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**Conference or Workshop Item:**
RDE in Congested Traffic with Cold Start

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Real Driving Emissions (RDE)
The current appalling press regarding RDE shows a lack of understanding of the issue and an industry that has not got its voice across to the public.
The VW issue in the press has been more about vehicles with higher emissions in RDE than on test cycles, which has been the situation since emissions regulations came in and applies equally well to SI engines as diesel, as I will show in this lecture on the cold start issue as part of the RDE emissions problem.
Whether VW have ‘cheated’ and made the RDE worse than they would otherwise be relative to the test cycle, is a separate issue, but the RDE would have been higher than on the test cycle irrespective of any RDE calibrations that were different to those on the test cycle.
Light-Duty Initiatives

Real-Driving Emissions (RDE)

Numerous reports have shown that in-use emissions from cars can be much higher than would be indicated by certification testing. For example more than half of the 14 Euro 6 diesel cars tested with SCR (selective catalytic reduction), LNT (lean NOx trap), or EGR (exhaust gas recirculation) systems had NOx emissions >6X higher than certified (2). Two cars, each with LNT or SCR systems, came in at ~25X higher than certified. In another study (3), of three such vehicles tested, the best (urea-SCR) was 3-4X higher, and the highest (EGR; and LNT+urea-SCR) were 5-7X the certified level in PEMS (portable emissions measurement system) testing. Even US Tier 3 light-duty diesel can show high in-use emissions (4), wherein two cars with either an LNT or SCR emitted 4-20X the Bin 5 allowable NOx, depending on route. Most SCR emissions were in the range of 10X. However, a third SCR vehicle had in-use emissions similar to the certification, demonstrating the feasibility of doing such. The investigators think engine calibrations, not additional hardware, can solve the problem of excessive NOx emissions.


This is the publication that suddenly made RDE a hot political issue – their findings were not new or published in a refereed publication!
Real Driving Emissions (RDE)
My research group on RDE at Leeds University have published over 40 SAE papers on RDE and why they are higher than on test cycles.

RDE higher than on test cycles applies to all vehicles SI and diesel and for SI vehicles the RDE effect is closely related to longer cold start in RD and higher acceleration rates and more stop/starts.

Modern Euro 6 diesels with particle filters have no real world issues with PM emissions and yet SI engines without a particle trap are now emitting more PM in RDE than diesels. The major RDE effect for diesels is on NOx and CO\textsubscript{2} and with catalysts to control NOx, either NSR or Urea SCR, the catalyst has to be above about 200\degree C to be active and the lower temperatures of diesel exhausts make this difficult.
Future low CO\textsubscript{2} vehicles will have lower exhaust temperatures due to more TC and associated leaner diesel engine operation.

deNO\textsubscript{x} catalyst for lean burn require T>200\textdegree C for light off. RD temperatures are lower than on test cycles and so NO\textsubscript{x} emissions will be higher.

Tsukamoto, Y. et al., Development of new concept catalyst for low CO\textsubscript{2} emissions Diesel engine using NO\textsubscript{x} adsorption at low temperatures. Toyota.
SAE 2012-01-0370
Factors that influence RDE – both SI and Diesel
1. Driver behaviour – aggressive drivers – high acc./decel
2. Ambient temperature – affects catalyst light off and water and lube oil warm-up times, related to cold start.
3. Congested traffic in urban driving – low average speed and more stop/starts – influence of other drivers.
4. Traffic lights and road junctions
5. Cold start in RDE is longer than on test cycles and often occurs in congested traffic.
6. Diesels have an additional problem that the catalyst can cool down after it has lit off – cruise and reaching congested traffic after a period of high speed driving.
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1. Driver behaviour

This is probably the single most important factor in RDE – the test cycle is designed to eliminate the high variability in human drivers. Indeed for best test repeatability robot drivers are used.

In Leeds some years ago we carried out a 20 driver variability over a simply real world real traffic driving loop. The drivers were instructed to obey the legal speed limit of 48kph maximum speed.

There were 3 sets of traffic lights at the junctions on this loop. Each driver drove 10 laps of the loop and the first was discarded from the data.

