SCIENCE
PASSION
TECHNOLOGY

Advancements in Remote Emission Sensing Instrumentation and Point Sampling

Martin Kupper | ERMES Plenary 2024

13.11.2024

www.ems.tugraz.at | martin.kupper@tugraz.at

Institute of Electrical Measurement and Sensor Systems Sensor Systems and Sensor Physics Group

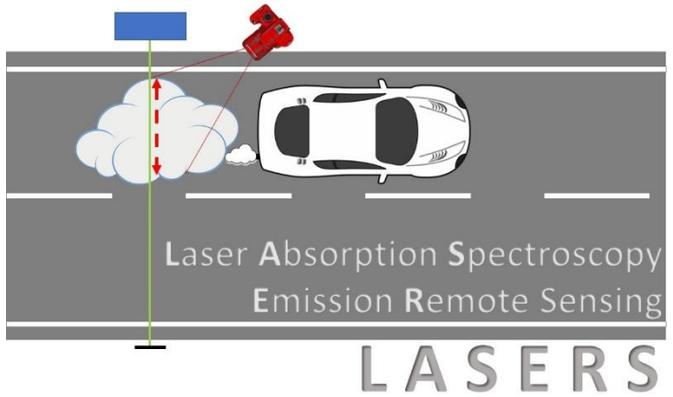
- Part of Institute of Electrical Measurement and Sensor Systems (EMS)
- Head of Group: Alexander Bergmann
- Currently ~ 25 Employees

- Research Areas:
  - Measurement of Traffic Related Emissions and Environmental Sensors
  - Photonic Sensors
  - Miniaturized IC-Sensor Technology and Silicon Photonics
  - Structured Matter Based Sensing

https://www.tugraz.at/en/institutes/ems/research/sensor-systems-and-sensor-physics-group/

Content

- Laser Spectroscopy for Remote Emission Sensing
  - TDLAS Approach
  - Optical Gas Imaging Technique
  - Current status
- Point Sampling
  - Approach
  - Aerosol Instruments
  - Results Overview



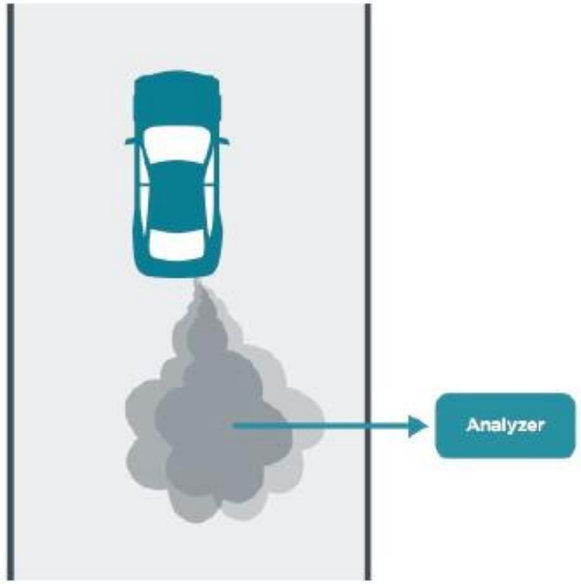
LENS L-vehicles Emissions and Noise mitigation Solutions

