changes are discussed further in Section 5 later in this report.
4.2 Peugeot 106 – Regulated Emissions Results

Table 6 shows all regulated emissions, CO\(_2\) (g/km) and fuel consumption (km/l) results from the Peugeot 106.

<table>
<thead>
<tr>
<th>Fuel Name</th>
<th>Total CO (g/km)</th>
<th>Total CO(_2) (g/km)</th>
<th>Total T.HC (g/km)</th>
<th>Total NOx (g/km)</th>
<th>Total PM (g/km)</th>
<th>Total Fuel (km/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
<td>0.067</td>
<td>127.9</td>
<td>0.035</td>
<td>0.412</td>
<td>0.027</td>
<td>20.61</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.080</td>
<td>128.4</td>
<td>0.026</td>
<td>0.410</td>
<td>0.027</td>
<td>20.51</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.075</td>
<td>125.6</td>
<td>0.026</td>
<td>0.407</td>
<td>0.026</td>
<td>20.98</td>
</tr>
<tr>
<td>RME5</td>
<td>0.072</td>
<td>122.8</td>
<td>0.031</td>
<td>0.399</td>
<td>0.023</td>
<td>21.50</td>
</tr>
<tr>
<td>RME5</td>
<td>0.075</td>
<td>123.1</td>
<td>0.023</td>
<td>0.399</td>
<td>0.024</td>
<td>21.45</td>
</tr>
<tr>
<td>RME5</td>
<td>0.080</td>
<td>123.9</td>
<td>0.022</td>
<td>0.401</td>
<td>0.024</td>
<td>21.32</td>
</tr>
<tr>
<td>RME5 $</td>
<td>0.099</td>
<td>125.0</td>
<td>0.025</td>
<td>0.402</td>
<td>0.024</td>
<td>21.12</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.098</td>
<td>122.5</td>
<td>0.035</td>
<td>0.400</td>
<td>0.023</td>
<td>21.50</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.071</td>
<td>123.7</td>
<td>0.024</td>
<td>0.405</td>
<td>0.024</td>
<td>21.30</td>
</tr>
<tr>
<td>ULSD $$</td>
<td>0.062</td>
<td>123.3</td>
<td>0.023</td>
<td>0.403</td>
<td>0.023</td>
<td>21.36</td>
</tr>
<tr>
<td>&quot;ULSD&quot;</td>
<td>0.082</td>
<td>141.4</td>
<td>0.025</td>
<td>0.399</td>
<td>0.024</td>
<td>21.23</td>
</tr>
<tr>
<td>&quot;ULSD&quot;</td>
<td>0.077</td>
<td>122.0</td>
<td>0.020</td>
<td>0.394</td>
<td>0.024</td>
<td>21.60</td>
</tr>
<tr>
<td>VVO100</td>
<td>0.241</td>
<td>125.8</td>
<td>0.045</td>
<td>0.408</td>
<td>0.014</td>
<td>23.14</td>
</tr>
<tr>
<td>VVO100</td>
<td>0.173</td>
<td>127.6</td>
<td>0.033</td>
<td>0.418</td>
<td>0.024</td>
<td>22.83</td>
</tr>
<tr>
<td>VVO100</td>
<td>0.163</td>
<td>126.3</td>
<td>0.031</td>
<td>0.412</td>
<td>0.022</td>
<td>23.07</td>
</tr>
<tr>
<td>VVO100 $$$</td>
<td>0.254</td>
<td>127.1</td>
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<td>0.414</td>
<td>0.026</td>
<td>22.89</td>
</tr>
<tr>
<td>&quot;ULSD&quot;</td>
<td>0.096</td>
<td>120.9</td>
<td>0.027</td>
<td>0.398</td>
<td>0.024</td>
<td>21.80</td>
</tr>
<tr>
<td>&quot;ULSD&quot;</td>
<td>0.076</td>
<td>120.1</td>
<td>0.020</td>
<td>0.402</td>
<td>0.024</td>
<td>21.93</td>
</tr>
<tr>
<td>&quot;ULSD&quot;</td>
<td>0.068</td>
<td>112.0</td>
<td>0.017</td>
<td>0.405</td>
<td>0.024</td>
<td>21.78</td>
</tr>
<tr>
<td>&quot;ULSD&quot; $$$</td>
<td>0.071</td>
<td>121.4</td>
<td>0.018</td>
<td>0.403</td>
<td>0.024</td>
<td>21.71</td>
</tr>
<tr>
<td>&quot;ULSD&quot; $$$</td>
<td>0.078</td>
<td>124.1</td>
<td>0.026</td>
<td>0.417</td>
<td>0.025</td>
<td>21.24</td>
</tr>
<tr>
<td>&quot;ULSD&quot; $$$</td>
<td>0.066</td>
<td>121.2</td>
<td>0.018</td>
<td>0.415</td>
<td>0.024</td>
<td>21.75</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.065</td>
<td>121.3</td>
<td>0.017</td>
<td>0.413</td>
<td>0.026</td>
<td>21.73</td>
</tr>
<tr>
<td>ULSD</td>
<td>0.055</td>
<td>121.8</td>
<td>0.015</td>
<td>0.420</td>
<td>0.028</td>
<td>21.65</td>
</tr>
</tbody>
</table>

$ - Repeat test due to failed not-to-exceed value (HC)
$$ - Repeat test due to failed not-to-exceed value (HC)
$$$ - Repeat test due to failed not-to-exceed value (HC)
$$$$ - Repeat test due to particulate sampling failure

It was necessary to undertake several extra tests on the Peugeot 106, generally because of HCs falling outside the specified repeatability criteria limits. During the post-VVO100 tests on "ULSD", particulate sampling failed due to the exhaust line on the sample pump becoming detached partway through the first test. This effectively meant that the pump was uncontrolled and sucking at its maximum capacity. These tests were repeated on the next working day in order to obtain the particulate data.

4.2.1 Repeatability

Repeatability of emissions from the Peugeot 106 was generally poorer than from the VW Passat, although it should be noted that absolute emissions levels from the Peugeot were lower; for example, average HCs were 0.066g/km on ULSD from the Passat compared to 0.025g/km on ULSD from the Peugeot.

Table 7 shows mean, standard deviations and coefficient of variance (COV) for Peugeot emissions for all results apart from failed PM on "ULSD", tabulated in Table 6 above.

CO\(_2\) and NO\(_x\) emissions generally show the best repeatability with COVs of 2.2 or less. Higher COVs for other emissions were evident; particularly for HCs on ULSD (~30) and CO and PM on VVO100 (~23 and ~25 respectively).
### Table 7: Means, Standard Deviations, COVs for Peugeot 106: All Results

<table>
<thead>
<tr>
<th></th>
<th>CO2 (g/km)</th>
<th>CO (g/km)</th>
<th>T.HC (g/km)</th>
<th>NOx (g/km)</th>
<th>PM (g/km)</th>
<th>Fuel (km/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
<td>124.3</td>
<td>0.073</td>
<td>0.025</td>
<td>0.409</td>
<td>0.025</td>
<td>21.20</td>
</tr>
<tr>
<td>RME5</td>
<td>123.7</td>
<td>0.081</td>
<td>0.025</td>
<td>0.400</td>
<td>0.024</td>
<td>21.35</td>
</tr>
<tr>
<td><em>ULSD</em></td>
<td>121.8</td>
<td>0.076</td>
<td>0.021</td>
<td>0.404</td>
<td>0.024</td>
<td>21.63</td>
</tr>
<tr>
<td>VVO100</td>
<td>126.7</td>
<td>0.204</td>
<td>0.037</td>
<td>0.412</td>
<td>0.021</td>
<td>22.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ULSD -stdev</th>
<th>RME5 - stdev</th>
<th><em>ULSD</em> - stdev</th>
<th>VVO100 - stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
<td>2.7</td>
<td>0.013</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>RME5</td>
<td>1.0</td>
<td>0.012</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td><em>ULSD</em></td>
<td>1.5</td>
<td>0.010</td>
<td>0.004</td>
<td>0.008</td>
</tr>
<tr>
<td>VVO100</td>
<td>0.8</td>
<td>0.047</td>
<td>0.007</td>
<td>0.005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ULSD -COV</th>
<th>RME5 - COV</th>
<th><em>ULSD</em> - COV</th>
<th>VVO100 - COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
<td>2.2</td>
<td>17.6</td>
<td>30.8</td>
<td>1.6</td>
</tr>
<tr>
<td>RME5</td>
<td>0.8</td>
<td>14.7</td>
<td>16.5</td>
<td>0.4</td>
</tr>
<tr>
<td><em>ULSD</em></td>
<td>1.2</td>
<td>12.6</td>
<td>18.8</td>
<td>2.0</td>
</tr>
<tr>
<td>VVO100</td>
<td>0.7</td>
<td>22.9</td>
<td>17.5</td>
<td>1.3</td>
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</tbody>
</table>

Figure 11 shows results of gaseous regulated emissions from all fuels in chronological order. It can be seen that there is some variability within fuel sets; for example, for the first set of tests on ULSD, the HCs were 0.035g/km, 0.030g/km and 0.026g/km. There is also evidence of variability between different fuel sets; for example, the last four tests in the programme showed generally higher NOx levels (>0.412g/km), than previous tests (typically < 0.407g/km).