There was no cold start.
# Driver behaviour Euro 1 TWC vehicle study 2004

<table>
<thead>
<tr>
<th>NEDC Euro 1</th>
<th>Max</th>
<th>Mean (20 drivers)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>CO\textsubscript{2} (g/km)</strong></td>
<td>194</td>
<td>425</td>
</tr>
<tr>
<td><strong>CO (g/km)</strong></td>
<td>2.7</td>
<td>28.1</td>
</tr>
<tr>
<td><strong>NO\textsubscript{x} (g/km)</strong></td>
<td>0.42</td>
<td>1.662</td>
</tr>
<tr>
<td><strong>HC (g/km)</strong></td>
<td>0.55</td>
<td>0.357</td>
</tr>
<tr>
<td><strong>Speed (km/h)</strong></td>
<td>33.6</td>
<td>38.6</td>
</tr>
<tr>
<td><strong>Acceleration (m/s\textsuperscript{2})</strong></td>
<td>1.06</td>
<td>Max</td>
</tr>
<tr>
<td><strong>Deceleration (m/s\textsuperscript{2})</strong></td>
<td>-1.39</td>
<td>Max</td>
</tr>
<tr>
<td><strong>Throttle Position (%)</strong></td>
<td>22.0</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Positive Jerk (%/s)</strong></td>
<td>26.9</td>
<td>7.17</td>
</tr>
<tr>
<td><strong>Negative Jerk (%/s)</strong></td>
<td>-7.86</td>
<td>-1.28</td>
</tr>
</tbody>
</table>

### References
Diesel Particulate and NOx Emissions 2015
Prof. Gordon E. Andrews, Energy Research Institute, U. Leeds, UK


Figure 1. Representation of the Moving Average Window (MAW) approach to determining applicability of PEMS data from in-use emissions. Solid lines represent test data. Dashed lines represent two levels of tolerance or acceptability of the data. (8)

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2. Ambient Temperature

This is related to cold start effects as a cold start is defined in the NEDC as $25^\circ C$ and this rarely occurs in the UK in RDE.

As a consequence the TWC light of time increases and the water and lube oil takes longer to warm up, which increases the fuel consumption and CO$_2$ emissions.

With diesels using deNOx catalysts and oxidation catalysts there will be a similar performance problem at temperatures $<25^\circ C$, which is all part of the cold start effect.

The Leeds work was carried out in winter on days of different temperatures using the same RD loop with four left hand turns.
RDE with cold start
Euro 1
Simple loop driving with little traffic.
Similar to NEDC Urban.

We also had similar results for congested traffic on a busy single lane road.
SAE Paper 2005-01-1617

Fig. 30 Relative increase of HC, CO and NOx normalised to the values at 25 °C

RDE in Congested Traffic with Cold Start

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3rd International Conference on Real Driving Emissions 2015, 27 – 29 October 2015, Berlin, Germany

SAE 2004-01-2903
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3. Congested traffic in urban driving

low average speed
and more stop/starts – influence of other drivers.

Congestion is normally defined as:

\[
\text{Congestion} = 1 - \left( \frac{\text{Ave. Speed}}{\text{legal speed limit}} \right)
\]

The legal limit in urban driving is 48 kph for in the UK.

The average speed on the NEDC is 33.6 kph and is an average congestion of 30%. For the urban part only of the NEDC the average speed is 17.2 kph and congestion is 64% which is more reasonable. However, in our work congestion levels up to 80% have been observed and 95% in the worst congested parts of the route. Emissions are much higher than in the NEDC.

The new WLTP is little improvement as the average speed is too high, which is the main reason why it has been found to give lower emissions than on the NEDC for many vehicles.
Features of congested roads:

1. A high traffic flow

2. Frequent junctions on the route with traffic joining and leaving the main flow. Main flow stops to let in vehicles from the right or left, at the discretion of the drivers in the main flow. Each car joining causes main traffic to halt.

3. Traffic lights at major junctions and pedestrian crossings. All traffic now halts periodically. For high traffic flows it can take several stop/starts to get through. The process of starting and moving about 10m is very energy intensive with high emissions.