CARES
CITY AIR REMOTE EMISSION SENSING

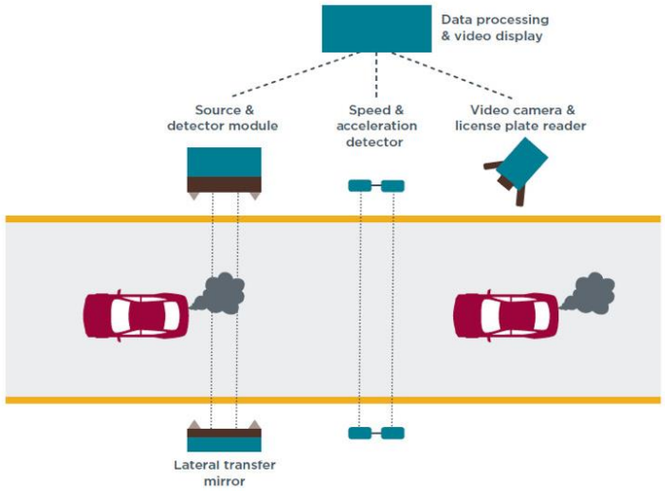
Introduction
Overview Techniques

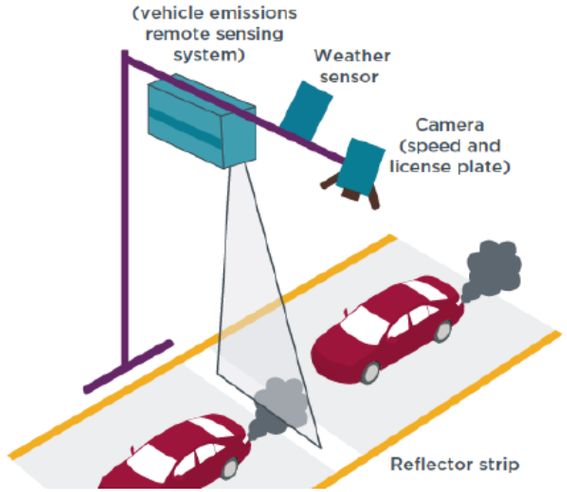
- Non-intrusive techniques
- Large scale screening of RDE in traffic
- Identification of high-emitters
- Point Sampling
  - + particle measurement
  - - capture rate
- Determination of fuel-based emission factors (EF)

$$EF_{\frac{pollutant}{kg\ fuel}} = \frac{\int c_{pollutant}\, dt}{\int c_{CO_2}\, dt} \cdot ER_{\frac{CO_2}{fuel}}$$



Point Sampling (PS)

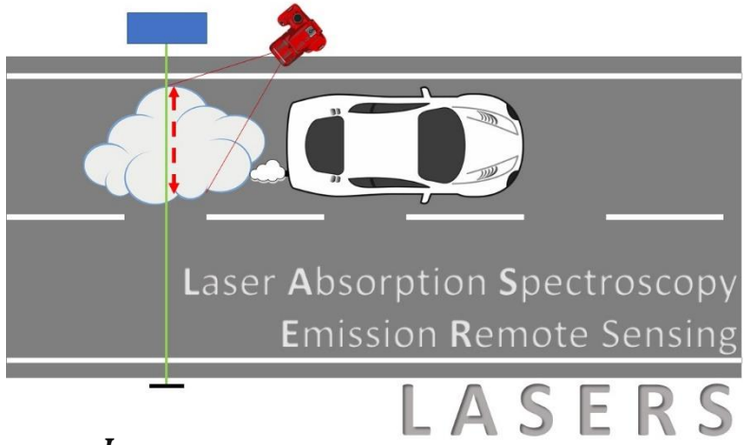




Remote Emission Sensing (RES)

