LABORATORY OF APPLIED THERMODYNAMICS

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On-Board Monitoring with Advanced Exhaust Sensors

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Acknowledgments

- Framework contract for studies and technical assistance in the field of emissions:
  - Study on post-EURO 6/VI emission standards in Europe
  - Measuring the fuel consumption of light- and heavy-duty vehicles and monitoring their real-world fuel consumption
- Smart Adaptive Remote Diagnostic Antitampering Systems (DIAS) - European Commission HORIZON 2020

Contents

- Open issues on emissions
- OBM and policies
- OBM components and framework
- Design targets of sensors
- Evaluation of NOx, NH_3, and PM/PN sensors
- Anti-tampering of OBM components

Open issues on emissions

- Euro 6/VI final stages, RDE and OBD have been successfully reduced tailpipe emissions
- But they did not solve all issues:
  - Tampering
  - High emitters with MIL-off
  - Restrictive ISC car selection rules
  - Etc.

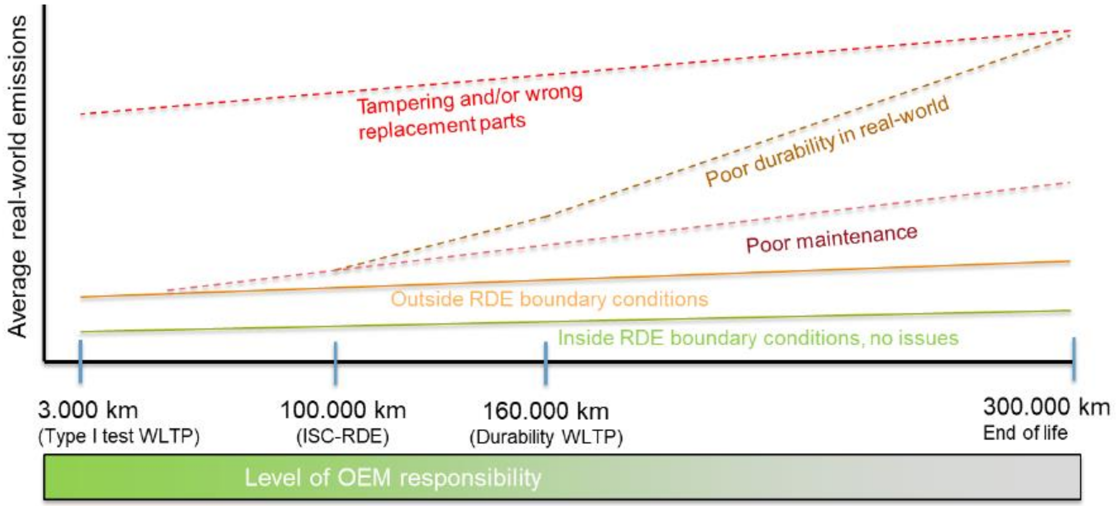


