Real driving emissions:
Challenges to regulating diesel engines in Europe

Vicente Franco & Peter Mock
vicente@theicct.org

Anil Agarwal Dialogue. New Delhi, March 11-12 2015
The European Problem with Diesels
Early Concerns about Mis-Aligned Diesel Policies in Europe

Table 2
Carbon dioxide-equivalent PM$_{2.5}$ emissions from new light-duty gasoline and diesel vehicles (g/km).
Source: Emission factors based on Bond et al., 2007. GWP values from Bond et al., 2011.

<table>
<thead>
<tr>
<th></th>
<th>No control</th>
<th>Engine Mods</th>
<th>Euro 1</th>
<th>Euro 2</th>
<th>Euro 3</th>
<th>Euro 4</th>
<th>Euro 5</th>
<th>Euro 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>−0.3</td>
<td>−0.3</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Diesel</td>
<td>251.7</td>
<td>167.9</td>
<td>129.7</td>
<td>54.6</td>
<td>30.2</td>
<td>15.4</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Note: Based on GWP-100 values of 2800 for black carbon and −154 for organic carbon. Negative values can be considered equivalent to a negative radiative forcing.

EU Diesel Penetration

Today’s Problem: Real-world diesel NOx emissions enforcement is non-existent

Results from a remote sensing study in Zurich (Switzerland)

Fig. 4. Mean hot NOx emission factors of gasoline (left) and diesel (right) passenger cars and light commercial vehicles as a function of model year. Whiskers represent the 95% confidence interval over the mean. Added are the type approval limit values for Euro 1 to Euro 5 passenger cars over the homologation test cycle in force in the respective year. For conversion from limit values in g per km see SI (using measured fuel consumption rates from Hausberger (2010)). For color plot consult online version.

New Diesel Car Emissions in Europe are Worse (on average) than 15 years ago

Diesel cars: Nitrogen oxides (NOₓ) emissions (in g/km)

- Euro 3
  - 2000
  - On-road measured value (Carslaw, 2011) / (ICCT, 2014)
  - Euro emission limit
  - 1.0

- Euro 4
  - 2005
  - On-road measured value (Carslaw, 2011) / (ICCT, 2014)
  - Euro emission limit
  - 0.8

- Euro 5
  - 2009
  - On-road measured value (Carslaw, 2011) / (ICCT, 2014)
  - Euro emission limit
  - 0.8
  - 0.18

- Euro 6
  - 2014
  - On-road measured value (Carslaw, 2011) / (ICCT, 2014)
  - Euro emission limit
  - 0.6
  - 0.08
Awareness of the ‘Diesel problem’ has triggered initiatives at the local level.

**The Telegraph**

London will follow Paris and ban diesel cars, campaigners warn

Pollution is so high in the capital, and diesel fumes so damaging, experts believe Boris Johnson will follow Paris' lead and ban the cars from London's roads within the decade.

**FINANCIAL TIMES**

Carmakers stuck in slow lane over fuel data and air pollution, say researchers.
Key message from Europe: Avoid our mistakes!

A chain is only as strong...

...as its weakest link

A solid pollutant regulation requires:

- A modern test procedure
- Independent retests
- On-road testing
- Transparency of test results

More info:

http://www.theicct.org/blogs/staff/trend-that-cant-continue-europes-car-co2-emissions-gap
http://www.theicct.org/blogs/staff/will-new-test-procedure-solve-problem-latest-developments-eu-vehicle-testing
http://www.theicct.org/wltp-how-new-test-procedure-cars-will-affect-fuel-consumption-values-eu
http://www.theicct.org/laboratory-road-2014-update
http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars
http://www.theicct.org/wltp-november2013-update

Photo credit: http://photoopia.com/view/6856-Schwaches+Glied+in+der+Kette.html
Assessing the problem

ICCT Diesel Passenger Car Meta-Study
ICCT Report: Real-World Exhaust Emissions from Modern Diesel Cars (October 2014)

- Multiple data sources
  - 15 vehicles (3 Tier 2 Bin 5 + 12 Euro 6)
  - 5 different sources
  - 96 trips/ 140 hrs / 6,400 km of recorded data