Remote Emission Sensing

Remote Emission Sensing
LASERS Project



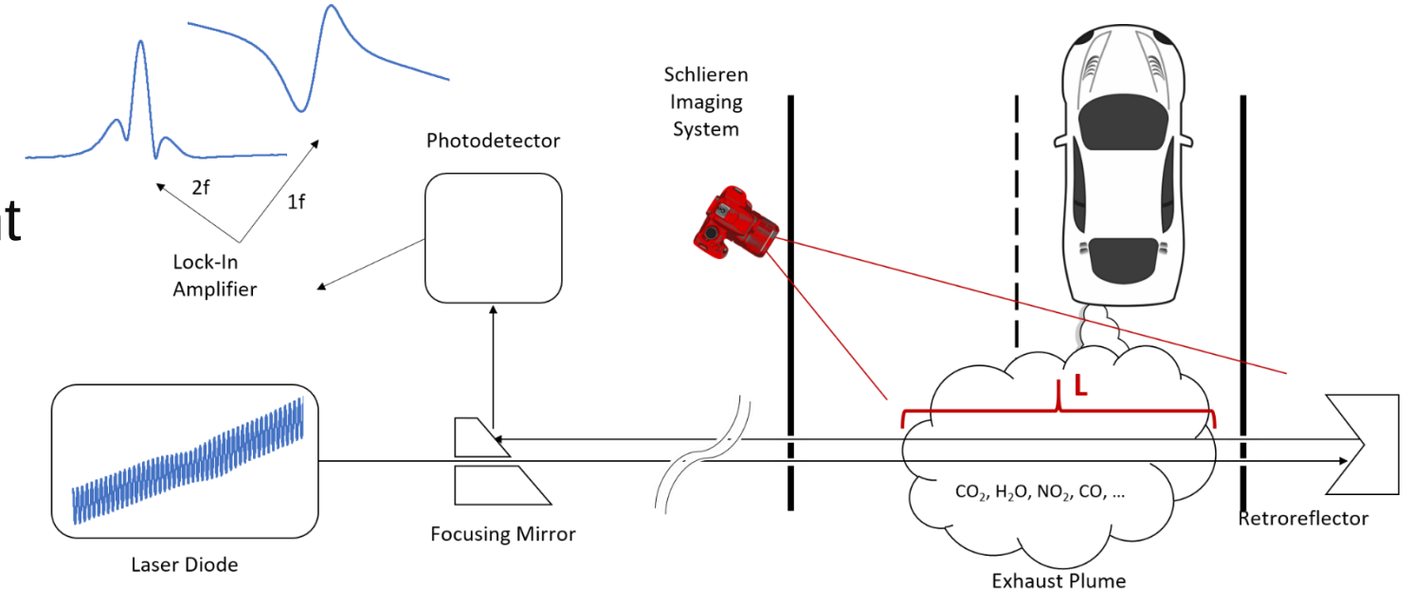
Research Topics

- Laser based spectroscopic system for RES
- Optical gas imaging techniques (OGIT)

$$T = \frac{I}{I_0} = e^{-\epsilon c L}$$

Goals

- Direct concentration measurement
- Imaging of exhaust plumes
- Prove monitoring approach