However, since there was no clear evidence of any carry-over or other effects on the data obtained, all results are included in graphical presentations and for discussion purposes (apart from failed Particulate Masses as tabulated in Table 6).
Figure 11: Peugeot 106 - Gaseous Regulated Emissions, All Fuels, Chronological Order

NEDC CO g/km

NEDC T.HC g/km

NEDC NOx g/km
Figure 12 shows that repeatability of measured particulate mass on most fuel sets was good; the exception being VVO100 where the first test (<0.150g/km) was much lower than subsequent tests (~0.023g/km). There was no clear explanation for this first seemingly low result, since no anomalies were identified during the test or sampling procedure.

Figure 13 shows that repeatability of measured CO₂ emissions also was good; the exception being VVO100 where the first test (~128g/km) was much higher than subsequent tests (~124g/km). There was no clear explanation for this first seemingly high result, since no anomalies were identified during the test or sampling procedure.
CO$_2$ emissions repeatability (Figure 13) within fuel sets was generally good. It can be seen that the first set of tests on ULSD is higher (range of ~125.5g/km to 128.3g/km) than subsequent sets of tests which were <124g/km (second set) and <122g/km (third set).

4.2.2 Comparison of Fuels

Figure 14: Peugeot 106 – Comparison of Fuels, Mean Gaseous Emissions
Fuels were compared using an assumption of log-normal distributions as outlined previously in Section 4.1.2.

Figure 14 and Figure 15 show a comparison of regulated gaseous emissions, and PM and fuel consumption respectively, between the four fuels. Each figure also shows error bars +/- one standard deviation of each fuel’s mean value. No data points have been discarded for these calculations.

ULSD vs *ULSD* - As seen for the VW Passat results, there was very little evidence that the emissions were influenced by the effects of running the diesel fuel through the conversion kit (auxiliary tank + heated fuel line). Figures 14 and 15 show that emissions results on a mean basis are very similar for ULSD and *ULSD*, and that scatter bands between the fuel sets overlap. For the purposes of percentage emissions comparisons, ULSD and *ULSD* are therefore taken as one dataset to give the “baseline”.

ULSD vs RME5 – Generally the emissions effects of RME5 on the Peugeot were small or indistinguishable from baseline ULSD results.

Figure 15: Peugeot 106 – Comparison of Fuels – Particulate Mass and Fuel Consumption

Figure 16 presents percentage change in emissions taking the whole ULSD and *ULSD* dataset as the baseline. “Ph 2” and “Ph 3” labelling refer to the two phases of the NEDC; the ECE and the EUDC respectively. Increases or decreases shown in emissions relative to baseline must be considered non-significant since all of the error bars of the ULSD and *ULSD* datasets, shown in Figures 14 and 15, overlap with those of RME5.
**Figure 16**: Peugeot 106 – Percentage Change from ULSD and *ULSD*

![Figure 16: Percentage Change from ULSD and *ULSD*](image)

**VVO100 vs ULSD** – Figure 14 shows that the VVO100 tested on Peugeot 106 produced higher levels of CO, HC, and CO₂ compared to baseline fuel. For example, CO emissions were approximately 2.6 times higher from VVO100 at ~0.20g/km compared to ~0.07 - ~0.08g/km on ULSD and *ULSD*. Mean NOx emissions were slightly higher at ~0.412g/km from VVO100 compared to ~0.404 - 0.409g/km from ULSD and *ULSD*. Mean PM emissions (Figure 15) were slightly lower from VVO100 than the other fuels, this effect primarily being due to the low PM obtained from the first test within the VVO100 set (Figure 12).

Figure 17 presents percentage change in emissions with VVO100. This shows that, compared to baseline, VVO100 gives approximately 170% increase in CO, and about 60% increase in HCs. Effects on other emissions in percentage terms are close to baseline.
Figure 17: Peugeot 106 –VVO100 – Percentage Change from ULSD and *ULSD*

|     | Total CO | Ph 2 CO | Ph 3 CO | Total CO2 | Ph 2 CO2 | Ph 3 CO2 | Total THC | Ph 2 THC | Ph 3 THC | Total NOx | Ph 2 NOx | Ph 3 NOx | Total PM | Ph 2 PM | Ph 3 PM | Total FC | Ph 2 FC | Ph 3 FC |
|-----|----------|---------|---------|-----------|----------|----------|-----------|----------|----------|-----------|----------|----------|----------|----------|--------|--------|----------|--------|--------|
|     |          |         |         |           |          |          |           |          |          |           |          |          |          |          |        |        |          |        |        |
|     |          |         |         |           |          |          |           |          |          |           |          |          |          |          |        |        |          |        |        |
|     |          |         |         |           |          |          |           |          |          |           |          |          |          |          |        |        |          |        |        |
|     |          |         |         |           |          |          |           |          |          |           |          |          |          |          |        |        |          |        |        |

4.3 Mass Weighted Particle Size Distribution Measurement

Mass distribution measurements were using a Micro Orifice Uniform Deposit Impactor (MOUDI) Model 110. This instrument separates particles according to their aerodynamic diameter (dAE) into 10 discrete lognormally spaced size fractions ranging from 56nm to 15µm. Below 56nm, all other particle sizes are collected on an ‘after-filter’ analogous to the conventional filter system employed for regulated PM analyses. Further details on the operating principles of the MOUDI are available on the manufacturers (MSP) website.

Data are shown for PM10, PM2.5, PM1 and all integrated stages. All but PM2.5 are simply integrated from the data tables. PM2.5 is interpolated from the 1.8µm to 3.2µm stage of the MOUDI.

4.3.1 Repeatability Of Mass and Size Distribution Measurements

4.3.1.1 VW Passat

The repeatability of MOUDI was generally very good and can be expressed in terms of the coefficient of variance (COV) from the various fuels’ replicate tests. The COV is the standard deviation quoted as a percentage of the mean. It should be noted that the dataset for all fuels is small.

As Table 8 shows, the COVs for the ULSD, *ULSD* and RME were similar and typically below 5%. Results for the VVO100 showed greater variability, with COVs around 10%. Closer inspection of the data in graphical form (Figure 18) showed that the masses from the three VVO100 tests gradually increased as the tests progressed.

1 http://www.mspcorp.com/model_100.htm
Table 8: COVs for Integrated MOUDI Data – VW Passat

<table>
<thead>
<tr>
<th></th>
<th>ULSD</th>
<th>RME5</th>
<th><em>ULSD</em></th>
<th>VVO100</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Stages</td>
<td>5.3</td>
<td>3.3</td>
<td>5.1</td>
<td>9.3</td>
</tr>
<tr>
<td>PM10</td>
<td>5.0</td>
<td>3.5</td>
<td>5.2</td>
<td>9.4</td>
</tr>
<tr>
<td>PM2.5</td>
<td>4.3</td>
<td>3.9</td>
<td>5.1</td>
<td>9.5</td>
</tr>
<tr>
<td>PM1.0</td>
<td>3.5</td>
<td>4.8</td>
<td>4.3</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Figure 18: Repeatability of Integrated MOUDI Masses – VW Passat

As shown in Figure 19, the repeatability of particle size distribution data also proved good. It is clear from this figure that the variability in VVO100 data comes at the peak of the size distribution.
Figure 19: Repeatability of MOUDI Size Distributions – VW Passat

4.3.1.2 Peugeot 106

On the Peugeot 106, the repeatability of the MOUDI was slightly poorer than observed from the VW Passat. This is likely to be a consequence of the near wide open throttle operation required for this vehicle to achieve the highest speed points of the EUDC cycle. The repeatability is expressed in terms of the coefficient of variance (COV) from the various fuels’ replicate tests in Table 9. It should be noted that the dataset for all fuels is small.

As Table 9 shows, the COVs for the ULSD, *ULSD* and RME were similar and typically at or below 10%. Results for the VVO100 showed greater variability, with COVs around 20%. These levels are approximately twice those observed for the Passat (Table 8).

Table 9: COVs for Integrated MOUDI Data – Peugeot 106

<table>
<thead>
<tr>
<th></th>
<th>ULSD</th>
<th>RME5</th>
<th><em>ULSD</em></th>
<th>VVO100</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Stages</td>
<td>10.8</td>
<td>11.8</td>
<td>6.4</td>
<td>19.6</td>
</tr>
<tr>
<td>PM10</td>
<td>10.7</td>
<td>12.0</td>
<td>6.4</td>
<td>18.4</td>
</tr>
<tr>
<td>PM2.5</td>
<td>10.1</td>
<td>9.4</td>
<td>6.1</td>
<td>16.9</td>
</tr>
<tr>
<td>PM1.0</td>
<td>9.7</td>
<td>9.2</td>
<td>6.9</td>
<td>18.9</td>
</tr>
</tbody>
</table>

This increased variability can be clearly seen in the integrated mass data shown in Figure 20.
The repeatability of particle size distribution data also proved to be worse than that seen with the Passat. As Figure 21 shows, it is clear that the variability in size distribution data comes across the entire range of the size distribution and reflects the general variability of the vehicle.