Figure source: TNO 2019 R10534v2

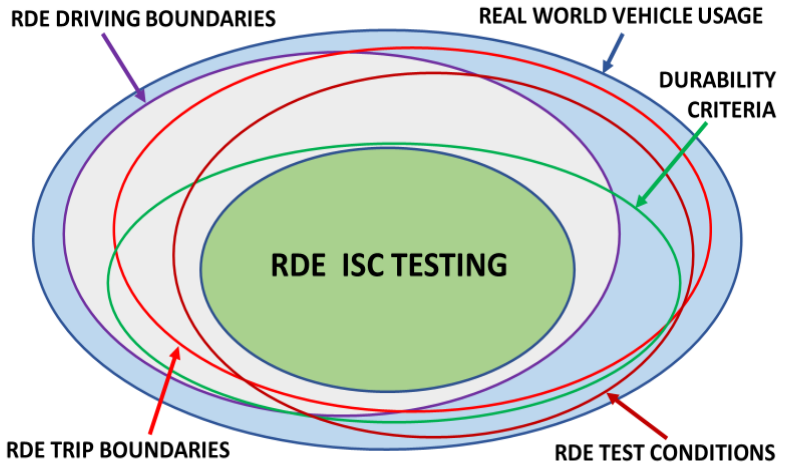


Figure source: TNO 2019

OBM-based policies

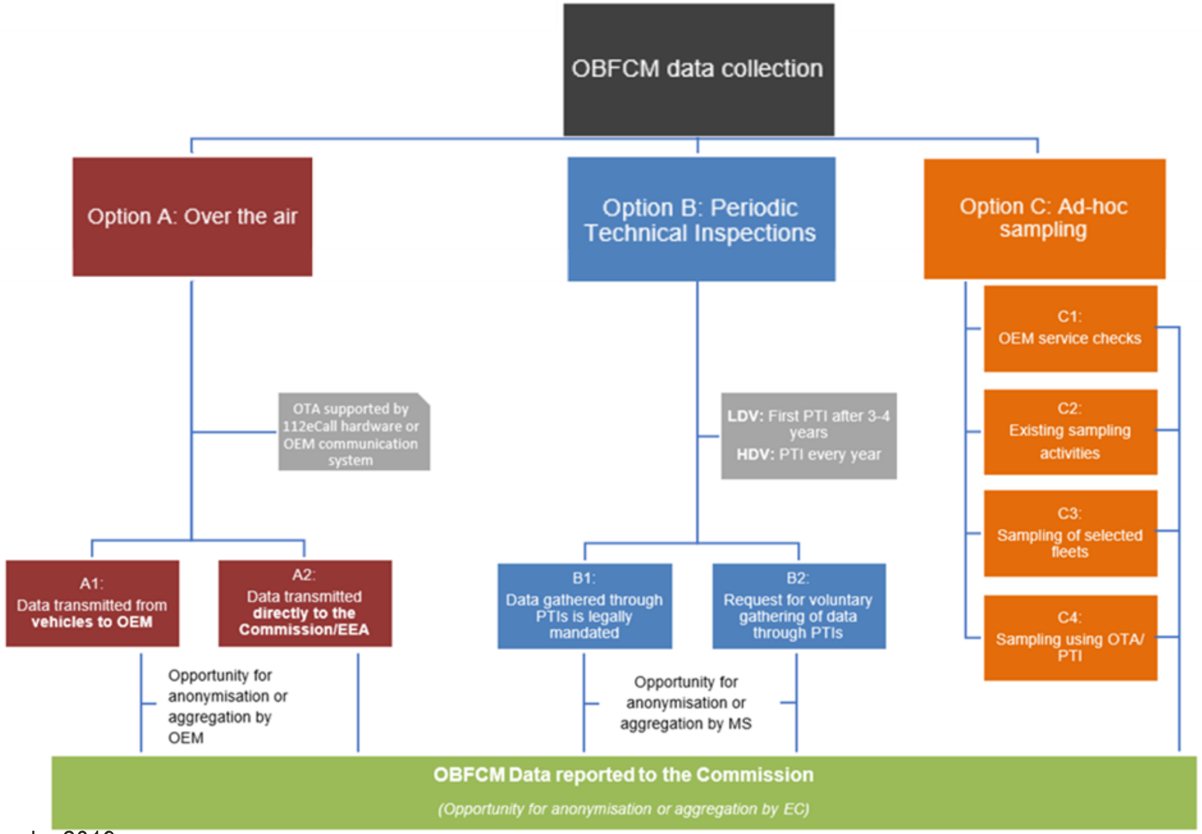
On-board monitoring of tailpipe emissions is capable for improved control of emissions:

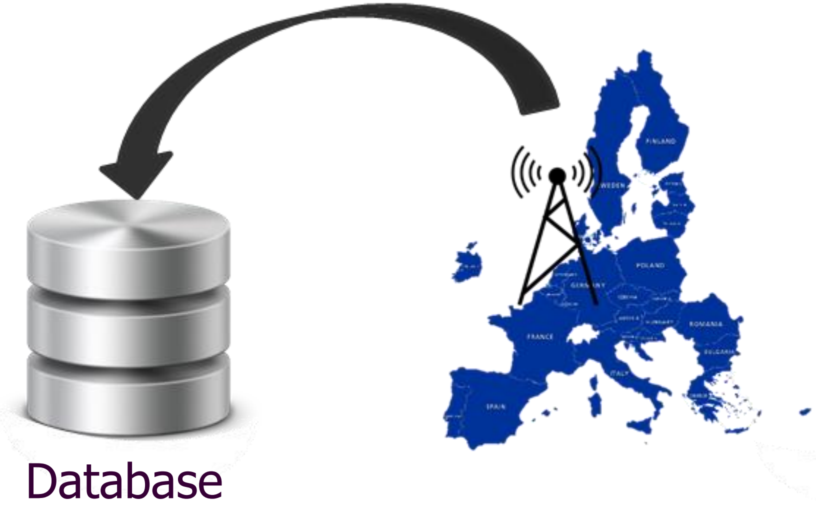
- <u>For individual vehicles</u>
  - Identification and measures for high-emitters
  - Anti-tampering
  - Improved roadworthiness inspections
  - Long-term evaluation of emission performance

- <u>For vehicle families</u>
  - Reduce the burden of In-Service Conformity (ISC) emission testing
  - ISC and Market Surveillance (MaS) vehicle preselection
  - Emission compliance (over NTE limit) and performance monitoring

OBM components

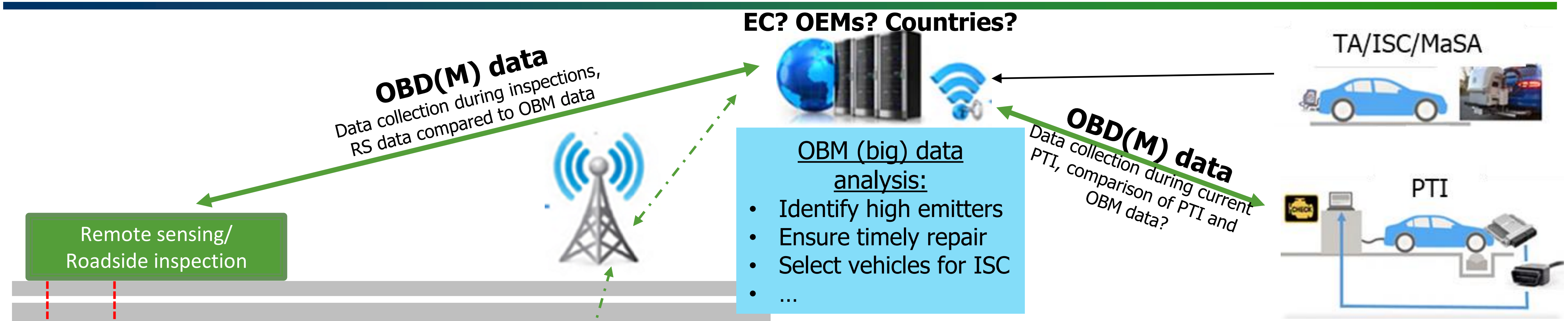
- Tracking of emission-related data:
  - There are Sensors (or are under development) to enable emission monitoring
  - Calculation models and OBD-based algorithms can provide data for those pollutants that cannot be directly measured
- OBM data collection: Based on OBFCM experience