- One multi-level analysis and reporting framework
  - Raw emission factors (trip averages)
  - Windowed emissions (‘on-road compliance’)
  - Situation-specific emissions
  - Instantaneous emissions

http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars
Overall Results

‘Raw’ average distance-specific emissions, by vehicle

http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars
Meta-study: Results for NO$_x$

Euro 6 conformity factor for NO$_x$, all vehicles

Mean CF = 7.1
Best vehicle: 1.0
Worst vehicle: 25
Meta-study: Results for CO

Euro 6 conformity factor for CO, all vehicles

Mean CF = 0.40
Diesel PC meta-study: Results

On-road compliance (all CO\textsubscript{2} windows of all trips)
Meta-study: Results for CO$_2$

Real-world CO$_2$ ratios, all vehicles

Mean on-road/type-approval ratio = 1.43
The solution to the EU Diesel NOx problem
Learn from others: Dramatic Differences Between US and European Enforcement Schemes

1. Pre-production testing
   Certificate of Conformity

2. Conformity tests
   about 10% of vehicles

3. Selective Enforcement Audit +
   Confirmatory Road Load Testing

4. In-use verification
   tests on random sample

5. In-use surveillance
   random / selected sample

vehicle design and build 0 km 50,000 km 100,000 km

BMW to fix fuel economy labels on Mini Coopers after U.S. EPA test

U.S. Fines Hyundai, Kia for Fuel Claims
Penalty of $300 Million Is Largest Ever, Could Set Pricey Precedent for Other Auto Makers

From laboratory to road: PEMS makes it possible to accurately measure real-world emissions

Road tests with PEMS

Chassis dyno measurements

Photo credit: AVL / ERMES Group
Vehicle photos unrelated to the results shown

http://www.theicct.org/use-emissions-testing-light-duty-diesel-vehicles-us
The Fix: Euro 6 RDE-LDV Process

1. An amendment to Euro 6 standards to make on-road testing with PEMS part of type-approval. Triggered by high on-road Diesel NO\textsubscript{X} results.

2. Stakeholder WG is defining how the tests should be conducted (boundary conditions), how the data should be analyzed and reported.

Conclusions

- A high share of European diesel passenger cars do not comply with the Euro 6 emission standard in the real-world
- An enforcement loophole allows cars to pass certification tests and still exceed emission limits in the real-world
- This problem will be addressed in Europe through:
  - Amend Euro 6 to require PEMS testing
  - Define testing process, data collection and reporting
  - Pilot testing in 2015 with full implementation by 2017
- Indian Bharat 6 regulations should leap-forward to this approach or adopt US best practices for enforcement to avoid high diesel NOx emissions
Thank you!

Vicente Franco,
vicente@theicct.org

Peter Mock, ICCT Managing Director for Europe
peter@theicct.org
Additional Slides
## Meta-study: Results by driving condition

**NO\textsubscript{X} emission factors [mg/km]**

<table>
<thead>
<tr>
<th></th>
<th>All driving conditions</th>
<th>Undemanding 1</th>
<th>Undemanding 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle A</td>
<td>482</td>
<td>17</td>
<td>234</td>
</tr>
<tr>
<td>Vehicle B</td>
<td>235</td>
<td>12</td>
<td>206</td>
</tr>
<tr>
<td>Vehicle C</td>
<td>72</td>
<td>14</td>
<td>93</td>
</tr>
<tr>
<td>Vehicle D</td>
<td>171</td>
<td>35</td>
<td>253</td>
</tr>
<tr>
<td>Vehicle E</td>
<td>819</td>
<td>114</td>
<td>860</td>
</tr>
<tr>
<td>Vehicle F</td>
<td>908</td>
<td>183</td>
<td>1522</td>
</tr>
<tr>
<td>Vehicle G</td>
<td>294</td>
<td>49</td>
<td>373</td>
</tr>
<tr>
<td>Vehicle H</td>
<td>1809</td>
<td>423</td>
<td>2166</td>
</tr>
<tr>
<td>Vehicle I</td>
<td>438</td>
<td>30</td>
<td>561</td>
</tr>
<tr>
<td>Vehicle J</td>
<td>279</td>
<td>12</td>
<td>362</td>
</tr>
<tr>
<td>Vehicle K</td>
<td>289</td>
<td>34</td>
<td>533</td>
</tr>
<tr>
<td>Vehicle L</td>
<td>1783</td>
<td>222</td>
<td>2350</td>
</tr>
<tr>
<td>Vehicle M</td>
<td>758</td>
<td>59</td>
<td>884</td>
</tr>
<tr>
<td>Vehicle N</td>
<td>388</td>
<td>45</td>
<td>558</td>
</tr>
<tr>
<td>Vehicle O</td>
<td>504</td>
<td>89</td>
<td>325</td>
</tr>
</tbody>
</table>