**Figure 20 : Repeatability of Integrated MOUDI Masses – Peugeot 106**

**Figure 21 : Repeatability of MOUDI Size Distributions – Peugeot 106**
4.3.2 Comparison Between Fuels

Comparisons between fuels have been made by comparing integrated masses and particle size distributions.

4.3.2.1 VW Passat – Fuels Data Compared

Table 10 shows size distribution and integrated mass data from the various fuels’ test sets. Data shown are geometric means.

<table>
<thead>
<tr>
<th>samples(n)</th>
<th>3</th>
<th>3</th>
<th>2</th>
<th>2</th>
<th>3</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/km</td>
<td>ULSD#1</td>
<td>RME5</td>
<td>ULSD#2</td>
<td>*ULSD#1</td>
<td>VVO100</td>
<td>*ULSD#2</td>
<td>ULSD#3</td>
</tr>
<tr>
<td>&lt;0.056</td>
<td>0.00067</td>
<td>0.00032</td>
<td>0.00041</td>
<td>0.00050</td>
<td>0.00086</td>
<td>0.00065</td>
<td>0.00075</td>
</tr>
<tr>
<td>0.056&lt;0.10</td>
<td>0.00230</td>
<td>0.00228</td>
<td>0.00202</td>
<td>0.00224</td>
<td>0.00328</td>
<td>0.00206</td>
<td>0.00237</td>
</tr>
<tr>
<td>0.10&lt;0.18</td>
<td>0.01219</td>
<td>0.01132</td>
<td>0.01230</td>
<td>0.01229</td>
<td>0.02055</td>
<td>0.01002</td>
<td>0.01064</td>
</tr>
<tr>
<td>0.18&lt;0.32</td>
<td>0.01105</td>
<td>0.01035</td>
<td>0.01084</td>
<td>0.01028</td>
<td>0.02715</td>
<td>0.01115</td>
<td>0.01083</td>
</tr>
<tr>
<td>0.32&lt;0.56</td>
<td>0.00845</td>
<td>0.00796</td>
<td>0.00831</td>
<td>0.00824</td>
<td>0.02128</td>
<td>0.00986</td>
<td>0.00859</td>
</tr>
<tr>
<td>0.56&lt;1.0</td>
<td>0.00760</td>
<td>0.00714</td>
<td>0.00747</td>
<td>0.00756</td>
<td>0.01703</td>
<td>0.00823</td>
<td>0.00722</td>
</tr>
<tr>
<td>1.0&lt;1.8</td>
<td>0.00543</td>
<td>0.00477</td>
<td>0.00423</td>
<td>0.00457</td>
<td>0.00862</td>
<td>0.00507</td>
<td>0.00466</td>
</tr>
<tr>
<td>1.8&lt;3.2</td>
<td>0.00203</td>
<td>0.00175</td>
<td>0.00161</td>
<td>0.00189</td>
<td>0.00269</td>
<td>0.00216</td>
<td>0.00171</td>
</tr>
<tr>
<td>3.2&lt;5.6</td>
<td>0.00140</td>
<td>0.00084</td>
<td>0.00087</td>
<td>0.00112</td>
<td>0.00165</td>
<td>0.00130</td>
<td>0.00096</td>
</tr>
<tr>
<td>5.6&lt;10</td>
<td>0.00083</td>
<td>0.00068</td>
<td>0.00047</td>
<td>0.00083</td>
<td>0.00107</td>
<td>0.00093</td>
<td>0.00059</td>
</tr>
<tr>
<td>10&lt;15</td>
<td>0.00078</td>
<td>0.00048</td>
<td>0.00044</td>
<td>0.00081</td>
<td>0.00094</td>
<td>0.00082</td>
<td>0.00064</td>
</tr>
<tr>
<td>All Stages</td>
<td>0.05299</td>
<td>0.04799</td>
<td>0.04904</td>
<td>0.05048</td>
<td>0.10535</td>
<td>0.05279</td>
<td>0.04911</td>
</tr>
<tr>
<td>PM10</td>
<td>0.0520</td>
<td>0.0474</td>
<td>0.0485</td>
<td>0.0495</td>
<td>0.1042</td>
<td>0.0518</td>
<td>0.0483</td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.0489</td>
<td>0.0452</td>
<td>0.0465</td>
<td>0.0468</td>
<td>0.1003</td>
<td>0.0487</td>
<td>0.0460</td>
</tr>
<tr>
<td>PM1.0</td>
<td>0.0423</td>
<td>0.0394</td>
<td>0.0413</td>
<td>0.0411</td>
<td>0.0901</td>
<td>0.0424</td>
<td>0.0404</td>
</tr>
</tbody>
</table>

Clearly the data from the ULSD and *ULSD* are highly similar. Consequently, in order to make comparisons between fuels, all repeats of tests on these fuels have been used to generate the data in Table 11.

<table>
<thead>
<tr>
<th>g/km</th>
<th>Geometric means</th>
<th>Standard Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ULSD</td>
<td>RME5</td>
</tr>
<tr>
<td>&lt;0.056</td>
<td>0.0006</td>
<td>0.0003</td>
</tr>
<tr>
<td>0.056&lt;0.10</td>
<td>0.0022</td>
<td>0.0023</td>
</tr>
<tr>
<td>0.10&lt;0.18</td>
<td>0.0117</td>
<td>0.0113</td>
</tr>
<tr>
<td>0.18&lt;0.32</td>
<td>0.0109</td>
<td>0.0103</td>
</tr>
<tr>
<td>0.32&lt;0.56</td>
<td>0.0094</td>
<td>0.0080</td>
</tr>
<tr>
<td>0.56&lt;1.0</td>
<td>0.0074</td>
<td>0.0071</td>
</tr>
<tr>
<td>1.0&lt;1.8</td>
<td>0.0047</td>
<td>0.0048</td>
</tr>
<tr>
<td>1.8&lt;3.2</td>
<td>0.0018</td>
<td>0.0017</td>
</tr>
<tr>
<td>3.2&lt;5.6</td>
<td>0.0011</td>
<td>0.0008</td>
</tr>
<tr>
<td>5.6&lt;10</td>
<td>0.0006</td>
<td>0.0007</td>
</tr>
<tr>
<td>10&lt;15</td>
<td>0.0006</td>
<td>0.0005</td>
</tr>
<tr>
<td>All Stages</td>
<td>0.0503</td>
<td>0.0480</td>
</tr>
</tbody>
</table>

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Shown graphically, these data indicate that particle size distributions (Figure 22) are similar between all four fuels with a major mode present between 0.10µm and 0.32µm and a secondary mode present in the 0.56µm to 1µm region. The only apparent difference between fuels is that the VVO100 mode tends towards the largest sizes of this range with a general increase in the magnitude of both modes observed with VVO100 relative to the other 3 fuels.

**Figure 22 : Comparison of MOUDI Size Distributions –VW Passat**

Graphical comparison of all stage data, PM10, PM2.5 and PM1 (Figure 23) reveals that VVO100 mass emissions (measured by MOUDI) were far higher than those of any of the other fuels, with RME showing a slight reduction in mass levels. Error bars indicate the standard deviation of each fuel's data.
Table 11 was used to generate the mean and standard deviation data shown in Figure 23. From these data the following statements regarding PM 10, PM2.5 and PM1 could be made:

- ULSD and *ULSD* datasets were indistinguishable
- RME mean emissions were between 4 and 5% lower than the ULSD and *ULSD* scatter
- VVO100 mean emissions were at least twice the emissions of all other fuels

Table 12 summarises the PM 10, PM2.5 and PM1.0 emissions from the VW Passat.