4. Traffic joining and leaving flows that can be comparable with the main flow.

5. Traffic mean velocity decreases as congestion increases.
Euro VI NOx in real service

- One Euro VI truck emits about the same NOx in g/km as one single Euro 5/6 passenger car

Emissions increase at low speed in proportion to congestion for diesels and at a lower rate for SI vehicles. Euro 5 and 6 diesel more emissions with congestion.
Lower speed = more congestion = more NOx pollution

NOx

Source: HBEFA, FPT
As part of a public enquiry over a trolley bus along the A660 traffic flow data have been measured between Ring Road and Hyde Park a distance of 3.5 km.

The Leeds A660 road has traffic monitoring and modelling by the City plus has an air quality monitoring station at the roadside in Headingley.
Congestion increases with traffic flow in urban driving. 7am flow was possibly different due to preferred route S to London, with little traffic leaving or joining the main route south at that time. Measurements using in road traffic counters and probe vehicles for vehicle journey time for the 3.5km Ring Road to Hyde Park on the A660 through Headingley. Traffic count taken at Hyde Park.
The average speed was the average over 3.5 km from the Ring Road to Hyde Park using both North and South flows. The lowest average speed in the emissions study was 10 kph. Period studied 7am – 7pm. Another definition of congestion is when the journey time is half the normal time congestion is 100% and the above results show that the A660 is congested for all times of the day.
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Example of emissions mapping using Horiba OBS g/s in a Ford Mondeo Euro 1 For Euro II – VI with lower emissions there are no significant emissions other than at junctions, so the effect of junctions is greater.

Pollution and CO$_2$ is predominantly at junctions for Euro 2 and increasingly so for Euro 4+

Junctions are the most important influence of congested traffic driving in urban locations. There are no junctions in the NEDC!
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This is a simple loop real driving with cold start and was designed to be similar to the NEDC urban part. 5 repeat journeys are shown, which demonstrate the differences caused by different traffic conditions for the same driver. Four loops were driven as in the NEDC urban driving procedures.
Comparison of Euro 1-4 Vehicles for Urban Driving Real World THC Emissions with Cold Start

SAE Paper 2008-01-0754
The HPL was a 1.96 km loop circuit, located in a busy residential area linked with major roads. AB was a dual carriage way on which the traffic speed can be up to ~60 km/h and there are fewer traffic interferences. The other three sides were two-way single carriageways with more traffic variation and interferences. The legal speed limit on all the roads was 48 km/hr (30 mph). The present work was for legal driving only.

The junctions A, B and D have a set of pedestrian lights. This loop was used for the cold start tests. HPL-A refers to loop ADCBA and HP:=B refers to loop ABCDA.
## Average emissions for 4 HPLA loops – SI For Mondeo $\lambda=1$

<table>
<thead>
<tr>
<th></th>
<th>Euro 1</th>
<th>Euro 2</th>
<th>Euro 3</th>
<th>Euro 4</th>
<th>RDE E4</th>
<th>X NEDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO g/km HPLA</td>
<td>7.2</td>
<td>5.9</td>
<td>2.1</td>
<td>3.4</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>LUBS* Euro</td>
<td>2.7</td>
<td>2.2</td>
<td>2.3</td>
<td>1.0</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>HC g/km HPLA</td>
<td>0.7</td>
<td>0.58</td>
<td>0.49</td>
<td>0.29</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>LUBS* Euro</td>
<td>0.55</td>
<td>0.29</td>
<td>0.2</td>
<td>0.1</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>NOx g/km HPLA</td>
<td>1.1</td>
<td>0.51</td>
<td>0.44</td>
<td>0.15</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>LUBS* Euro</td>
<td>0.42</td>
<td>0.21</td>
<td>0.15</td>
<td>0.08</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

* SAE 2008-01-1307
As part of a public enquiry over a trolley bus along the A660 traffic flow data have been measured between Ring Road and Hyde Park a distance of 3.5 km.

The Leeds A660 road has traffic monitoring and modelling by the City plus has an air quality monitoring station at the roadside in Headingley.
Influence of congestion on GHG emissions – CO₂, CH₄, N₂O for cold start journeys in a Euro 4 Ford Mondeo.

\[ Y = 416.43807 - 8.64204 \times X \]
\[ R^2 = 0.64202 \]

\[ Y = 0.02073 - 0.000447118 \times X \]
\[ R^2 = 0.47966 \]

\[ Y = 0.05063 - 0.00149 \times X \]
\[ R^2 = 0.76268 \]

Note that the average speed is low due to congestion not due to steady state slow speed driving. High emissions at low speed are due to high congestion.

