Measurement of late-model diesel automobile real driving emissions of reactive nitrogen compounds with on-board FTIR analyzer

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Particulate matter and ground-level ozone are responsible for over 400 thousands premature deaths in the EU (traffic accidents for „only“ 39 thousands)
Problematic pollutants in engine exhaust

- **Particles** + secondary aerosol
- **NO\textsubscript{x}**  + tropospheric ozone
- **CO**, benzene, lead - no longer a problem

**New and emerging problems:**
- **NO\textsubscript{2}** - formation in oxidation catalysts
- **NH\textsubscript{3}** - formation in reduction catalysts
- - formation in three-way catalysts when run rich
- **Aldehydes** - oxygenated fuels (ethanol)

**Greenhouse gases**
- **N\textsubscript{2}O** - NOx reduction catalysts (SCR, LNT)
- **CH\textsubscript{4}** - natural gas engines, LNT catalyst
Project BIOTOX - Mechanisms of Toxicity of Particles from Biofuels

PM measurement and sampling using high-volume samplers

Gasoline MPI and direct injection, diesel,
Traditional and alternative fuels (ethanol, butanol, biodiesel, NExBTL, blends)
Real driving emissions measurement
Portable on-board monitoring systems (PEMS)

Cars, buses, trucks, tractors, loaders, mowers, small airplanes, mopeds, ferries, locomotives, construction machinery

FTIR measurement of real driving emissions of reactive nitrogen – Vojtisek et al. – TAP May 2016
Evaluation of real driving emissions (RDE) with portable on-board emissions monitoring systems (PEMS)

Type-approval grade:
AVL - gaseous pollutants
NanoMet 3 - particle number (PN)

In-house built research-grade:
“Mini-PEMS” (13 kg, 60 W)
On-board portable FTIR
(non-regulated compounds)
On-board particle counters and particle classifier (EEPS)

Services: PEMS & laboratory testing
Test design and facilitation
Data analysis and interpretation

Staff: Michal Vojtisek designed the first commercially available PEMS
20 years PEMS & RDE in USA & EU
Real driving emissions (RDE) measurement using Portable Emissions Monitoring Systems (PEMS)

Work by the author

One of the first PEMS
Pittsburgh, USA, 1996-1999

First commercially available PEMS – OEM-2100
Manufactured 1999-2002

Pennsylvania State University
USA, 2001-2003

Real driving emissions (RDE) measurement using Portable Emissions Monitoring Systems (PEMS)

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Work by the author

Commercially sold PEMS
Montana system
2002-2005

PEMS FTIR
2004-2006
Portable on-board exhaust emissions monitoring system (current version)
HC, CO, NO, NO\textsubscript{2}, PM mass, PM length

heated ionization “fire detector”
undiluted raw exhaust
(multiplied by intake air flow for comparison measurements)

~ 0.1 mg/m\textsuperscript{3}
sensitivity

cheap (100 EUR)
“poor man’s PEMS” concept

Online real-world measurements
Incl. PM on SI
SAE 2013-24-0102
SAE 2013-24-0168

Installs on motorcycles to locomotives
This example → from a Euro 4 diesel car

Length vs. PN>23 nm with volatiles
On-board monitoring system

Response approximately proportional to PM mass concentrations for a given engine

Nephelometer (laser scattering)

Modified ionization smoke alarm (a 100 EUR system) - response proportional to total particle length (close to lung deposited surface area?)

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On-board system versatility: Motorcycle to locomotive

- 5 Hz GPS receiver
  - Speed, position, altitude
- Intake air manifold absolute pressure
- Raw exhaust sampling point (no dilution)
- Special adapter fabricated and inserted before muffler (outside air penetrates well into tailpipe)
- Engine speed measured with optical tachometer
- Battery
- 2009 Coliber Fartt scooter
  - 0.049 liter carbureted engine
- Triplicate of real driving emissions of reactive nitrogen – Vojtisek et al. – TAP May 2016