<table>
<thead>
<tr>
<th></th>
<th>ULSD</th>
<th>RME5</th>
<th><em>ULSD</em></th>
<th>VVO100</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM10</td>
<td>0.0495</td>
<td>0.0474</td>
<td>0.0505</td>
<td>0.1042</td>
</tr>
<tr>
<td>% reduction</td>
<td>0</td>
<td>4.2</td>
<td>-2.1</td>
<td>-110.6</td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.0471</td>
<td>0.0452</td>
<td>0.0476</td>
<td>0.1003</td>
</tr>
<tr>
<td>% reduction</td>
<td>0</td>
<td>4.1</td>
<td>-1.2</td>
<td>-113.2</td>
</tr>
<tr>
<td>PM1.0</td>
<td>0.0413</td>
<td>0.0394</td>
<td>0.0416</td>
<td>0.0901</td>
</tr>
<tr>
<td>% reduction</td>
<td>4.7</td>
<td>-0.8</td>
<td>-118.3</td>
<td></td>
</tr>
</tbody>
</table>

4.3.2.2 Peugeot 106 – Fuels Data Compared

For the Peugeot 106, Table 13 shows geometric means of size distribution and integrated mass data from the various fuels' test sets.
Table 13 : Peugeot 106 Fuels Repeats - MOUDI Data

<table>
<thead>
<tr>
<th>/stage (g/km)</th>
<th>ULSD#1</th>
<th>RME5</th>
<th>ULSD</th>
<th>&quot;ULSD*&quot;</th>
<th>VVO100</th>
<th>&quot;ULSD*&quot;</th>
<th>ULSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>-&lt;0.056</td>
<td>0.00079</td>
<td>0.00092</td>
<td>0.00114</td>
<td>0.00070</td>
<td>0.00035</td>
<td>0.00070</td>
<td>0.00067</td>
</tr>
<tr>
<td>0.056-&lt;0.10</td>
<td>0.00203</td>
<td>0.00182</td>
<td>0.00197</td>
<td>0.00162</td>
<td>0.00155</td>
<td>0.00179</td>
<td>0.00212</td>
</tr>
<tr>
<td>0.10-&lt;0.18</td>
<td>0.00369</td>
<td>0.00326</td>
<td>0.00357</td>
<td>0.00374</td>
<td>0.00396</td>
<td>0.00391</td>
<td>0.00409</td>
</tr>
<tr>
<td>0.18-&lt;0.32</td>
<td>0.00301</td>
<td>0.00262</td>
<td>0.00280</td>
<td>0.00285</td>
<td>0.00292</td>
<td>0.00255</td>
<td>0.00334</td>
</tr>
<tr>
<td>0.32-&lt;0.56</td>
<td>0.00187</td>
<td>0.00201</td>
<td>0.00242</td>
<td>0.00257</td>
<td>0.00234</td>
<td>0.00219</td>
<td>0.00267</td>
</tr>
<tr>
<td>0.56-&lt;1.0</td>
<td>0.00250</td>
<td>0.00205</td>
<td>0.00241</td>
<td>0.00276</td>
<td>0.00250</td>
<td>0.00224</td>
<td>0.00303</td>
</tr>
<tr>
<td>1.0-&lt;1.6</td>
<td>0.00197</td>
<td>0.00137</td>
<td>0.00200</td>
<td>0.00194</td>
<td>0.00181</td>
<td>0.00174</td>
<td>0.00217</td>
</tr>
<tr>
<td>1.8-&lt;3.2</td>
<td>0.00079</td>
<td>0.00039</td>
<td>0.00095</td>
<td>0.00070</td>
<td>0.00093</td>
<td>0.00079</td>
<td>0.00099</td>
</tr>
<tr>
<td>3.2-&lt;5.6</td>
<td>0.00043</td>
<td>0.00026</td>
<td>0.00052</td>
<td>0.00023</td>
<td>0.00068</td>
<td>0.00071</td>
<td>0.00063</td>
</tr>
<tr>
<td>5.6-&lt;10</td>
<td>0.00027</td>
<td>0.00000</td>
<td>0.00050</td>
<td>0.00018</td>
<td>0.00055</td>
<td>0.00044</td>
<td>0.00049</td>
</tr>
<tr>
<td>10-&lt;15</td>
<td>0.00010</td>
<td>0.00000</td>
<td>0.00033</td>
<td>0.00022</td>
<td>0.00065</td>
<td>0.00048</td>
<td>0.00031</td>
</tr>
<tr>
<td>All Stages</td>
<td>0.01767</td>
<td>0.01488</td>
<td>0.01866</td>
<td>0.01777</td>
<td>0.01838</td>
<td>0.01803</td>
<td>0.02062</td>
</tr>
<tr>
<td>PM10</td>
<td>0.0173</td>
<td>0.0147</td>
<td>0.0183</td>
<td>0.0173</td>
<td>0.0176</td>
<td>0.0174</td>
<td>0.0202</td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.0163</td>
<td>0.0143</td>
<td>0.0168</td>
<td>0.0166</td>
<td>0.0160</td>
<td>0.0159</td>
<td>0.0187</td>
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<tr>
<td>PM1.0</td>
<td>0.0139</td>
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<td>0.0143</td>
<td>0.0142</td>
<td>0.0136</td>
<td>0.0137</td>
<td>0.0159</td>
</tr>
</tbody>
</table>

Clearly the data from all fuels, with the possible exception of RME5, appear similar. However, as shown in Figure 20, there did not appear to be any systematic differences in emissions between separate ULSD or "ULSD*" data sets. Therefore, in order to make the most robust comparisons between fuels, all repeats of tests on these fuels’ have been used to generate the data in Table 14.

Table 14 : Mean MOUDI Emissions and Standard Deviation (g/km)

<table>
<thead>
<tr>
<th>g/km</th>
<th>ULSD</th>
<th>RME5</th>
<th>&quot;ULSD*&quot;</th>
<th>VVO100</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.056</td>
<td>0.00008</td>
<td>0.00009</td>
<td>0.00007</td>
<td>0.00003</td>
</tr>
<tr>
<td>0.056-&lt;0.10</td>
<td>0.00020</td>
<td>0.00018</td>
<td>0.00017</td>
<td>0.00016</td>
</tr>
<tr>
<td>0.10-&lt;0.18</td>
<td>0.00038</td>
<td>0.00033</td>
<td>0.00038</td>
<td>0.00040</td>
</tr>
<tr>
<td>0.18-&lt;0.32</td>
<td>0.00030</td>
<td>0.00026</td>
<td>0.00027</td>
<td>0.00029</td>
</tr>
<tr>
<td>0.32-&lt;0.56</td>
<td>0.00023</td>
<td>0.00020</td>
<td>0.00024</td>
<td>0.00023</td>
</tr>
<tr>
<td>0.56-&lt;1.0</td>
<td>0.00026</td>
<td>0.00020</td>
<td>0.00027</td>
<td>0.00025</td>
</tr>
<tr>
<td>1.0-&lt;1.8</td>
<td>0.00020</td>
<td>0.00014</td>
<td>0.00018</td>
<td>0.00018</td>
</tr>
<tr>
<td>1.8-&lt;3.2</td>
<td>0.00009</td>
<td>0.00004</td>
<td>0.00007</td>
<td>0.00009</td>
</tr>
<tr>
<td>3.2-&lt;5.6</td>
<td>0.00005</td>
<td>0.00003</td>
<td>0.00004</td>
<td>0.00007</td>
</tr>
<tr>
<td>5.6-&lt;10</td>
<td>0.00004</td>
<td>0.00000</td>
<td>0.00003</td>
<td>0.00005</td>
</tr>
<tr>
<td>10-&lt;15</td>
<td>0.00002</td>
<td>0.00000</td>
<td>0.00003</td>
<td>0.00007</td>
</tr>
<tr>
<td>All Stages</td>
<td>0.01899</td>
<td>0.01489</td>
<td>0.0179</td>
<td>0.0184</td>
</tr>
<tr>
<td>PM10</td>
<td>0.0185</td>
<td>0.0147</td>
<td>0.0172</td>
<td>0.0176</td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.0172</td>
<td>0.0143</td>
<td>0.0162</td>
<td>0.0160</td>
</tr>
<tr>
<td>PM1.0</td>
<td>0.0146</td>
<td>0.0127</td>
<td>0.0159</td>
<td>0.0136</td>
</tr>
</tbody>
</table>

Geometric means

<table>
<thead>
<tr>
<th>Standard Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULSD</td>
</tr>
<tr>
<td>0.0003</td>
</tr>
<tr>
<td>0.0002</td>
</tr>
<tr>
<td>0.0004</td>
</tr>
<tr>
<td>0.0003</td>
</tr>
<tr>
<td>0.0006</td>
</tr>
<tr>
<td>0.0004</td>
</tr>
<tr>
<td>0.0003</td>
</tr>
<tr>
<td>0.0002</td>
</tr>
<tr>
<td>0.0002</td>
</tr>
<tr>
<td>0.0021</td>
</tr>
<tr>
<td>0.0020</td>
</tr>
<tr>
<td>0.0017</td>
</tr>
<tr>
<td>0.0014</td>
</tr>
</tbody>
</table>

In graphical form, these data indicate that particle size distributions (Figure 24) are similar between all four fuels with a major mode present between 0.10µm and 0.18µm and a secondary mode present in the 0.56µm to 1µm region. The only apparent difference between fuels is a small reduction in the magnitude of the two modes observed with RME5 relative to the other 3 fuels.
Further graphical comparison of integrated MOUDI stage data, PM10, PM2.5 and PM1.0 (Figure 25) reveals that RME5 mass emissions were measurably lower than those of any of the other fuels, although not at a significant level since error bars from other fuel’s datasets overlap.
Interestingly, the differences between RME5 and the other fuels diminish as larger particles are excluded.

From these data the following statements regarding PM10, PM2.5 and PM1.0 can be made:

- ULSD, *ULSD* and VVO100 datasets were indistinguishable
- RME mean emissions were lower but within scatter of other fuel’s datasets

Table 15 summarises the PM10, PM2.5 and PM1.0 emissions from the Peugeot 106 showing that PM10 emissions from RME5 were up to 20% lower than those from straight ULSD.

*ULSD* and VVO100 also showed reductions in PM10 emissions relative to ULSD (7% and 5% respectively), but again it should be noted that emissions from these fuels lay within the scatter of the ULSD data.