The variability at a given velocity is due to the different stop/start proportions for the same mean velocity. Lower emissions will occur where the peak velocity is higher but the idle periods are longer, for the same journey length.
RDE in Congested Traffic with Cold Start

Euro 4 Ford Mondeo

Day 3 EURO4 0722 CSR2

Day 5 EURO4 1157 CSR2

NO
NO₂
NH₃
N₂O
CH₄
Benzene
1,3 Butadiene
Hexane
Isohexane
THC
Speed & λ
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Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions. 

SAE International 2013
Powertrain, Fuels and Lubricants, Oct., Seoul, S. Korea
Warm up of the lubricating oil under real world cold start
20 mins. warm up for diesel and SI

<table>
<thead>
<tr>
<th>Run</th>
<th>Time to raise lube oil by 60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>900s</td>
</tr>
<tr>
<td>D2</td>
<td>800s</td>
</tr>
<tr>
<td>B50-1</td>
<td>900s</td>
</tr>
<tr>
<td>B50-2</td>
<td>950s</td>
</tr>
<tr>
<td>B100-1</td>
<td>750s</td>
</tr>
<tr>
<td>B100-2</td>
<td>1000s</td>
</tr>
<tr>
<td>Petrol</td>
<td>950s</td>
</tr>
</tbody>
</table>

The variability was due to traffic differences not to the fuel or engine type.

SAE International 2013
Powertrain, Fuels and Lubricants, Oct., Seoul, S. Korea
Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions.

SAE 2013-01-2528
Note that in a Euro 6 engine exhaust temperatures will be lower than this.

Exhaust gas temperatures, ($^\circ$C)
Time, (s)

<table>
<thead>
<tr>
<th>Run</th>
<th>Catalyst</th>
<th>Vehicle time to 30 km/hr</th>
<th>CO Light off</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>180s</td>
<td>180s</td>
<td>160s</td>
</tr>
<tr>
<td>D2</td>
<td>190s</td>
<td>200s</td>
<td>230s</td>
</tr>
<tr>
<td>B50-1</td>
<td>140s</td>
<td>120s</td>
<td>170s</td>
</tr>
<tr>
<td>B50-2</td>
<td>120s</td>
<td>50s (Cat at 100$^\circ$C)</td>
<td>150s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120s (2$^{nd}$ vel. Peak)</td>
<td></td>
</tr>
<tr>
<td>B100-1</td>
<td>150s</td>
<td>160s</td>
<td>220s</td>
</tr>
<tr>
<td>B100-2</td>
<td>250s</td>
<td>260s</td>
<td>300s</td>
</tr>
</tbody>
</table>
Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions.


SAE International 2013 Powertrain, Fuels and Lubricants, Oct., Seoul, S. Korea

At each of these CO peaks the OxCat is below 200°C and the Ø is close to stoichiometric which increases CO
## Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions


### Table 1: Mean Values for Various Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Diesel Run1</th>
<th>Diesel Run2</th>
<th>B50 Run1</th>
<th>B50 Run2</th>
<th>B100 Run1</th>
<th>B100 Run2</th>
<th>ECE urban test cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. Acc, m/s²</td>
<td>0.50</td>
<td>0.62</td>
<td>0.54</td>
<td>0.54</td>
<td>0.47</td>
<td>0.51</td>
<td>0.64</td>
</tr>
<tr>
<td>Max Acc m/s²</td>
<td>3.41</td>
<td>4.91</td>
<td>2.99</td>
<td>3.8</td>
<td>2.98</td>
<td>4.94</td>
<td>0.74</td>
</tr>
<tr>
<td>Dec, m/s²</td>
<td>-0.47</td>
<td>-0.57</td>
<td>-0.53</td>
<td>-0.56</td>
<td>-0.44</td>
<td>-0.50</td>
<td>-0.60</td>
</tr>
<tr>
<td>Max. Dec m/s²</td>
<td>-2.87</td>
<td>-8.29</td>
<td>-4.7</td>
<td>-2.93</td>
<td>-3.22</td>
<td>-8.29</td>
<td>-0.74</td>
</tr>
<tr>
<td>V, km/h</td>
<td>20.4</td>
<td>17.3</td>
<td>22.0</td>
<td>20.4</td>
<td>18.3</td>
<td>19.9</td>
<td>17.2</td>
</tr>
<tr>
<td>Idle, %</td>
<td>26</td>
<td>38</td>
<td>19</td>
<td>24</td>
<td>30</td>
<td>32</td>
<td>28.6</td>
</tr>
<tr>
<td>Transients, %</td>
<td>27</td>
<td>26</td>
<td>32</td>
<td>30</td>
<td>28</td>
<td>22</td>
<td>44.8</td>
</tr>
<tr>
<td>Urban cruise &lt;48 kph, %</td>
<td>46</td>
<td>32</td>
<td>47</td>
<td>46</td>
<td>41</td>
<td>45</td>
<td>26.6</td>
</tr>
<tr>
<td>High speed &gt;48 kph, %</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Congestion, %</td>
<td>53</td>
<td>63</td>
<td>51</td>
<td>54</td>
<td>58</td>
<td>54</td>
<td>64</td>
</tr>
</tbody>
</table>

*SAE International 2013*  
*Powertrain, Fuels and Lubricants, Oct., Seoul, S. Korea*  
*SAE 2013-01-2528*
Mean emissions for B100, B50 and diesel, g/km

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>B50</th>
<th>B100</th>
<th>Euro 3 Limit</th>
<th>RDE Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂, g/km</td>
<td>318</td>
<td>261</td>
<td>312</td>
<td>172*</td>
<td>1.7</td>
</tr>
<tr>
<td>CO, g/km</td>
<td>2.2</td>
<td>2.6</td>
<td>2.7</td>
<td>0.8</td>
<td>3.1</td>
</tr>
<tr>
<td>THC+NOx, g/km</td>
<td>1.5</td>
<td>1.8</td>
<td>2.5</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>THC, g/km</td>
<td>0.19</td>
<td>0.25</td>
<td>0.68</td>
<td>0.07</td>
<td>5.3</td>
</tr>
<tr>
<td>NOₓ, g/km</td>
<td>1.29</td>
<td>1.59</td>
<td>1.78</td>
<td>0.65</td>
<td>2.4</td>
</tr>
<tr>
<td>NO, g/km</td>
<td>0.99</td>
<td>1.19</td>
<td>1.50</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>NO₂, g/km</td>
<td>0.30</td>
<td>0.39</td>
<td>0.27</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>NO₂/NO %</td>
<td>30%</td>
<td>33%</td>
<td>18%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O, g/km</td>
<td>0.20</td>
<td>0.04</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amb Temp., °C</td>
<td>6</td>
<td>11</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The CO and THC are much higher than Euro 3 limit mainly due to the much longer cold start. NOx is higher due to the much higher acceleration rates and fuelling.

*SAE 2013-01-2528*
Diesel Cold Start into Congested Real World Traffic: Comparison of Diesel, B50, B100 for Gaseous Emissions.

**Journey average emissions of the most congested part in units of g/km**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Diesel Run1</th>
<th>Diesel Run2</th>
<th>B50 Run1</th>
<th>B50 Run2</th>
<th>B100 Run1</th>
<th>B100 Run2</th>
<th>Euro 3 Limit</th>
<th>RDE Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO, g/km</td>
<td>8.7</td>
<td>6.3</td>
<td>7.0</td>
<td>5.5</td>
<td>8.2</td>
<td>12.9</td>
<td>0.8</td>
<td>10.1</td>
</tr>
<tr>
<td>THC, g/km</td>
<td>0.72</td>
<td>0.64</td>
<td>0.69</td>
<td>0.47</td>
<td>1.46</td>
<td>2.78</td>
<td>0.07</td>
<td>9.7 (D)</td>
</tr>
<tr>
<td>NO\textsubscript{x}, g/km</td>
<td>4.0</td>
<td>3.5</td>
<td>3.3</td>
<td>2.9</td>
<td>4.2</td>
<td>5.2</td>
<td>0.65</td>
<td>12.6</td>
</tr>
<tr>
<td>CO\textsubscript{2}, g/km</td>
<td>737</td>
<td>1189</td>
<td>579</td>
<td>543</td>
<td>789</td>
<td>942</td>
<td>172</td>
<td>3.7</td>
</tr>
<tr>
<td>(V_{\text{mean}}), km/h</td>
<td>6.8</td>
<td>4.5</td>
<td>7.6</td>
<td>7.7</td>
<td>6.6</td>
<td>5.4</td>
<td>17.2</td>
<td></td>
</tr>
</tbody>
</table>