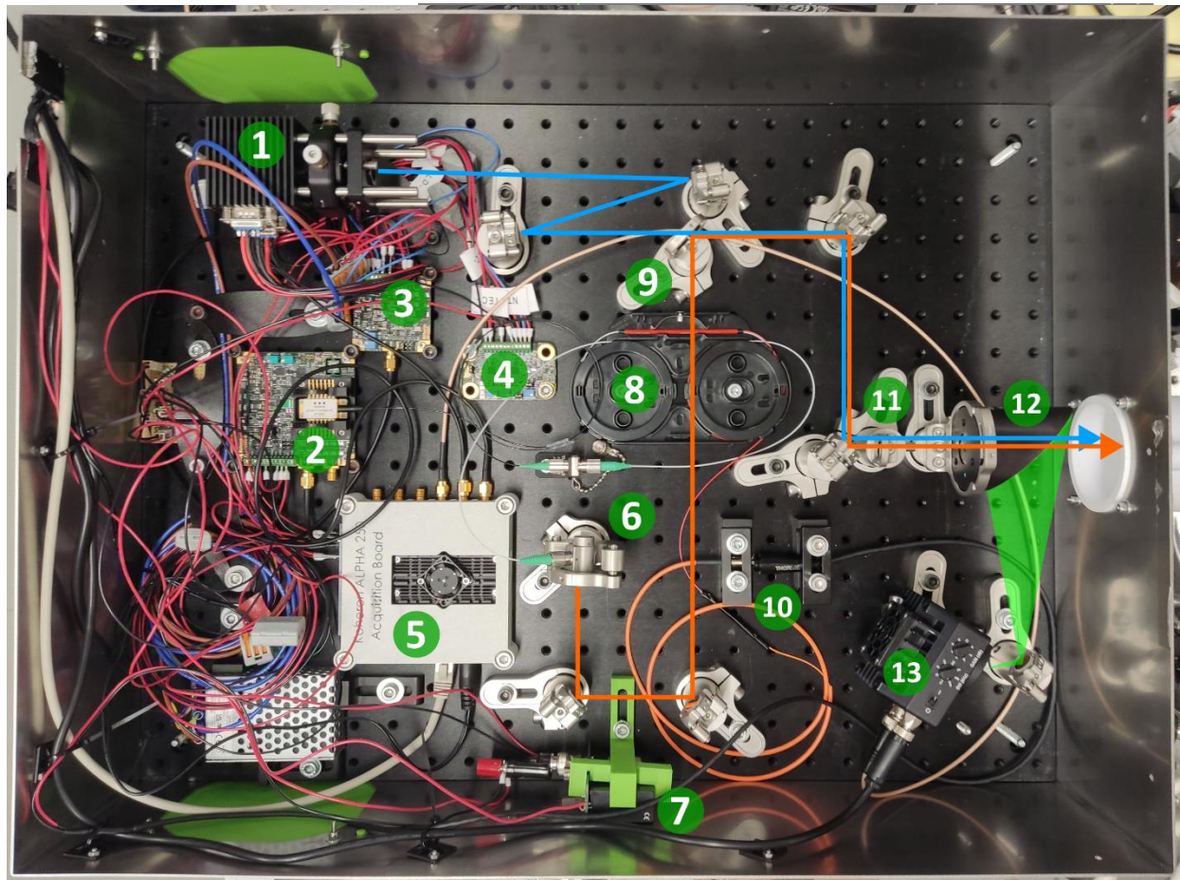
The developments in the LASERS project are part of the PhD-thesis of Paul Schaffer and Hafiz Hashim Imtiaz.

Remote Emission Sensing TDLAS Instrument

Spectroscopic Approach

- 2f WMS with 10 m open path
- Multiple laser sources
  - Currently CO_2 and NO_2
  - NO in pipeline
- TDLAS is a calibration free method
- 1f/2f analysis allows robust measurement
- Assessed sensitivities in ppb regieme

1. 3421 nm ICL (NO_2)
2. 2004 nm DFB Laser + Driver (CO_2)
3. ICL Current Controller
4. ICL Temperature Controller
5. DAQ System
6. Reflective Collimator
7. Alignment Laser Driver
8. Wavelength Division Multiplexer
9. Bandpass Filter
10. Alignment Laser
11. Pinhole
12. Off-Axis Parabolic Mirror
13. Photodetector