### Table 15 : Summarised PM Masses and Reductions Relative to ULSD (g/km)

<table>
<thead>
<tr>
<th></th>
<th>ULSD</th>
<th>RME5</th>
<th><em>ULSD</em></th>
<th>VVO100</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM10</td>
<td>0.0185</td>
<td>0.0147</td>
<td>0.0172</td>
<td>0.0176</td>
</tr>
<tr>
<td>% reduction</td>
<td>20.6</td>
<td>7.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.0172</td>
<td>0.0143</td>
<td>0.0162</td>
<td>0.0160</td>
</tr>
<tr>
<td>% reduction</td>
<td>17.1</td>
<td>5.7</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>PM1.0</td>
<td>0.0146</td>
<td>0.0127</td>
<td>0.0139</td>
<td>0.0136</td>
</tr>
<tr>
<td>% reduction</td>
<td>13.3</td>
<td>4.7</td>
<td>6.9</td>
<td></td>
</tr>
</tbody>
</table>

### 4.3.3 Comparison between MOUDI and Regulated PM Masses

This section compares the integrated mass emissions determined with the MOUDI, with the regulated PM Mass.

#### 4.3.3.1 VW Passat

For all fuels, the mass emissions observed from the MOUDI reflect those observed with the regulated filter method. As (Figure 26) shows a linear relationship exists between the two methods, with the integral of all MOUDI stage masses comprising approximately 70% of the masses determined by the filter method.
This 0.7:1 relationship between MOUDI masses and PM was also observed in the DETR/SMMT/CONCAWE Particulate Research Programme\textsuperscript{2}.

### 4.3.3.2 Peugeot 106

A similar relationship exists between the MOUDI and filter mass emissions determined during Peugeot 106 testing (Figure 27).

\textit{Figure 27: Correlation between MOUDI and PM Masses – Peugeot 106}
These data show a poor $R^2$ value due to the close similarity of the mass emissions from all fuels on this vehicle. However, when the data from both vehicles are plotted together, a better indication of the PM and MOUDI correlation can be observed (Figure 28).

**Figure 28 : Correlation between MOUDI and PM Masses – Both vehicles**

![Comparison of MOUDI Mass Emissions and Regulated PM](image)

This difference is likely to be a consequence of the different collection methods used in the two methods: Unlike regulated PM where filtration is the only mechanism, the MOUDI acquires material by impaction, and also is subject to diffusional deposition. These mechanisms allow volatiles to be collected and soak into each of the individual MOUDI stages and be retained, but also permits volatiles to diffuse to the walls within the MOUDI where they remain unmeasured.

In the regulatory method, hydrocarbons collected by the filter can be revolatilised, or ‘washed away’ by lighter hydrocarbons in the sample aerosol as the test progresses. Similarly, some of the hydrocarbons collected on MOUDI stages may be revolatilised from the filter surface and carried out of the MOUDI.

The exact reasons for the differences between methods are unclear, but the consistency of the relationship between the two methods and near origin intercept is evidence of consistent MOUDI performance.

### 4.4 Non-Regulated Pollutants

The FTIR measures concentration of exhaust species, expressed as ppm. Mass is calculated from exhaust volume data determined via raw emissions data collection. The FTIR is a semi-quantitative tool with typical measurement deviations quoted as $<20\%$. In Ricardo experience, typical deviations for some individual species are better than quoted levels, often $<10\%$. 
4.4.1 VW Passat Results

4.4.1.1 Repeatability

Two species have been chosen to represent repeatability of emissions results obtained from the FTIR. Figure 29 shows NO, as ppm measured in real time. It can be seen that the 3 tests repeat very well, and that nitric oxide emissions closely track the accelerations and decelerations of the drive cycle.

Figure 29: VW Passat, Repeatability, Nitric Oxide Emissions

Ethene emissions (Figure 30), show that while this emission is much more “noisy” than NO, and is present at low levels (generally <8ppm), the three repeat tests still track each other well.

Figure 30: VW Passat, Repeatability, Ethene emissions
4.4.1.2  Comparison of Fuels

The main trends identified via the regulated emissions results: i.e. increases in HC, CO and reductions in NOx with the VVO100 fuel compared to ULSD, are confirmed in greater detail with the data obtained from FTIR measurements.

Nitrogen Species

Figure 31 shows that the majority of NOx was emitted as NO, on all fuels. NO₂ levels were in the range of ~0.046 – 0.054g/km, representing between 5-7% of total NOx for all fuels. The lower NOx levels of about 8% from VVO100 which were measured via the regulated emissions trolley, are shown by the FTIR to be due to a reduction in NO and not NO₂.

Nitrous Oxide, N₂O, was present at low levels in the range of ~0.007g/km on ULSD, *ULSD* and RME5. VVO100 had slightly higher emissions at ~0.01g/km.

Ammonia, NH₃, was also present at low levels of ~4ppm or less for all fuels. Since these levels were close to baseline noise, fuels effects were difficult to identify.

Methane and Ethene (Figure 32)

These small hydrocarbons are both products of combustion and were present at levels of 0.002g/km – 0.003g/km for methane and ~0.006g/km for ethane for non-VVO100 fuels. These levels rose to ~0.007g/km and 0.038g/km respectively for VVO100.

1,3-butadiene  1,3-butadiene is also a combustion product. It was present at low concentrations of ~4ppm or less on all fuels.
Formaldehyde (Figure 33)

Formaldehyde is a partial oxidation product and was present at levels of ~0.013g/km for non-VVO100 fuels. There were no apparent differences between ULSD and RME5 in terms of formaldehyde emissions, which is perhaps surprising since Ricardo experience indicates that even quite low levels of oxygenates in fuel can give increases in aldehyde emissions. VVO100, however did show large increases in formaldehyde compared to other fuels at 0.069g/km.

Figure 32 : VW Passat, Mean Methane and Ethene Emissions

![Methane Emissions Graph](image)

![Ethene Emissions Graph](image)

Figure 33 : VW Passat, Formaldehyde Emissions, Mean g/km and Real-Time ppm Data

![Formaldehyde Emissions Graph](image)

Effect Of Vegetable Oil On FTIR Emissions

![PPM vs Time Graph](image)
Acetaldehyde – emissions of acetaldehyde showed very similar trends to formaldehyde, although from the VVO100 fuel acetaldehyde was present at slightly lower levels (Figure 34).

Figure 34 : VW Passat, Acetaldehyde Emissions, ppm

![Acetaldehyde Emissions Graph](image)

4.4.2 Peugeot 106 Results

4.4.2.1 Repeatability

Figure 35 and Figure 36 show NO and ethene emissions respectively as an illustration of repeatability of emissions measurement via FTIR on the Peugeot 106. NO is present at levels typically <200ppm over most of the drive cycle, rising to a peak of 350ppm during the high speed, high load portion. The three tests shown in Figure 35 repeat well.
Ethene (Figure 36) is present at low levels; typically <4ppm and is far more “noisy”, however even at these levels, the repeat tests track each other reasonably well.
4.4.2.2 Comparison of Fuels

Nitrogen Species

Figure 37 shows that the majority of NOx was emitted as NO on all fuels. NO\textsubscript{2} emissions were in the range of \(\sim0.03\text{g/km} - \sim0.04\text{g/km}\), representing \(\sim7 - 8\%\) of total NOx on all fuels.

Differences between fuels on the Peugeot 106 are less clear than those seen from the Passat; however it can be seen that VVO100 gave the lowest average NO emissions at just below 0.26g/km, although the VVO100 dataset overlaps slightly with that of "ULSD". There is also an indication of lowest average NO\textsubscript{2} emissions on VVO100, although this effect was indistinguishable from the datasets of other fuels.

Nitrous Oxide, \(\text{N}_2\text{O}\) emissions were low throughout; in the range of \(\sim0.004\text{g/km} - 0.005\text{g/km}\) on non-VVO100 fuels and \(\sim0.006\text{g/km}\) on VVO100.

Ammonia, \(\text{NH}_3\) was present at very low levels (typically <3ppm) on all fuels.

**Figure 37– Peugeot 106 – Mean NO and NO\textsubscript{2} Emissions**

Methane and Ethene

Methane was typically present at levels of <4ppm on all fuels. Ethene was present at <0.003g/km on non-VVO100 fuels, rising to just under 0.008g/km on VVO100.

1,3-butadiene As with the VW Passat, 1,3-butadiene was present at concentrations of \(\sim4\text{ppm}\) on all fuels.
Formaldehyde (Figure 38) and Acetaldehyde

Formaldehyde was present at levels of ~0.006g/km for non-VVO100 fuels, rising to ~0.017g/km on VVO100. Acetaldehyde was present at levels of <4ppm. No clear effects of RME5 on aldehyde emissions were identified.

Figure 38: Peugeot 106 – Formaldehyde Emissions, Mean Results

4.5 Polycyclic Aromatic Hydrocarbons (PAHs)

4.5.1 VW Passat Results

Individual PAH results for the VW Passat are shown in Table 16 below.