**SAE International 2013**  
*Powertrain, Fuels and Lubricants, Oct., Seoul, S. Korea*  
**SAE 2013-01-2528**
As part of a public enquiry over a trolley bus along the A660 traffic flow data have been measured between Ring Road and Hyde Park a distance of 3.5 km.

The following results were for this complete journey with a fully warmed up catalyst undertaken after a cold start run.
### Mean emissions for B100 and diesel, g/km

<table>
<thead>
<tr>
<th>g/km</th>
<th>B100</th>
<th>Diesel</th>
<th>Euro 3 Limit</th>
<th>RDE Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN (5°C)</td>
<td>SD</td>
<td>MEAN (13°C)</td>
<td>SD</td>
</tr>
<tr>
<td>CO₂</td>
<td>172.9</td>
<td>11.8</td>
<td>173.6</td>
<td>5.9</td>
</tr>
<tr>
<td>CO</td>
<td>0.067</td>
<td>0.011</td>
<td>0.153</td>
<td>0.038</td>
</tr>
<tr>
<td>THC+NOₓ</td>
<td>1.342</td>
<td>0.045</td>
<td>2.004</td>
<td>0.593</td>
</tr>
<tr>
<td>THC</td>
<td>0.194</td>
<td>0.034</td>
<td>0.145</td>
<td>0.026</td>
</tr>
<tr>
<td>NOₓ</td>
<td>1.148</td>
<td>0.031</td>
<td>1.858</td>
<td>0.567</td>
</tr>
<tr>
<td>NO</td>
<td>0.695</td>
<td>0.045</td>
<td>1.491</td>
<td>0.693</td>
</tr>
<tr>
<td>NO₂</td>
<td>0.454</td>
<td>0.065</td>
<td>0.367</td>
<td>0.136</td>
</tr>
<tr>
<td>NO₂/NO</td>
<td>0.653</td>
<td></td>
<td>0.246</td>
<td></td>
</tr>
</tbody>
</table>

*CO is lower than diesel with B100 but THC are higher and NOₓ is lower.*

*NOₓ was higher than NEDC due to higher acc. which uses more power.*
Journey average emissions of congested part in units of g/km

<table>
<thead>
<tr>
<th></th>
<th>B 100 Run1</th>
<th>B 100 Run2</th>
<th>B 100 Run3</th>
<th>B100 Ave.</th>
<th>Diesel Run1</th>
<th>Diesel Run2</th>
<th>Diesel Run3</th>
<th>Diesel Average</th>
<th>Euro 3 Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO, g/km</td>
<td>0.297</td>
<td>0.501</td>
<td>0.396</td>
<td>0.398</td>
<td>0.189</td>
<td>0.112</td>
<td>0.144</td>
<td>0.148</td>
<td>0.8</td>
</tr>
<tr>
<td>THC, g/km</td>
<td>0.887</td>
<td>0.993</td>
<td>1.032</td>
<td>0.971</td>
<td>0.359</td>
<td>0.151</td>
<td>0.174</td>
<td>0.228</td>
<td>0.07</td>
</tr>
<tr>
<td>NO\textsubscript{x}, g/km</td>
<td>3.87</td>
<td>4.926</td>
<td>2.320</td>
<td>3.705</td>
<td>2.988</td>
<td>1.891</td>
<td>2.536</td>
<td>2.472</td>
<td>0.65</td>
</tr>
<tr>
<td>CO\textsubscript{2}, g/km</td>
<td>745</td>
<td>810</td>
<td>528</td>
<td>694</td>
<td>507</td>
<td>613</td>
<td>740</td>
<td>620</td>
<td>172</td>
</tr>
<tr>
<td>$V_{\text{mean}}$, km/h</td>
<td>5.54</td>
<td>7.09</td>
<td>9.13</td>
<td>7.25</td>
<td>6.35</td>
<td>5.09</td>
<td>5.40</td>
<td>5.61</td>
<td></td>
</tr>
</tbody>
</table>