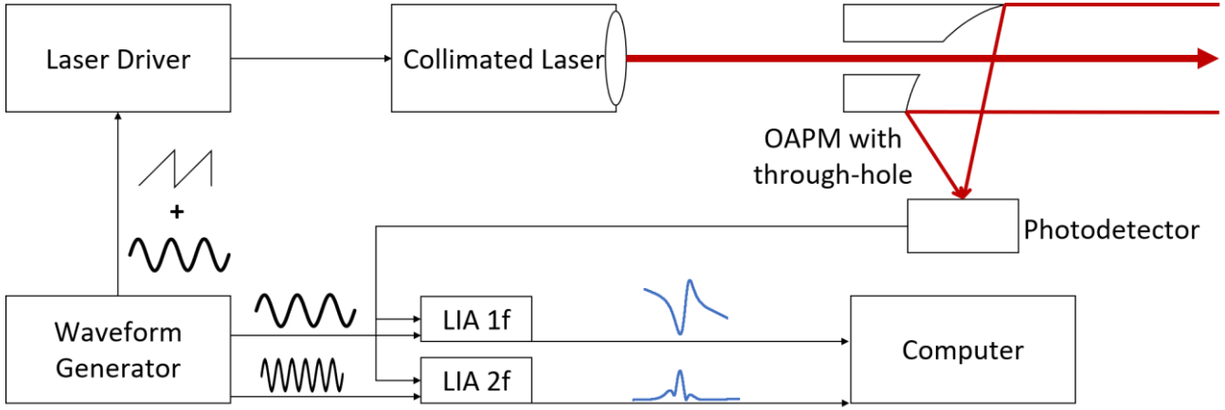


[Schaffer, P.; Imtiaz, H. H.; Lang, B.; Kupper, M.; Bergmann, A. Simulations of a NIR TDLAS Sensor for Stand-Off Measurement of Carbon Dioxide for Remote Emission Sensing. In: Proceedings of 25th International Transport and Air Pollution Conference, Vol 1, Gothenburg, 25-26 September 2023, 137-142. https://publications.jrc.ec.europa.eu/repository/handle/JRC136825]

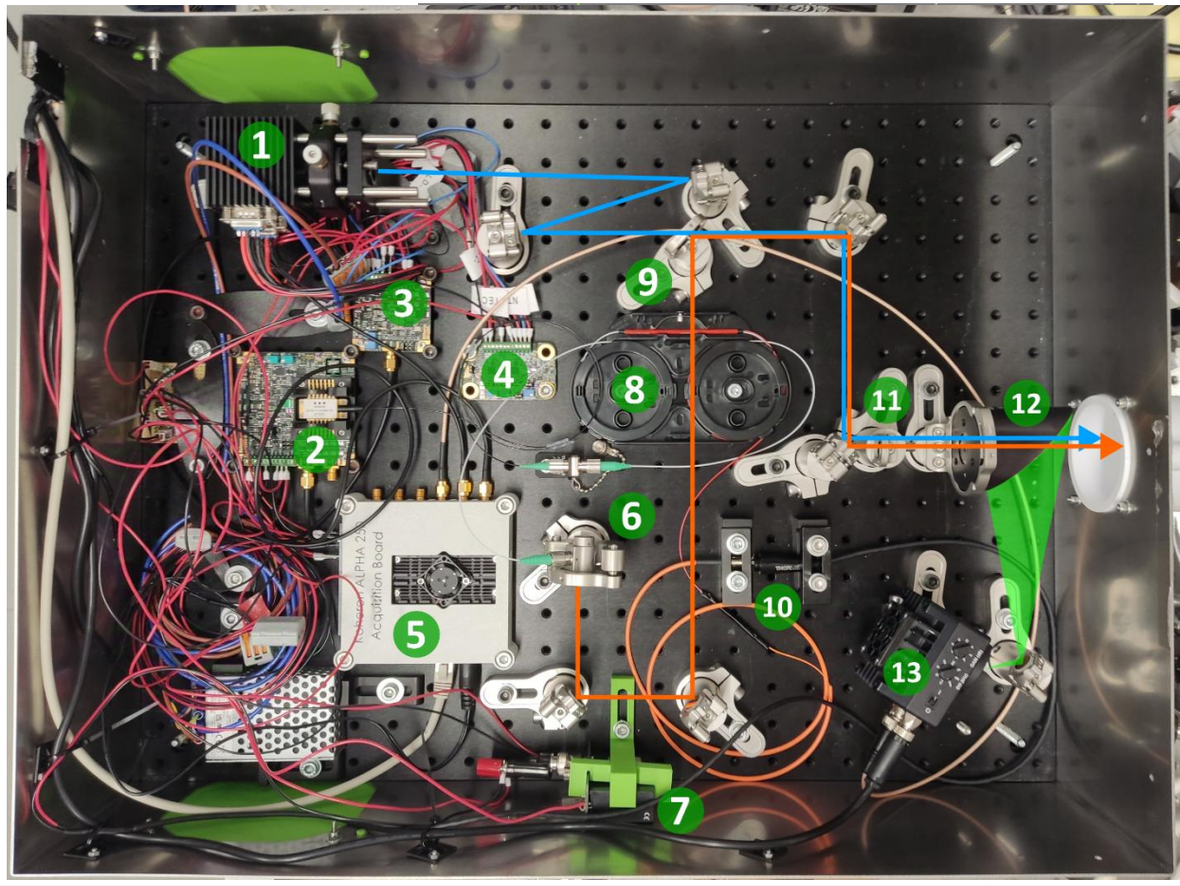
Remote Emission Sensing TDLAS Instrument