Table 16 - VW Passat, Individual PAH Emissions, µg/km

<table>
<thead>
<tr>
<th>TOTAL ug/km</th>
<th>ULSD</th>
<th>RME5</th>
<th>RME5</th>
<th>ULSD</th>
<th>&quot;ULSD&quot;</th>
<th>VVO100</th>
<th>VVO100</th>
<th>&quot;ULSD&quot;</th>
<th>ULSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAPHTHALENE</td>
<td>233.3</td>
<td>22.9</td>
<td>11.3</td>
<td>1.9</td>
<td>0.97</td>
<td>784.9</td>
<td>862.0</td>
<td>230.5</td>
<td>43.7</td>
</tr>
<tr>
<td>2-METHYL-NAPHTHALENE</td>
<td>36.1</td>
<td>14.8</td>
<td>8.8</td>
<td>1.0</td>
<td>0.85</td>
<td>55.6</td>
<td>56.6</td>
<td>39.8</td>
<td>21.8</td>
</tr>
<tr>
<td>1-METHYL-NAPHTHALENE</td>
<td>35.5</td>
<td>15.3</td>
<td>11.2</td>
<td>2.9</td>
<td>3.1</td>
<td>45.7</td>
<td>46.6</td>
<td>37.8</td>
<td>19.8</td>
</tr>
<tr>
<td>ACE.THENE+ACE.THYLENE</td>
<td>27.7</td>
<td>3.9</td>
<td>3.5</td>
<td>1.4</td>
<td>1.4</td>
<td>33.6</td>
<td>45.1</td>
<td>28.1</td>
<td>5.3</td>
</tr>
<tr>
<td>FLUORENE</td>
<td>18.4</td>
<td>12.0</td>
<td>12.4</td>
<td>8.5</td>
<td>11.4</td>
<td>46.9</td>
<td>54.9</td>
<td>19.5</td>
<td>12.7</td>
</tr>
<tr>
<td>PHENANTHRENE</td>
<td>50.1</td>
<td>39.2</td>
<td>36.5</td>
<td>34.1</td>
<td>43.2</td>
<td>134.7</td>
<td>152.9</td>
<td>60.7</td>
<td>49.7</td>
</tr>
<tr>
<td>ANTHRACENE</td>
<td>1.0</td>
<td>0.58</td>
<td>0.11</td>
<td>0.20</td>
<td>0.03</td>
<td>5.17</td>
<td>7.37</td>
<td>1.83</td>
<td>0.92</td>
</tr>
<tr>
<td>FLUORANTHENE</td>
<td>10.3</td>
<td>9.1</td>
<td>9.4</td>
<td>8.3</td>
<td>8.6</td>
<td>57.4</td>
<td>68.5</td>
<td>14.2</td>
<td>12.1</td>
</tr>
<tr>
<td>PYRENE</td>
<td>5.5</td>
<td>4.8</td>
<td>4.7</td>
<td>4.2</td>
<td>4.5</td>
<td>51.9</td>
<td>62.3</td>
<td>8.7</td>
<td>7.0</td>
</tr>
<tr>
<td>BENZ(A)ANTHRACENE</td>
<td>2.1</td>
<td>1.9</td>
<td>1.5</td>
<td>1.5</td>
<td>1.3</td>
<td>9.9</td>
<td>12.3</td>
<td>2.9</td>
<td>2.3</td>
</tr>
<tr>
<td>CHRYSENE</td>
<td>3.9</td>
<td>3.4</td>
<td>3.5</td>
<td>3.2</td>
<td>3.5</td>
<td>12.5</td>
<td>14.7</td>
<td>5.0</td>
<td>4.2</td>
</tr>
<tr>
<td>BENZO(B)FLUORANTHENE</td>
<td>0.81</td>
<td>0.83</td>
<td>0.87</td>
<td>0.72</td>
<td>0.82</td>
<td>7.20</td>
<td>8.38</td>
<td>0.80</td>
<td>0.73</td>
</tr>
<tr>
<td>BENZO(K)FLUORANTHENE</td>
<td>0.26</td>
<td>0.23</td>
<td>0.28</td>
<td>0.27</td>
<td>0.28</td>
<td>2.2</td>
<td>2.6</td>
<td>2.1</td>
<td>0.19</td>
</tr>
<tr>
<td>BENZO(A)PYRENE</td>
<td>0.34</td>
<td>0.26</td>
<td>0.11</td>
<td>0.18</td>
<td>0.10</td>
<td>3.2</td>
<td>4.91</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td>DIBENZ(A,H)ANTHRACENE</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.34</td>
<td>0.59</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BENZO(GH)PERYLENE</td>
<td>0.38</td>
<td>0.47</td>
<td>0.47</td>
<td>0.40</td>
<td>0.51</td>
<td>11.5</td>
<td>14.2</td>
<td>0.35</td>
<td>0.28</td>
</tr>
<tr>
<td>INDENO(1,2,3CD)PYRENE</td>
<td>0.56</td>
<td>0.72</td>
<td>0.66</td>
<td>0.54</td>
<td>0.51</td>
<td>13.8</td>
<td>13.5</td>
<td>0.40</td>
<td>0.33</td>
</tr>
<tr>
<td>TOTAL PAH</td>
<td>426.4</td>
<td>130.5</td>
<td>105.4</td>
<td>69.4</td>
<td>81.2</td>
<td>1276.6</td>
<td>1427.6</td>
<td>453.2</td>
<td>181.2</td>
</tr>
</tbody>
</table>
4.5.1.1 Repeatability

From Table 16 it can be seen that ULSD and *ULSD* PAH results, where only one sample was taken per fuel set, repeat less well than VVO100 and RME5, where two analyses per fuel set were conducted. This lack of repeatability between ULSD and *ULSD* is especially evident for some of the lighter PAH emissions (illustrated by naphthalene, Figure 39, below), where emissions between fuel sets are sometimes orders of magnitude different. For example, naphthalene emissions from ULSD in chronological order: 233.3µg/km, 1.9µg/km, 43.7µg/km. The fact that naphthalene and total PAH emissions were highest on the first ULSD test and on the post-VVO100 *ULSD* test is notable and may indicate carry over of components from the dilution tunnel and sampling system. The very low levels of naphthalene and other light species from the set of tests midway through the programme are surprising, although there was no evidence at this point of any sampling losses.

However for the heavier species, repeatability is much better; e.g. chrysene emissions from ULSD in chronological order: 3.9µg/km, 3.2µg/km and 4.2µg/km.

From previous experience it is expected that the majority of naphthalene emissions, and a significant proportion of some of the other light species, would be present in the vapour phase\(^3\). However, Ricardo experience is that generally the repeatability of both vapour and particulate-phase PAHs is excellent\(^3\), therefore a major factor may be the comparison of single samples between fuel sets.

Repeatability of the duplicate samples taken from RME5 and VVO100 tests is typically very good for most species.

---

\(^3\) SAE paper 982727
4.5.1.2 Comparison Between Fuels

Due to the limited data set, no averaging of results was carried out. Comments are made on a trends basis.

For all fuels, naphthalene and phenanthrene were the most significant contributors towards total PAH emissions. Phenanthrene, for example, was present in the range of ~35µg/km - 60µg/km on non-VVO100 fuels and ~135µg/km - 150µg/km on VVO100. The 1- and 2-methyl derivatives of naphthalene, acenaphthene & acenaphthylene, fluorene and fluoranthrene were also important contributors.

Because of the variability in results, it was difficult to distinguish any differences between ULSD and *ULSD*. PAH species from RME5 were typically at levels similar to those from ULSD and *ULSD*. This is illustrated by benzo(a)pyrene results (Figure 40) and total PAH emissions (Figure 41).

VVO100 gave highest PAH results throughout: for example, benzo(a)pyrene emissions were increased by ~ 20 times compared to other fuels. Total PAH emissions increased to ~1300µg/km on VVO100 from typically <200µg/km on other fuels.

Figure 40: VW Passat – Benzo(a)pyrene Emissions, µg/km
4.5.2 Peugeot 106

Table 17 shows individual PAH results for the Peugeot 106.

<table>
<thead>
<tr>
<th></th>
<th>ULSD</th>
<th>RME5</th>
<th>RME5</th>
<th>ULSD</th>
<th>RME5</th>
<th>ULSD</th>
<th>VVO100</th>
<th>VVO100</th>
<th><em>ULSD</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>NAPHTHALENE</td>
<td>37.9</td>
<td>35.9</td>
<td>17.2</td>
<td>38.8</td>
<td>5.7</td>
<td>48.1</td>
<td>33.4</td>
<td>37.3</td>
<td>30.0</td>
</tr>
<tr>
<td>2-METHYL(NAPHTHALENE)</td>
<td>4.3</td>
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<td>11.3</td>
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<td>0.1</td>
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<td>0.0</td>
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<td>INDENO(1,2,3CJ)PERYLENE</td>
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<td>97.3</td>
<td>71.7</td>
<td>82.7</td>
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</tbody>
</table>

4.5.2.1 Repeatability

From Table 17, it can be seen that most PAH species generally repeat well and no large differences in the lighter species, such as naphthalene, between fuel sets were seen as for VW Passat results. For example, naphthalene emissions on ULSD in chronological order: 37.9µg/km, 38.9µg/km and 30.0µg/km. Repeatability on the heavier species was also reasonable; for example, benz(a)anthracene emissions on ULSD in chronological order: 0.61µg/km, 0.39µg/km and 0.68µg/km.
4.5.2.2 Comparison Between Fuels

As for the VW Passat, the major contributors towards total PAH emissions on all fuels were naphthalene (representing almost half of total PAH emissions from VVO100), phenanthrene, acenaphthene & acenaphthylene and fluorene.