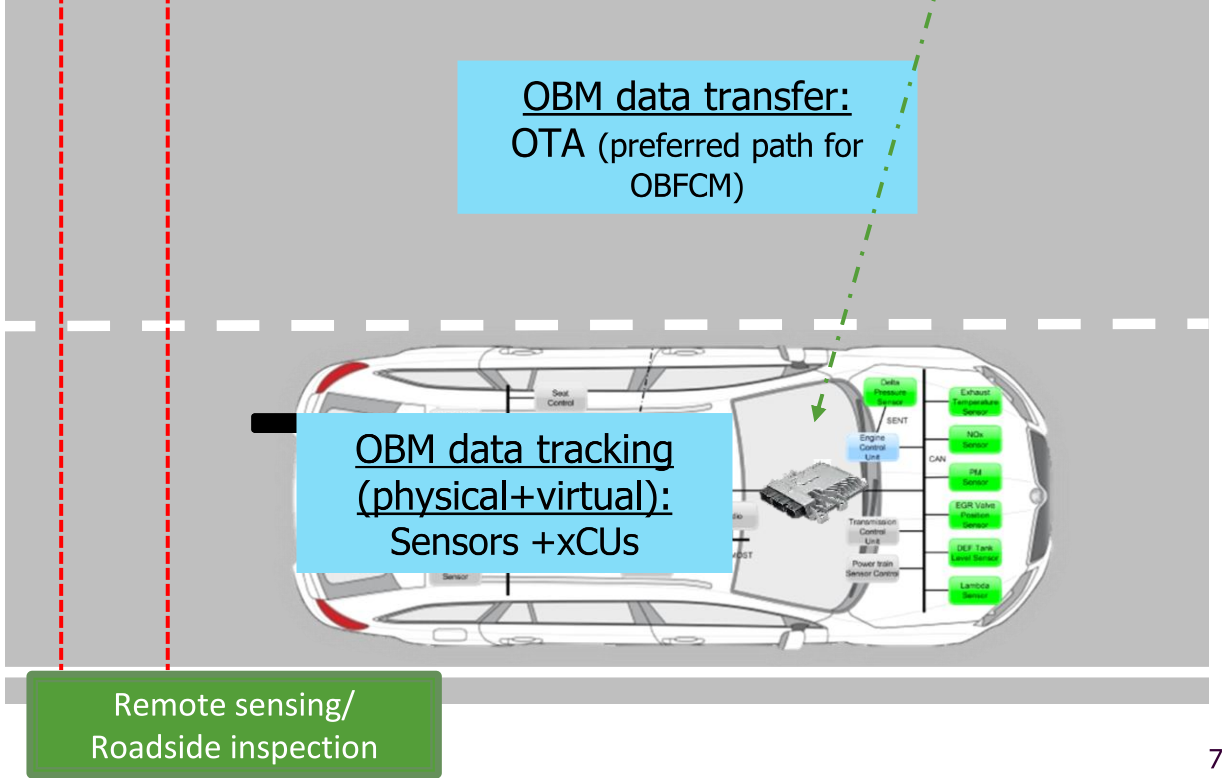




Source: Ricardo, 2019

OBM: part of an overall emissions compliance framework



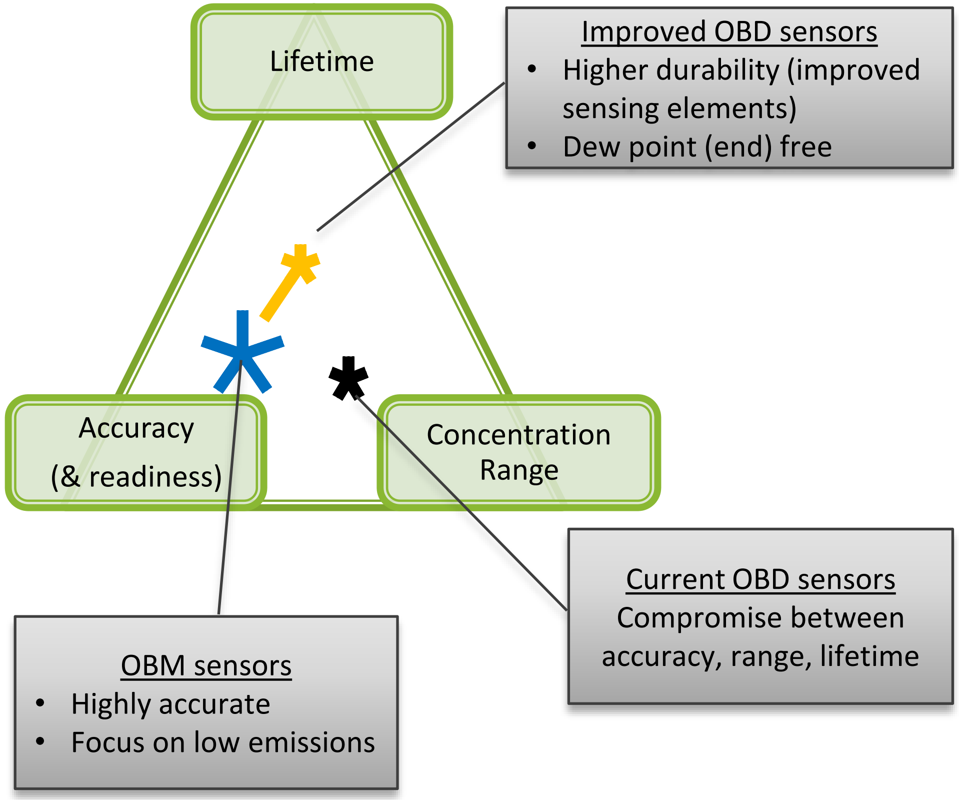


Our main focus in this paper on:

- Available technologies, accuracy, cross-sensitivities, low-emission performance, cold start effect etc. of physical **sensors** (NO_x, NH_3, PM)
- Anti-tampering of **OBM components** (sensor data, communication between xCUs and to the cloud)

Design target for OBM sensors

- **Extended lifetime:**
  - Current focus (due to OBD needs)
  - Significantly affected by readiness i.e. low dew-point temperature for cold-start measurements can reduce lifetime
- **Reduced concentration range:**
  - Different engine-out (for NOx control) and tailpipe sensors (OBM) for increased accuracy
- **Improved accuracy:**
  - In the low range, high accuracy is expected for advanced OBM sensors
  - Correction functions and models can improve accuracy