- Truck
- Battery
- 2009 Coliber Fartt scooter
  - 0.049 liter carbureted engine
- Engine speed measured with optical tachometer
- 163 liter diesel
Portable on-board exhaust emissions monitoring system
HC, CO, CO₂, NO, NO₂, PM mass, PM length
Calculated exhaust flow
“Motorcycle to locomotive”
Full-flow dilution tunnel with particle sampling for small non-road engines
PM sizes and count:
Electric mobility classifier and spectrometer
EEPS model 3090, TSI
1 Hz measurement
5-560 nm

Dilution for PM:
Rotating disc microdiluter
MD-19, Matter Engineering
150 C dilution head
150:1 dilution ratio

MEDETOX prototype

Gases:
FTIR spectrometer
650-4000 cm\(^{-1}\)
6 m optical length
0.5 cm\(^{-1}\) resolution
Methane, formaldehyde, CO, CO\(_2\), NO, NO\(_2\), ...

Sampling line
Superinsulated
Heated to 150 C

FTIR measurement of real driving emissions of reactive nitrogen – Vojtisek et al. – TAP May 2016
Euro 6 diesel truck (DOC, DPF, SCR)
Two FTIR-PEMS & “ordinary” PEMS & particle counter

Particle counter

Batteries
Charger
Inverter

3 tons of weights
(total payload 3,5 t = 58%)
12 tons gross weight
9.5 tons actual weight

FTIR
MEDETOX
TU Liberec

FTIR
Czech Tech
Univ Prague

3 tons of weights (total payload 3.5 t = 58%)
12 tons gross weight
9.5 tons actual weight
Student projects: E85, n-butanol, isobutanol in unmodified gasoline engines in Škoda cars

On-board FTIR
~ 30 kg
~ 300-400 W
3 hours on
26 kg of batteries
ADAC test results:

Diesel cars

WLTP cycle

NOx
Why are NOx higher during real driving

• **Technology limits**
  - low SCR temperature - cold start, creep

• **Optimization for cycle / off-cycle emissions**
  - No EGR at full load
  - Catalyst sized for low flow and too small for high loads

• „No one is watching“
  - Switching off EGR, LNT fuel / SCR urea injection
  - „Cycle beating“ strategy
Heavy vehicle creep problem

* Deterioration of combustion at idle
* Low exhaust gas temperatures decrease efficiency of catalytic devices (DOC, SCR)
* Particulate matter stored in exhaust system to be released later

Increase in PM emissions “getting out of creep”

Practical efficiency limit of DOC, SCR
Congestion effects: DAF 1505 truck, 2006, Euro 5 Paccar engine, 540 thousands km, with loaded trailer (39 tons total weight)
The horror of transit truck traffic

We took a DAF truck with semi-trailer, 39 tons, EURO 5 but no DPF, and circulated the Prague perimeter road waiting for congestion to happen

“Urban creep”:
combustion worsens, DOC cools down, SCR cools down, EGR not feasible

Result: NOx and PM up to one order of magnitude higher

Euro 5 equivalents at 250 g/kWh: 2.0 g/kWh ~ 8 g NOx/kg fuel / 0.02 g/kWh ~ 0.08 g PM/kg fuel
Challenges of EU automobile diesel engines
Euro 4 Skoda Fabia - chassis dynamometer runs
NEDC vs. full-power loaded accelerations

Problem compounded by downsizing & turbocharging: Relatively low torque at idle.

Problem compounded by cold DOC during accelerations after long idle.

Maintaining adequate excess air competes with desire for additional torque.

NOx: Use of EGR competes with the desire for additional torque.

Long idle / low load: DOC cooldown, combustion deterioration, high fraction of OC in PM.