Figure 42 shows phenanthrene emissions which were typically in the range of $\sim 9\mu g/km - 12\mu g/km$ - and illustrates that no clear differences were apparent between the fuels.

Figure 42: Peugeot 106 – Phenanthrene Emissions, $\mu g/km$

![Graph of Peugeot 106 PAH Emissions](image)

This lack of clear discrimination between fuels is also apparent in the heavier species (illustrated by Figure 43), and total PAH emissions, (Figure 44).
Figure 43: Peugeot 106 – Benzo(a)pyrene Emissions, µg/km

Figure 44: Peugeot 106 – Total PAH Emissions, µg/km
5. DISCUSSION

It is well known, through both Ricardo experience of fuel studies, and from other published studies (e.g.⁴), that the emissions characteristics of a fuel are influenced by both the chemical and physical properties of that fuel. Key chemical parameters include: Aromatic and olefinic content, and sulphur content, whereas key physical characteristics include: Density, viscosity, boiling range and volatility.

It can be seen from the comparative table of diesel vs. canola oil properties published in Appendix 3, that while the cetane number and calorific value of the two fuels are similar, the canola oil is highly viscous, having a viscosity of 37 mm²s⁻¹ @ 40°C compared to diesel viscosity of 4-5 mm²s⁻¹ @ 40°C. It is for this reason that it is necessary to fit a conversion kit, to enable a vehicle to run on pure vegetable oil. The kit consists primarily of a heated line to maintain the vegetable oil at 80°C, an auxiliary tank, and a manual switch to enable the vehicle to be started on diesel fuel and switched manually over to vegetable oil after warm-up.

With a 5% splash blend of RME in ULSD, the physical and chemical properties of RME5 are broadly similar to those of the base diesel.

This programme of work has highlighted some large changes in emissions across the NEDC when running on vegetable oil compared to baseline ULSD. This was especially apparent in the VW Passat where HCs were increased by ~250%, CO by ~420% and particulates by just over 100%. Effects on the Peugeot were influenced by the overall lower emissions level and generally poorer repeatability of the vehicle; even so increases in HCs of ~60% and CO of ~170% were identified.

Alternatively, operation of both vehicles on RME5 produced CO and CO₂ emissions which were broadly similar to those observed from the baseline diesel. There were some directional trends of small (1 - 3%) reductions in NOx and PM (4 - 7%) although most of these reductions were not at a significant level.

Several studies (see references in accompanying Ricardo literature review, RD 03/305301.1) have proposed the major cause of increasing HC and CO emissions with pure vegetable oil to be relatively poor atomisation of the fuel in the combustion chamber due to the high molecular weight and low volatility plus the highly viscous nature of the fuel. Poor atomisation leads to high levels of fuel survival and elevated levels of partial oxidation products. This was illustrated by the increases seen in small combustion products, e.g.: methane and ethene, with vegetable oil, and also increases in oxygenated species such as formaldehyde and acetaldehyde.

In the VW Passat, NOx decreases on VVO100 and PM increases compared with ULSD. This effect may be essentially due to the heavier density VVO100 causing a shift along the NOx/PM trade-off curve. It is also highly likely that the increases in particulate mass with vegetable oil are primarily due to an increase in the Volatile Organic Fraction (VOF), rather than a large increase in carbon content. This is supported by visual inspection; since despite the obvious mass increases, the appearance of the filter papers did not indicate an increased level of elemental carbon.

In this study the RME5 fuel contained an oxygenated component in the form of 5% rapeseed methyl ester. The advantage with oxygenated fuels for particulate control is that bound oxygen enhances in-cylinder oxidation. It is probable that reductions in the

⁴ EUROPEAN PROGRAMME ON EMISSIONS, FUELS AND ENGINE TECHNOLOGIES - EPEFE REPORT / ACEA, EUROPIA, 1996
carbonaceous fraction of PM are achieved by the enhanced availability of oxygen on the fuel rich side of the flame front. Greater oxidation of carbon will reduce the number concentration of primary carbon particles and lead to a reduced carbon contribution to the overall particulate mass. It should be noted that the VVO100 fuel also contains oxygen, since organic fats and oils exist in the form of triglycerides, consisting of three hydrocarbon chains connected together by glycerol; the bonding point being an ester bond. However, it is probable that the effects of VVO100 on PM are confounded by the high molecular weight and viscosity of the fuel, as discussed previously.

The generally low volatility of the VVO100 may be used to explain the effect of increased MOUDI mass emissions from the three VVO100 tests on the Passat with test progression observed in Figure 18. It should be noted that this same effect was also observed in the PM data. The semi-volatile species present in VVO100 are large molecules which can survive combustion and are difficult for a diesel catalyst to oxidise. These components then slip past the oxidation catalyst and may recondense in the tailpipe. Through the three consecutive tests the exhaust system heats up progressively and more of these materials may be released and collected with the MOUDI and filter method.

This effect was not observed with the Peugeot 106, where combustion and tailpipe temperatures were likely to be considerably higher than in the Passat, especially at the hard acceleration towards the end of the EUDC cycle. This may have enabled better vapourisation of the fuel and better combustion, leading to lower fuel survival in the Peugeot 106.

It is important to note that the semi-volatile hydrocarbons trapped by the MOUDI and PM may not be effectively retained by the heated filter upstream of the FID and thus may also be measured as gaseous HCs (Figure 3). This possibility should be considered when comparing the hydrocarbon emissions of VVO100 with those from more conventional fuels.

In general, the larger engine size (1.9/l) and greater power (100PS) available during operation of the VW Passat probably leads to lower combustion chamber temperatures at fixed NEDC driving conditions than would be observed with the smaller Peugeot 106 (1.5/l and 80kW). It should also be noted that the Peugeot 106 is an IDI diesel, while the VW Passat is a directly injected Diesel type. The difference in injection type will influence the probability of efficient fuel vaporisation of VVO100. The DI vehicle will have higher injection pressures and hence potential for more spray penetration, although DI injections does provide less opportunity for fuel evaporation and dispersal than IDI; hence the net effect of the injection system is difficult to assess without more investigation.

The combustion chamber temperature effect would be most significant at the highest load points of the NEDC cycle – during accelerations and in particular the transitions up to the 100km/h and 120km/h cruises. Higher combustion chamber temperatures may well lead to improved fuel dispersal upon injection and explain some of the differences in the response of the two vehicles to operation on VVO100. It is also possible that excess VVO100 present in the combustion chamber will reduce the magnitude of the leanest combustion regions and lead to reduced NOx.

NOx emissions are mainly a function of combustion temperature and the presence of local rich zones within the combustion, and as such can be engine specific. Some studies have reported slight decreases in NOx when running on vegetable oil, (see
references in accompanying Ricardo literature review, RD 03/305301.1), and this was the trend seen in the VW Passat where NOx reduced by about 8% compared to baseline. FTIR analysis confirmed that reductions in NOx were mainly due to reductions in NO. For the Peugeot, however, NOx effects were neutral.

PAH emissions in exhaust are known to originate from either survival from fuel or lubricant species, or from pyrolysis in the combustion chamber. Although fuel effects on PAHs in the Peugeot 106 were unclear, the Passat clearly showed an increase in individual species and total PAH with vegetable oil; total PAHs were 1300µg/km compared to <200µg/km on ULSD and RME5 fuels. It is possible that some pyrolysis occurs at the periphery of localised rich regions within the combustion chamber, or at the chamber walls where unburned VVO100 has impinged. This would lead to increased PAH emissions.

6. CONCLUSIONS

This programme undertook testing of two vehicles over the current European legislative Drive Cycle with the aim of identifying emissions effects of VVO100 compared to a baseline ULSD fuel. RME5 was also evaluated. The main conclusions of the programme were as follows:

Fuel Effects:

- The conversion kit, fitted to enable the vehicle to run on VVO100, had a negligible effect on the emissions performance of baseline ULSD. Therefore it is considered valid to directly compare emissions results from VVO100, delivered via the conversion kit, to baseline ULSD running from the main tank.
- The effects of RME5 on emissions compared to baseline ULSD were small in most cases.
- There was some evidence of carry-over effects on HC emissions on post-VVO100 tests in the VW Passat. Therefore the post-VVO100 tests were not included in the discussion and graphs for fuel comparisons of HC emissions.
- VVO100 showed increases in HC emissions of ~250% and CO emissions of ~420% in the VW Passat and increases in HC and CO emissions of 170% and 60% respectively in the Peugeot 106, compared to baseline ULSD.
- VVO100 also gave increases in PM of ~100% in the VW Passat and 8% reduction in NOx compared to baseline ULSD. These effects were not seen in the Peugeot 106 vehicle.
- The rise in HC emissions on VVO100 in the VW Passat was mirrored by a rise in small combustion products, such as methane and ethane, and partial oxidation products, such as formaldehyde. The reduction in NOx was shown to be primarily due to a reduction in NO.
- The effects of RME5 on unregulated pollutants were unclear, for example no discernible effects on aldehyde emissions were seen.
- VVO100 gave clear increases in PAH emissions compared to baseline ULSD in the VW Passat; for example, benzo(a)pyrene increased by nearly 20 times. Such effects on PAH emissions were not identifiable on the Peugeot 106.
- It is likely, from emissions evidence and published studies, that many of the emissions effects seen on VVO100 fuel were associated primarily with poor atomisation due to the high viscosity/molecular weight of the fuel. However, the magnitude of these effects was engine-specific.
• From both vehicles, the RME5 fuel provided a reduction in particulate mass measured by the MOUDI relative to the ULSD baseline. For PM10, this was ~4% for the Passat and ~20% for the Peugeot 106.