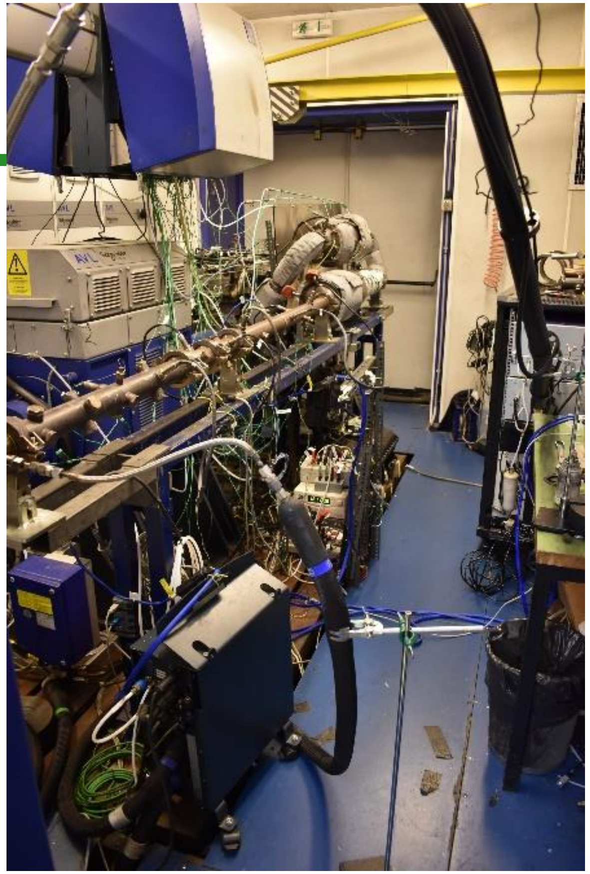


Emission sensing capabilities for OBM

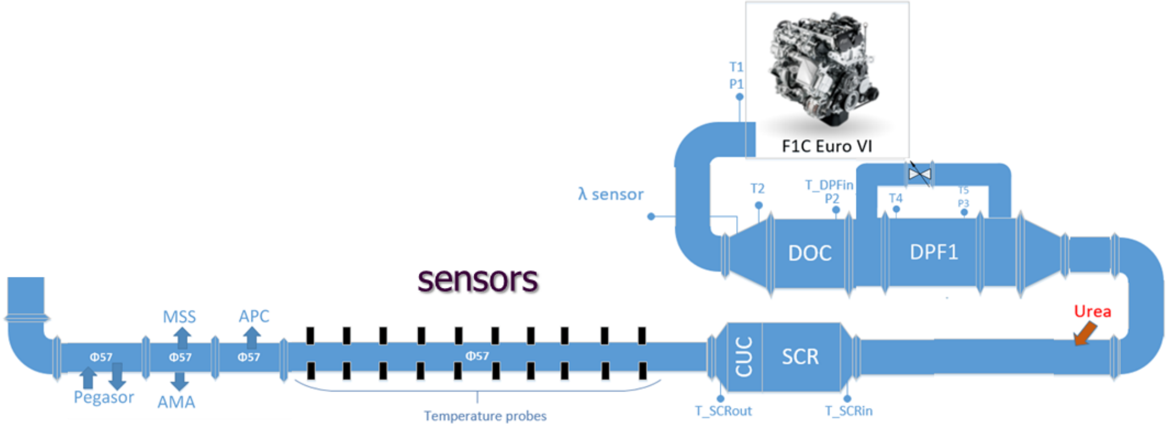
Short-term capabilities	Long-term capabilities
• **NOx:** Amperometric next generation sensors • **NH_3** (diesel): Mixed-potential next gen. sensor • **NH_3** (gasoline): Utilize cross sensitivity of NOx sensor ($\lambda<1$) • **PM(/PN)** (diesel): Based on advanced filter diagnostics → resistive next generation sensors • **(PM/)PN** (gasoline): Based on advanced filter diagnostics → pressure or temperature or OSC-based • **$CO/HC/CH_4$ (+ other species):** Only with model-based monitoring	• **NOx, NH_3** : Improved NOx and NH_3 sensors or multigas sensors: ❖ Accuracy: <±7 ppm or <± 7% ❖ “Dew-point” free + Water resistance improvements ❖ Separate Engine-out and tailpipe sensors • **PM/PN:** Advanced sensor technologies (Resistive, Electrostatic, Diffusion Charge, Laser Induced Incandescence) • **$CO/HC/CH_4$, other species:** no current plans for sensors, limited information for feasibility of sensing technology

Note: For all pollutants, the applicability of the current micro-PEMS, nano-PEMS and SEMS for OBM (long-term) can be examined on the premise of further miniaturization

Test campaigns on EU6 diesel engine



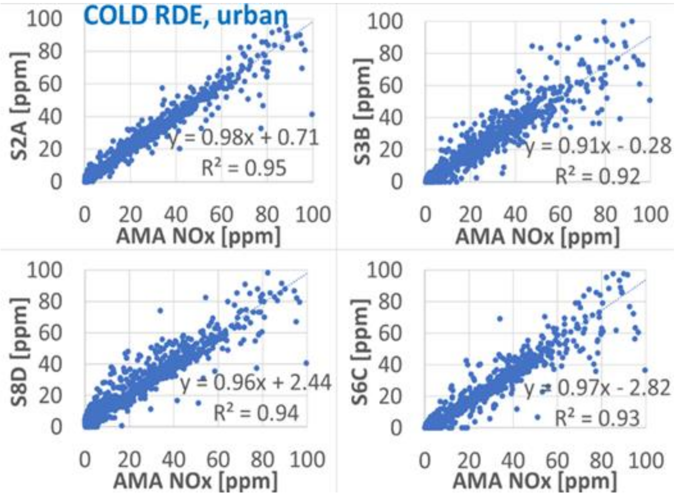
- Examined sensors:
  - Amperometric NOx sensors
  - Mixed-potential NH_3 sensors
  - Resistive PM sensors
  - Electrostatic PM/PN sensor
  - Miniaturized Diffusion Charge PM/PN sensor
- Optimized sensors’ installation (to eliminate shadowing effect, long distance downstream of pipe bends, above horizontal for water protection)
- Reference equipment: AVL AMA i60, FTIR, MSS, EEPS, APC_{10}
- Different campaigns for NOx, NH_3 and PM/PN
- Emissions levels are controlled by control of urea injection, DPF by-pass and adaptation of engine load
- Transient and steady-state measurements in the same set-up
- Transient: WLTC, WHTC, RDE compliant