Spectroscopic Approach

- 2f WMS with 10 m open path
- Multiple laser sources
  - Currently CO_2 and NO_2
  - NO in pipeline



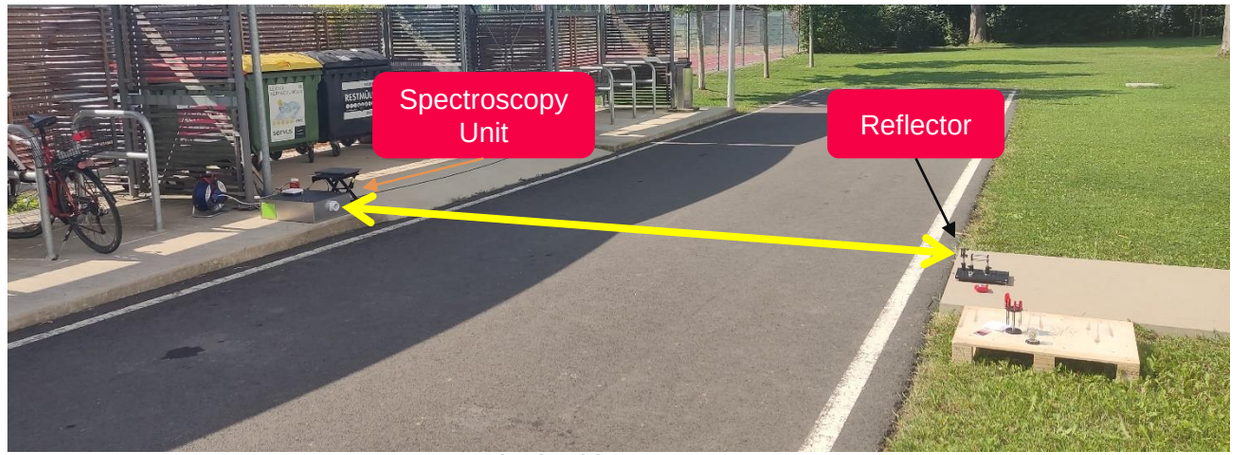
1. 3421 nm ICL (NO_2)
2. 2004 nm DFB Laser + Driver (CO_2)
3. ICL Current Controller
4. ICL Temperature Controller
5. DAQ System
6. Reflective Collimator
7. Alignment Laser Driver
8. Wavelength Division Multiplexer
9. Bandpass Filter
10. Alignment Laser
11. Pinhole
12. Off-Axis Parabolic Mirror
13. Photodetector