The RDE factor relative to the NEDC was 0.34 for CO, 3.3 for HC, 4.8 for NO\textsubscript{x} and 3.8 for CO\textsubscript{2} for the most congested part of the route through Headingley.

These results illustrate the advantage of diesel hybrids as operation in electric mode would always be done for these congested traffic conditions.

SAE International 2012
Powertrain, Fuels and Lubricants, Sept., Malmo, Sweden

SAE 2012-01-1674
The present work was not designed to include a cold start, the time at the start of the test while instruments and data loggers were set up was sufficiently long for catalyst cooling to occur.

The low oxidation catalyst temperatures at the start of the test resulted in high CO and HC emissions during the subsequent warm up period. For most of the journeys the catalyst temperature was well above 200°C. However, there were times when the catalyst cooled down to around 150°C in congested traffic, where CO and HC increased.

This is a different catalyst behavior to that in SI vehicles operating at $\lambda=1$ as the exhaust temperature are higher and there is greater heat release at the catalyst due to CO and HC oxidation.
Contents

1. Real Driving Emissions
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6. Cold start influence on RDE for SI TWC vehicles Euro 4
7. Cold start influence on RDE for Diesels – Euro 3
8. Cold start RDE for a HDD Euro 5
9. Conclusions
WHTC sequence as specified in ECE-R49

Cold test

1. Test

soak

2. Test

10 min

HDD cold start is not as significant as for passenger cars.

Weighting factor

14%  86%
What is the importance of cold start in the WHTC for HDD?

14% weighting to the cold start. 10min. soak with engine off then a repeat test. Is the second test truly a ‘hot start’ – depends on catalytic system thermal insulation. This cannot be too good or it will lead to overheating at maximum power conditions.

Current de-NOx catalytic systems for diesels are taking 200s to light off, so the city part of the test cycle emits raw emissions for most of the time.

Let the ratio of Test 1/Test 2 = y

Let the emissions of a pollutant in Test 2 =x

Then the weighted emissions are:

Total emissions = 0.14 yx + 0.86x

Proportion of Test1 of the total weighted emissions =

0.14yx / (0.14yx + 0.86x) = 0.14/(0.14 + 0.86/y)

Example: y = 10 then cold start is 62% of the total

y = 2 then cold start is 24.6% of the total

Clearly a good cold start performance is essential if NOx, HC and CO legislation is to be met for HDD vehicles.
Mercedes Benz AXOR-C6x2
Engine Mercedes-Benz  OM457LA  Euro V
Euro 5 with SCR deNOx
Unit injectors, TCIC, 4v/cyl.

Note that Euro V HDD did not have any cold start requirements to meet.
The RDE are dominated by cold start issues
Cold start

SAE 2015-01-0905
Exhaust temp.
Note the fall in temperature during cruise,
A high flow velocity is cooling the catalyst.
Cruise is a low fuel flow condition especially, as in this case when it is downhill.
NOx rises due to SCR reduced activity in some runs.

Cold Start 500s to 200°C
Fluctuations in CO over 2 order of magnitude of mass indicates an oxidation Catalyst going in and out of activity due to exhaust temperature fluctuations. Note high CO during motorway downhill cruise, where the catalyst cools. Similar effect for HC in the next slide.
This is the NOx mass emission results from the ppm measurements in the previous slide. Clearly the deNOx efficiency is poor on this journey and the cold start effect is very clear over the first 300s. The spikes are likely to be due to inadequate Urea control and the rise in the mean NOx to inadequate catalyst temperature.
Several NOx mass emissions for different trips on the same journey are shown in this and the next slide.
Gordon E. Andrews. Hu Li, Ali S. Hadavi, Ahmad Khalfan
School of Chemical and Process Engineering, University of Leeds, UK