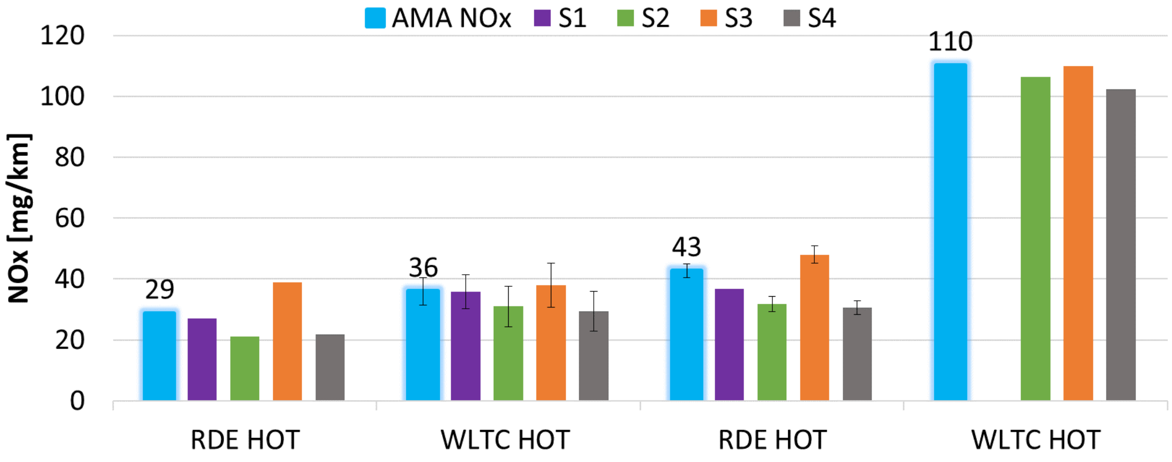


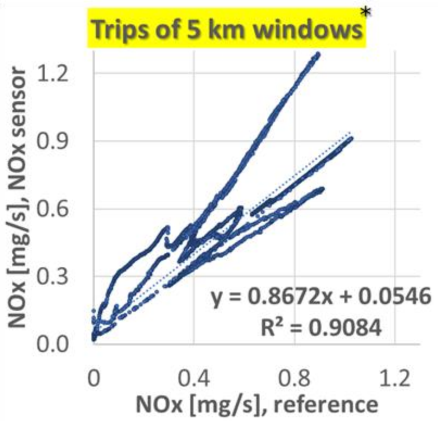
NOx sensors results

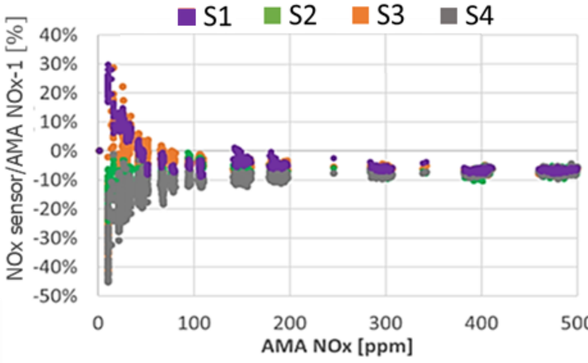
- **Tested sensors:** Current amperometric NOx sensors
- **Cycles:** RDE and WLTC at 30-45 mg/km, down to “near-zero” steady-state
- **Performance**:
  - 10mg/km (±35%) max deviation on transient low NOx emissions for all sensors.
  - 5km moving windows for S3: good correlation, positive deviations observed due to exhaust pressure and NH_3 cross-sensitivities
  - Good accuracy & correlation with reference equipment even at cold conditions (50-100°C, 1s analysis)
  - Steady-state <10 ppm (near-zero emissions): up to ± 40% ppm gain error