NOx reduced by EGR?
Euro 4 Skoda Octavia - real-world city driving tests

Measurement by the author.
Euro 4 Škoda Octavia - high-speed freeway tests

Aggressive, high-speed driving on a freeway, not atypical for Czech roads
Results contrasted with ECE cycle test on a chassis dynamometer
Cumulative NOx emissions over cold vs. hot start NEDC
Euro 5, VW Passat

Euro 5 limit 180 mg/km
This work: Škoda Octavia Euro 5 diesel, LNT

Goal: Examination of RDE emissions of nitrogen species: NO, NO₂, NH₃, N₂O

TU Liberec to EC Joint Research Center (Ispra, Italy)

About 8 hours of instrument run time (6:45 sampling time)
(limited by battery and liquid nitrogen capacity)

Germany (high speed) & Switzerland (hills and high altitude)

Germany:
431.75 km, 4:52
6.4 mg/km N₂O
687 mg/km NOₓ
158 g/km CO₂

Switzerland:
84.66 km, 1:53
217 mg/km NOₓ
140 g/km CO₂
Euro 5 diesel car, LNT

LNT regeneration: spikes in CO2 (> 14%) and CO
Spikes in CH4, N2O (otherwise negligible)
No regeneration = saved fuel, high NOx
Škoda Octavia Euro 5 diesel, LNT

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Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution

1 km resolution

NOx - both absolute and per CO2 (per kg fuel) - Exponentially increase with fuel consumption (g/km CO2)
Škoda Octavia Euro 5 diesel, LNT

> 500 km of data

100 m resolution 1 km resolution

NOx exponentially increase with road speed
Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution

1 km resolution

NOx per kg CO2 (per kg of fuel) exponentially increase with road speed
Škoda Octavia Euro 5 diesel, LNT
> 500 km of data

100 m resolution

1 km resolution

NOx – both per km and per kg CO2 (or kg of fuel) exponentially increase with road speed
Škoda Octavia Euro 5 diesel, LNT

> 500 km of data

NOx appear to be well comparable with Euro 5 standards throughout Switzerland (max. 120 km/h, avg. 0.217 g/km).

On the autobahn in Germany, NOx were generally higher (>0.18 g/km >70% of the distance, avg. 0.69 g/km).
SOR CN12 Euro 6 diesel bus
Hradčany military airport
Braunschweig driving cycle

Goal: Evaluation of production of N2O, NH3, NO2 by diesel and CNG buses
SOR CN12 Euro 6 diesel bus – Hradčany military airport

NO, NO2, N2O, NH3, …., CO, CO2, PM

(NO, NO2 [mg/s])

Fuel-from-ECU [dm3/h], fuel-from-CO2 [dm3/h], actual speed [km/h], prescribed speed, NO [mg/s], NO2 [mg/s], palivo-dle-ECU [dm3/h], palivo-dle-CO2 [dm3/h], rychlost [km/h], NO [mg/s], NO2 [mg/s]
**SOR CN12 Euro 6 diesel bus - Hradčany military airport**

**Average emissions - Braunschweig cycle:** 195 mg/km NO$_x$.

At 37 liters / 100 km, 220 g/kWh: 162 mg/kWh (Euro 6: 460 mg/kWh)

**Diesel car NOx limit:** 180 mg/km Euro 5, 80 mg/km Euro 6

**Diesel car real driving NOx:** Euro 3-5: 1000 mg/km

One Euro 5 car = 1000 mg/km = 5 buses !!!

But 5 buses can transport 100x more people.
Do we limit the diesel engine to heavy-duty vehicles, just like in the United States?

Is car really the best way for high-speed intercity travel?
Conclusions & Implications

Real driving emissions of NO, NO2, NH3, N2O (+ more) measured with portable FTIR

> 500 km, 6 ¾ hours on batteries and liquid nitrogen

Measurement is possible

Interpretation of spectra for additional compounds is also possible later after the measurement

Difficult to generalize based on one or several vehicles

Results suggest NOx elevated at higher (off-cycle) speeds, and “compliant” results throughout Switzerland (≤ 120 km/h)

Germany: 431.75 km, 4:52
6.4 mg/km N2O, very low NH3
687 mg/km NOx, 158 g/km CO2

Switzerland: 84.66 km, 1:53
217 mg/km NOx, 140 g/km CO2
Thank you!

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Support of Research Teams at Czech Technical University in Prague.

Warning: This engine may produce nanoparticles that are harmful when inhaled.

EU LIFE+ program, project MEDETOX - Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic (LIFE10 ENV/CZ/651)

Czech Science Foundation project BIOTOX (13-0148S): Mechanisms of toxicity of particles from biofuels

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