Vehicle Effects:

• The net effect of the base engine technology (i.e. IDI vs DI) in terms of emissions was difficult to discern since both technologies are converging in terms of emissions capability.
• The Peugeot 106 showed poorer repeatability than the VW Passat, although it should be borne in mind that absolute emission levels were lower from the Peugeot.
• Generally fuel effects on emissions were much more easily identifiable on the VW Passat than the Peugeot 106. It is possible that the higher combustion chamber temperatures which would be evident in the smaller, lower powered Peugeot, especially over the highest speed points of the NEDC cycle, may well lead to improved fuel dispersal upon injection and explain some of the differences in the response of the two vehicles to operation on VVO100.
• With operation in the Passat, the VVO100 generated PM10 emissions levels over twice as high as those from the reference ULSD. Alternatively, emissions from the Peugeot 106 were similar to those from ULSD.
• While the addition of RME5 appears beneficial for PM10 in both vehicle types – probably since it enhances in cylinder oxidation and reduces carbon generation, the low volatility of the VVO100 may mean that larger engines when running at cooler combustion and exhaust temperatures may produce higher levels of particulate mass.

Recommendations:

• The conclusions from this study are based on a limited dataset from two vehicles only. Greater emissions understanding would be gained from expanding the fuels and vehicles test matrix.
• This study does not consider the long term effects on engine durability as a result of running on VVO100. The accompanying literature study (RD 03/235501.1) suggest that durability issues with VVO100 may be significant, and hence this would warrant further investigation in this area.
Appendix 1: Background on IDI and DI Technology

IDI Diesel engines were originally significantly cleaner than DI engines because of their vastly superior air/fuel mixing qualities. As the piston rose, the majority of the air was compressed into a swirl-chamber (or pre-chamber) in the cylinder head, via a tangential entry port. This generated a significant amount of turbulence into which fuel was injected. Injectors typically had only one hole, or orifice, which therefore was quite large and had only a limited capacity to atomise fuel, but the air turbulence in the pre-chamber was typically sufficient to ensure adequate air/fuel mixing.

However, following combustion and expansion, the air/fuel/exhaust gas had to pass back through the entrance to the pre-chamber back into the main part of the cylinder. This created a lot of friction and gas flow-reversal and was a major inefficiency of IDI engines.

During the late 1980s and 1990s, several enabling technologies for High Speed Direct injection (HSDI) engines arose, without which HSDI engines would not be a viable solution today:

- Manufacturing improvements to ensure minimal tolerances in FIE components allowing for higher injection pressures, and thus improved atomisation of fuel, and multi-hole nozzles
- Improved turbocharger efficiencies led to the achievement of much greater air flow rates and cylinder pressures which in turn led to increased power densities. The increased air flow led the demand for improved engine breathing arrangements and 4-valve per cylinder engine structures. 4-valves per cylinder is not easily compatible with IDI because of the issues surrounding packaging a large pre-chamber in a crowded cylinder head.
- Increased cylinder pressures do not favour the adoption of a pre-chamber for reasons of structural integrity.

Once the DI engine was a viable technology, it became the preferred option over IDI because of its efficiency advantages. One of the principal drawbacks was the noise...
increase of DI compared to IDI engines. During the late 1990s, there has been a massive uptake of common rail technology which has effectively removed this drawback of DI engines.

When DI engines were initially launched (Ford and MG in the early 1980s) they were protected by less stringent particulate emissions legislation than for IDI engines. However, with advances in technology noted above, this no longer became necessary and by 2000, this differentiation was phased out. DI engines are now equally capable in terms of emissions and, going forward, will be developed further as IDI is phased out.

In terms of absolute capability for low emissions, DI engines are certainly no less capable than IDI engines, yet they are significantly more efficient and powerful. The figure below represents current and anticipated passenger car sales in Europe. As can be seen from Figure 2, the proportion of IDI vehicles is already very low in terms of sales and will continue to diminish. However, the proportion of IDI vehicles currently in circulation on European roads is still significant.

Figure 2: Future European Passenger Car Types

Future European Passenger Car Engine Types

Predictions based on Ricardo industry knowledge.
## Appendix 2: Analysis of Fuels

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<td>Mono-glycerides % mass</td>
<td>prEN14015</td>
<td>0.07</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Di-glycerides % mass</td>
<td>prEN14015</td>
<td>0.39</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Tri-glycerides % mass</td>
<td>prEN14015</td>
<td>92.51</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Total glycerol % mass</td>
<td>prEN14015</td>
<td>9.6</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Iodine Value</td>
<td></td>
<td>112</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>

**Notes:** * CFPP not possible on VVO100 due to viscosity  
** Cetane calculated by blend with reference fuel  
*** Distillation on VVO100 not possible
### Appendix 3: GERMAN QUALITY STANDARD FOR RAPESEED OIL

<table>
<thead>
<tr>
<th>Properties /Contents</th>
<th>Unit</th>
<th>Limiting Value min.</th>
<th>Limiting Value max.</th>
<th>Testing Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristic properties for Rapeseed Oil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (15°C)</td>
<td>kg/m³</td>
<td>900</td>
<td>930</td>
<td>DIN EN ISO 3675 DIN EN ISO 12185</td>
</tr>
<tr>
<td>Flash Point by P.-M.</td>
<td>°C</td>
<td>220</td>
<td>-</td>
<td>DIN EN 22719</td>
</tr>
<tr>
<td>Calorific Value</td>
<td>kJ/kg</td>
<td>35000</td>
<td>-</td>
<td>DIN 51900-3</td>
</tr>
<tr>
<td>Kinematic Viscosity (40°C)</td>
<td>mm²/s</td>
<td>-</td>
<td>38</td>
<td>DIN EN ISO 3104</td>
</tr>
<tr>
<td>Low Temperature Behaviour</td>
<td></td>
<td></td>
<td></td>
<td>Rotational Viscometer (testing conditions will be developed)</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>Mass-%</td>
<td>-</td>
<td>0.40</td>
<td>DIN EN ISO 10370</td>
</tr>
<tr>
<td>Carbon Residue</td>
<td>g/100 g</td>
<td>100</td>
<td>120</td>
<td>DIN 53241-1</td>
</tr>
<tr>
<td>Iodine Number</td>
<td>mg/kg</td>
<td>-</td>
<td>20</td>
<td>ASTM D5453-93</td>
</tr>
</tbody>
</table>

| Variable properties | | | | |
| Contamination | mg/kg | - | 25 | DIN EN 12662 |
| Acid Value | mg KOH/g | - | 2.0 | DIN EN ISO 660 |
| Oxidation Stability (110°C) | h | 5.0 | - | ISO 6886 |
| Phosphorus Content | mg/kg | - | 15 | ASTM D3231-99 |
| Ash Content | Mass-% | - | 0.01 | DIN EN ISO 6245 |
| Water Content | Mass-% | - | 0.075 | pr EN ISO 12937 |
Comparison of properties of diesel, canola oil and commercial US biodiesel

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>Canola Oil</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density kgL⁻¹ @ 15.5 deg C</td>
<td>0.84</td>
<td>0.92</td>
<td>0.88</td>
</tr>
<tr>
<td>Calorific value MJL⁻¹</td>
<td>38.3</td>
<td>36.9</td>
<td>33-40</td>
</tr>
<tr>
<td>Viscosity mm²s⁻¹ @ 20 deg C</td>
<td>4-5</td>
<td>70</td>
<td>4-6</td>
</tr>
<tr>
<td>Viscosity mm²s⁻¹ @ 40 deg C</td>
<td>4-5</td>
<td>37</td>
<td>4-6</td>
</tr>
<tr>
<td>Viscosity mm²s⁻¹ @ 70 deg C</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cetane number</td>
<td>45</td>
<td>40-50</td>
<td>45-65</td>
</tr>
</tbody>
</table>

From "Waste Vegetable Oil as a Diesel Replacement Fuel" by Phillip Calais, Environmental Science, Murdoch University, Perth, Australia, and A.R. (Tony) Clark, Western Australian Renewable Fuels Association Inc.