Focus on urban cold-start (<100 ppm), 4 different sensors





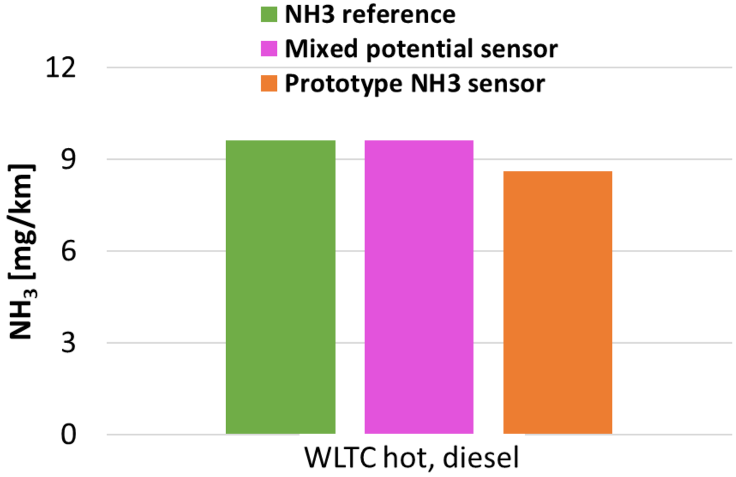


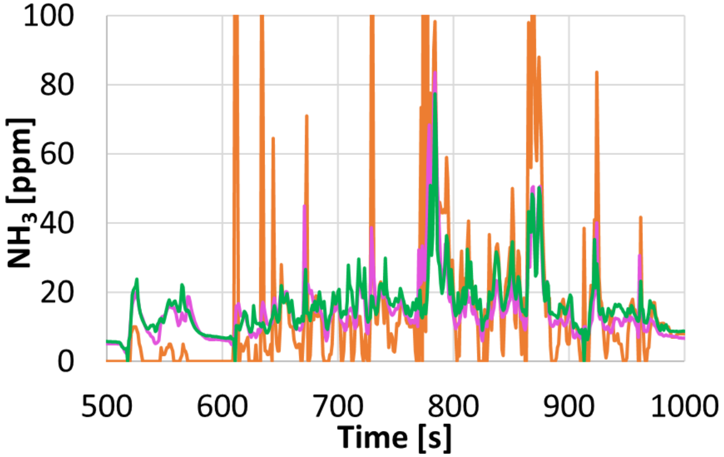


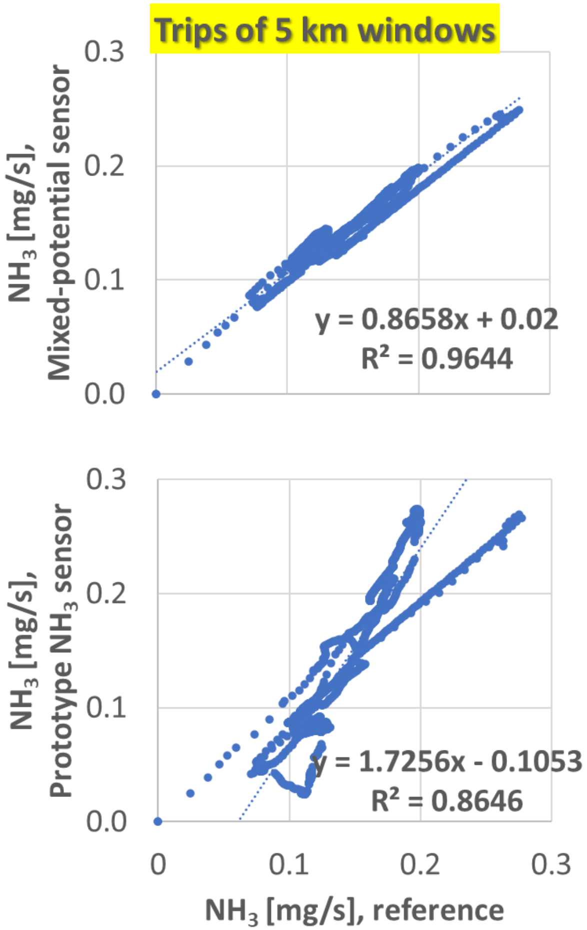
moving average, new window starts every 1 sec (WLTC hot cycle)

NH_3 sensor results

- **Tested sensors:** Currently available mixed-potential, prototype mixed potential
- **Cycles:** WLTC at ~10 mg/km
- **Performance**:
  - Good correlation between reference, current (mixed-potential) and prototype NH_3 sensors
  - Noise on prototype under investigation
  - 5km moving windows:
    - Very good correlation for current mixed-potential
    - Worse behavior (under investigation) for the prototype sensor