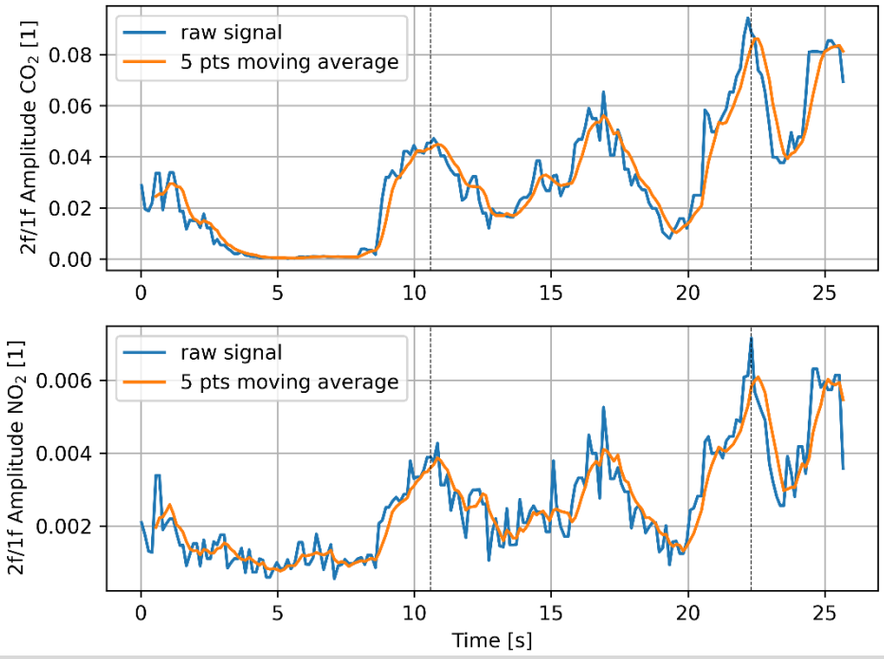
[Schaffer, P.; Imtiaz, H. H.; Lang, B.; Kupper, M.; Bergmann, A. Simulations of a NIR TDLAS Sensor for Stand-Off Measurement of Carbon Dioxide for Remote Emission Sensing. In: Proceedings of 25th International Transport and Air Pollution Conference, Vol 1, Gothenburg, 25-26 September 2023, 137-142. https://publications.jrc.ec.europa.eu/repository/handle/JRC136825]

Remote Emission Sensing TDLAS Instrument

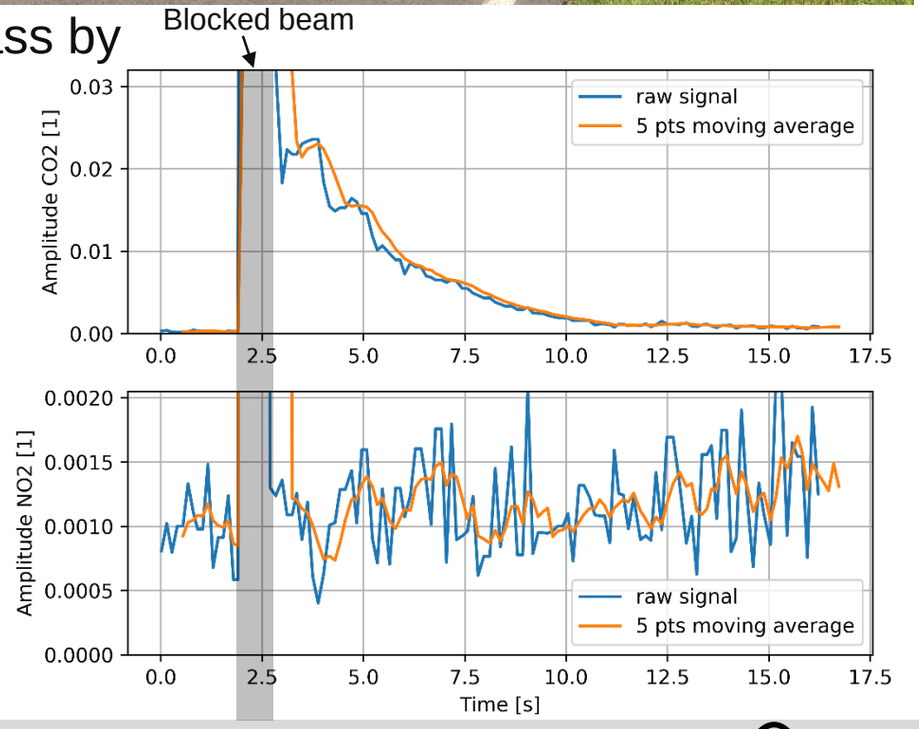
- Outdoor system validation
  - EURO 6 Diesel