*RDE in Congested Traffic with Cold Start*

Low T

700s
Cold start

EI, NOx, g/kgf

vehicle speed, km/h

Time, s
NO\textsubscript{2} emissions from the previous slide for total NOx
NO\textsubscript{2} also increases when the catalyst is at a low T during downhill cruise
Note cold start for NO\textsubscript{2} is 300s compared with 700s for NO due to the lower light off temperature for NO\textsubscript{2}.
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9. Conclusions
Conclusions
1. RDE are strongly influenced by
   a) the driver actions; b) ambient temperature; c) traffic congestion
do) road junctions and traffic lights; e) cold start
2. Both SI and diesel vehicles have all the above influences, but SI are also sensitive to quality of $\lambda$ control.
3. The RDE multiplier was higher for cold start than hot start, as shown below.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cold/Hot start</th>
<th>Loop/Road</th>
<th>CO$_2$</th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>Cold E4</td>
<td>Loop</td>
<td></td>
<td>3.3</td>
<td>3.3</td>
<td>1.9</td>
</tr>
<tr>
<td>SI</td>
<td>Cold E4</td>
<td>Road</td>
<td>1.0 – 1.4</td>
<td>1.4 – 2.6</td>
<td>3.0 - 5.5</td>
<td>1.4 – 3.1</td>
</tr>
<tr>
<td>SI</td>
<td>Cold E4</td>
<td>Congested</td>
<td>4.1</td>
<td>54</td>
<td>20</td>
<td>1.8</td>
</tr>
<tr>
<td>Diesel E3</td>
<td>Cold E3</td>
<td>Loop</td>
<td>1.7</td>
<td>3.1</td>
<td>5.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Diesel E3</td>
<td>Cold E3</td>
<td>Congested</td>
<td>3.7</td>
<td>10.1</td>
<td>9.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Diesel E3</td>
<td>Hot E3</td>
<td>Road</td>
<td>1.0</td>
<td>0.2</td>
<td>2.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Diesel E3</td>
<td>Hot E3</td>
<td>Congested</td>
<td>3.8</td>
<td>0.34</td>
<td>3.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Driver SI</td>
<td>Hot E1 SI</td>
<td>Loop no traffic</td>
<td>2.2 – 1.2</td>
<td>10.4 -0.1</td>
<td>0.65 – 0.1</td>
<td>4.0 – 0.6</td>
</tr>
</tbody>
</table>
Conclusions (cont)

4. Catalysts light off time in RDE with cold start was a major factor in the high RDE. This light off time varied depending on the traffic conditions:

- SI Euro 4 TWC: 120 – 220s
- Diesel E3 OxCat: 150 – 300s
- HDD EV SCR: 300 – 700s

The worst case is the HDD SCR – where there has been no requirement at Euro V for cold start emission measurements. This is going to be a major area that has to be improved in HDD for the new test cycle.

5. Diesel exhaust catalyst, both oxcat and SCR exhibit cooling of the catalyst after encountering congested traffic after a high speed period and during cruise downhill where the high exhaust flow at low temperature cools the catalyst and reduces the NOx conversion.

6. To overcome these cold start effects, especially in diesel vehicles active heating of the exhaust is required and it is considered that direct combustion in the exhaust is the most effective way of doing this. Current burner designs are far from optimum for this purpose and better designs are required.
Acknowledgements

We would like to thank the UK EPSRC for supporting the early stages of this research and for providing the heated FTIR. This was through two large grants

LANTERN and RETEMM 2001 - 2008

More recent work has been through PhD students.

The recent HDD vehicle RDE diesel work was through a UK Department for Transport and Technology Strategy Board for supporting the research element within the project “Environmental and Performance Impact of Direct use of used cooking oil in 44 tonne trucks under real world driving conditions” which is part of the Low Carbon Truck Demonstration Trial.”

Thanks go to United Biscuits Midland Distribution Centre for the provision of a truck and general support and collaboration in field tests. Thanks also go to Bioltec System GmbH for advice and permission to use some technical information and Convert2Green for the provision of Ultra Biofuels for the tests.