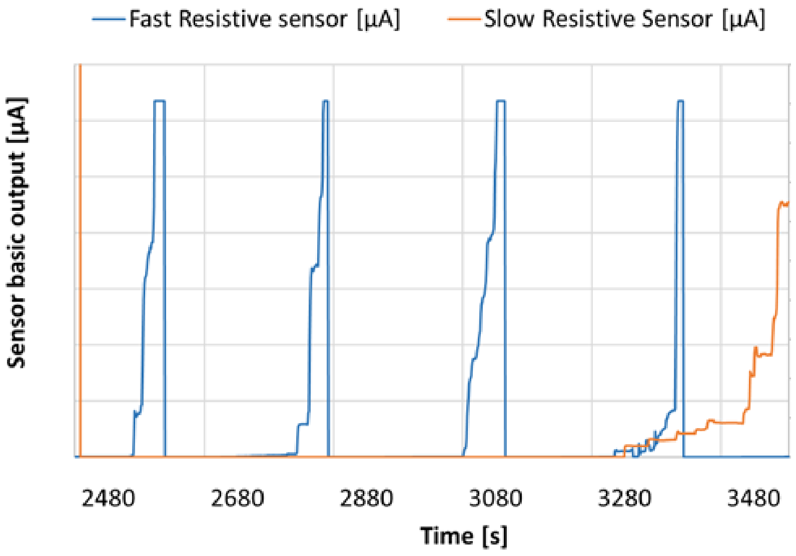


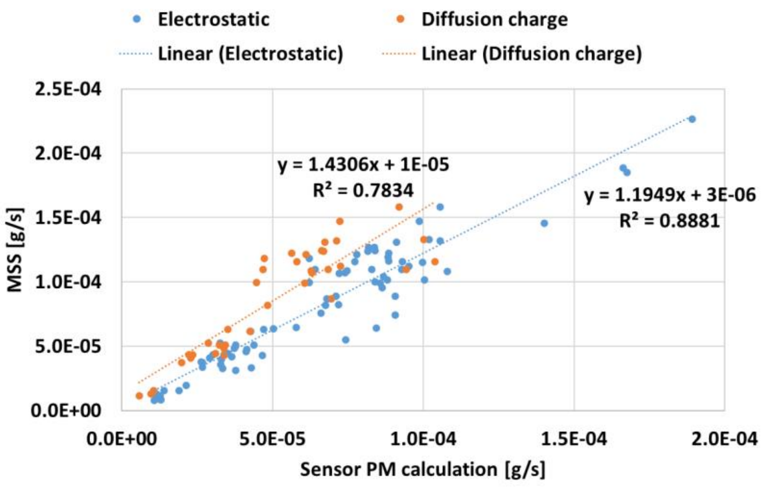


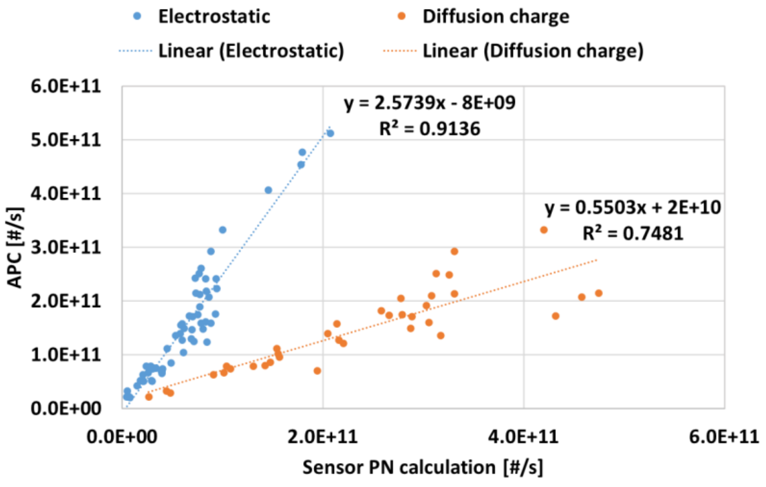


PM/PN sensors results

- **Tested sensors:** Next generation resistive, Electrostatic, DC miniaturized
- **Cycles:** RDE and WLTC at 3-4.5 mg/km
- **Performance**:
  - Fast resistive compared to currently available (slow) → 4x more loadings
  - Electrostatic PM/PN and miniaturized DC (less data available):
    - PM → Good correlation with reference equipment (MSS), similar regression models for both technologies
    - PN → Good correlation with reference equipment (APC_{10}), different slopes of the regression models