*Idling emissions in mg/min
Meta Study: Results in more detail

- CO, NOx, THC emissions under different conditions:
  - Velocity
  - Gradient
  - Acceleration velocity
  - Temperature

Distance categories:
- Rolling, speed < 2 km/h
- Speed 2 to 50 km/h
- Speed 50 to 90 km/h
- Speed > 90 km/h

- Strong downhill (< -4%)
- Mild downhill (-4 to -1%)
- Pretty flat (-1 to 1%)
- Mild uphill (1 to 4%)
- Strong uphill (>4%)

- Strong negative a*V (< -9.2 W/kg)
- Mild negative a*V (-9.2 to 0 W/kg)
- Zero or mild positive a*V (0 to 9.2 W/kg)
- Strong positive a*V (>9.2 W/kg)

Temperature categories:
- Cold temperature
- Medium temperature
- Hot temperature

Euro 5 and Euro 6 limits

ICCT
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION
Diesel PC meta-study: Part 2

Coming soon: detailed investigation of on-road emissions from the vehicles studied in Part 1
## Meta-study: Results by driving condition

### Situation-specific analysis: undemanding driving conditions

<table>
<thead>
<tr>
<th>Combination</th>
<th>Filtering</th>
<th>Descriptor</th>
<th>Color ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undemanding driving (1)</td>
<td>Data are binned by velocity. Only Points with motorway speed below 120 km/h are included. Likewise, only the points in the ‘Pretty flat’, ‘Medium temperature’ and ‘Mild negative a<em>v’ or ‘Zero or mild positive a</em>v’ bins are included.</td>
<td>Undemanding Urban 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undemanding Rural 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undemanding Motorway 1</td>
<td></td>
</tr>
<tr>
<td>Undemanding driving (2)</td>
<td>Same as ‘Undemanding driving (1)’, but including the ‘Mild uphill’ and ‘Mild downhill’ bins.</td>
<td>Undemanding Urban 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undemanding Rural 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undemanding Motorway 2</td>
<td></td>
</tr>
</tbody>
</table>
Real Driving Emissions | Regulatory aspects of on-road emission measurements
Real Driving Emissions | Conclusions
Conclusions

• Euro 6 Diesel PCs have no on-road compliance issues for CO and THC.

• On-road Diesel NO\textsubscript{X} compliance issue present across aftertreatment techs, manufacturers and driving situations, not just in the more demanding operating conditions (e.g., uphill driving, instances of high acceleration*velocity), but also during the situations that would in principle be most favorable to achieve low NO\textsubscript{X} emissions.

• This is the result of insufficient regulation, which incentivized manufacturers to design their aftertreatment control systems to pass the dynamometer test instead of achieving low real-world emissions.
Conclusions

• $\text{NO}_x$ mass emissions concentrate in small events (transient load increases: gradient and acceleration); setting dynamic boundary conditions/data exclusions can dramatically affect results.

• No regulation is perfect, but the RDE amendment should improve Euro 6, providing manufacturers with the right incentives to design robust aftertreatment systems.

• India could benefit from RDE tests tailored to reflect Indian driving conditions, which would give its regulators further assurance that real-world emissions are kept under control.
Real Driving Emissions: regulating Diesel passenger car emissions in Europe

- Current challenges: results from Diesel PC meta-study
- Regulatory aspects of on-road emission measurements
- Conclusions
Real Driving Emissions

Current challenges: results from Diesel PC meta-study
Diesel PC meta-study: Results
Benefits of RDE-LDV Process

- Novel application of on-road tests to pollutant regulations, fundamentally different from chassis dynamometer cycles (more representative of real-world conditions)
- Europe, India are the markets with the largest Diesel share
- Some markets to follow Europe soon (e.g., South Korea)
- Driver of changes in Diesel NO\textsubscript{X} aftertreatment; implications on viability of small Diesel PC market