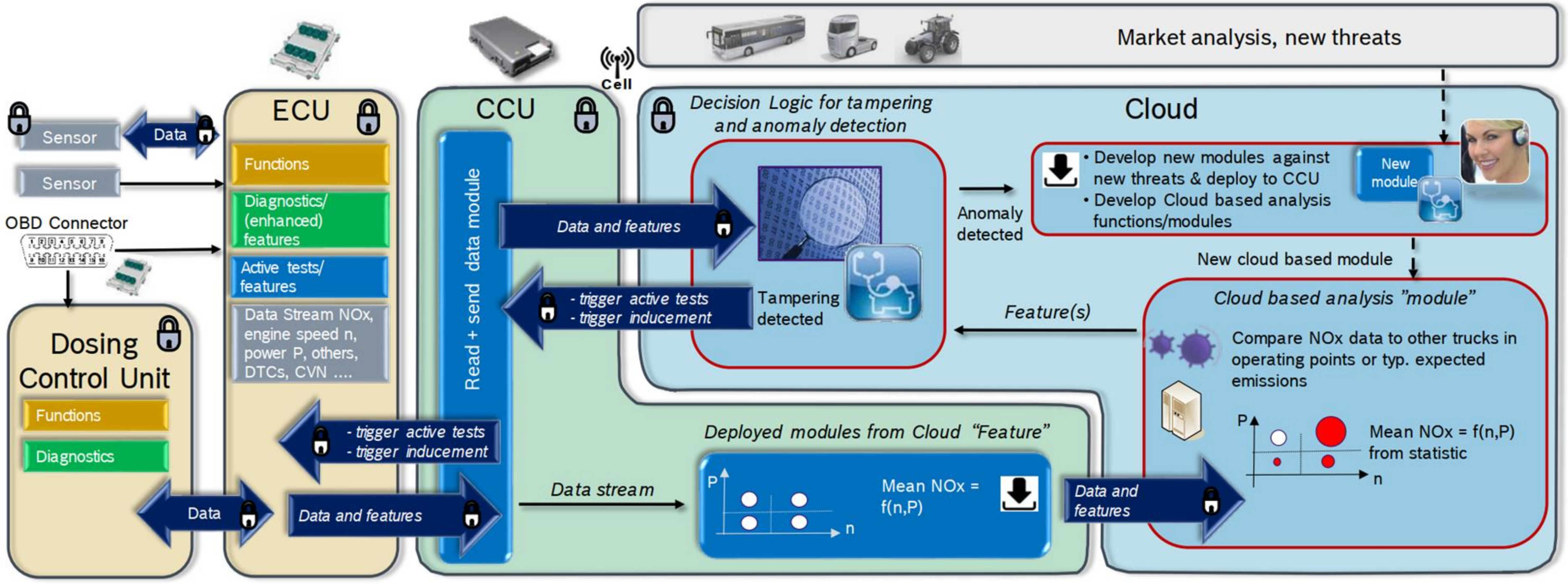


Note: Fluxes for electrostatic were calculated from sensor signal (nA) using a linear correction based on low and moderate PM emissions for WLTC and RDE cycles

Anti-tampering of OBM components

- Tamper-proof OBM components are prerequisite for valid OBM
- OBD is not optimized to diagnose tampering
- The challenge is to ensure that sensor data are not manipulated
- This can be realized via 2 approaches (based on DIAS H2020 project):
  - Advanced in-vehicle security techniques:
    - **Communication security** between Sensor Control Unit (SCU) and Engine Control Unit (ECU)
    - **Component security** against installation of emulators (i.e. NOx sensor emulator)
  - ECU - CCU - Cloud-based distributed **overall diagnostic system (ODS)**

Overall Diagnostic System (ODS)
Example for SCR tampering



Our concept: combining the cloud capabilities with the engine management system and after-treatment controls and sensors

Summary and next steps

- On-board monitoring of tailpipe emissions can be established for improved control of emissions
- Main focus: technical feasibility of sensors and anti-tampering provisions for sensors and OBM components
- Sensors are there or are under development to enable emission monitoring
- Results from dedicated sensor test campaigns (diesel engine) provided promising results for NOx, NH_3 and PM/PN sensors. Tests on prototypes and on gasoline engine are on-going.
- Anti-tampering solutions are currently investigated by DIAS project for data integrity
- Next steps:
  - Completion of gasoline tests and analysis
  - Multigas (NOx, NH_3, O_2) sensors
  - Additional prototypes for PM/PN
  - Demonstration of anti-tampering solutions

Thank you for your attention

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