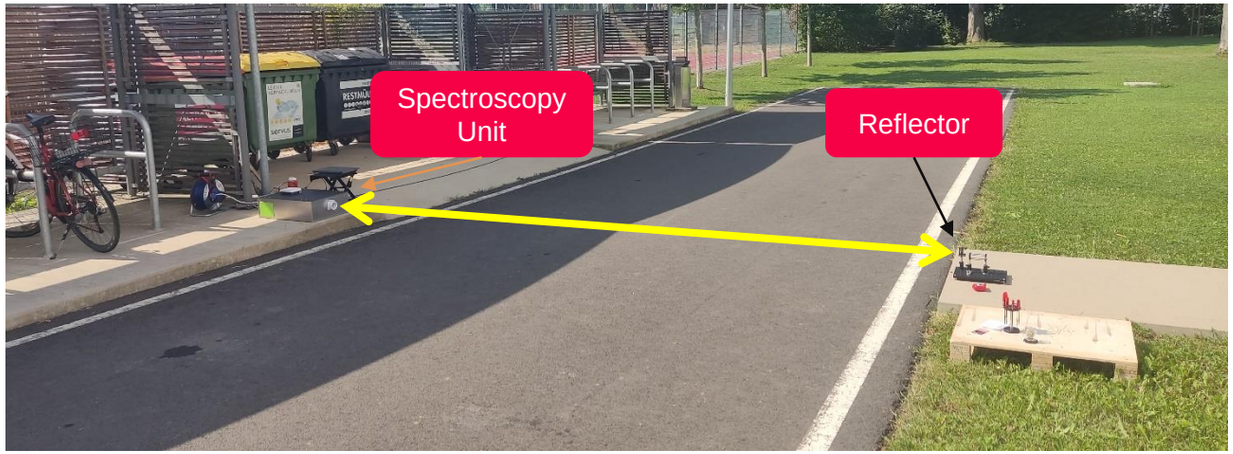
Tests in idle



Pass by



Remote Emission Sensing TDLAS Instrument

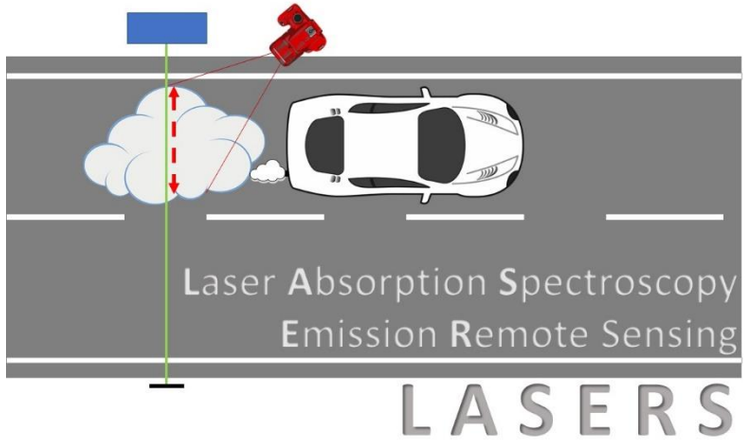


- Outdoor system validation
  - EURO 6 Diesel

- Currently improving the fit of absorption signal
  - TDLAS is an absorption measurement
  - Allows assignment of concentration values

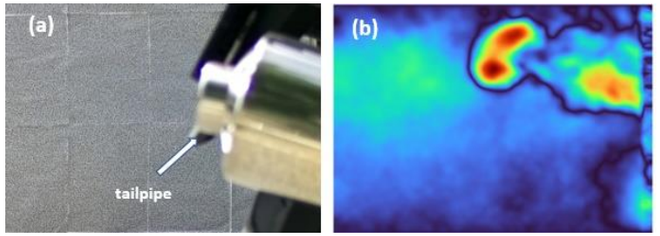
- Comparison to PEMS planned early 2025

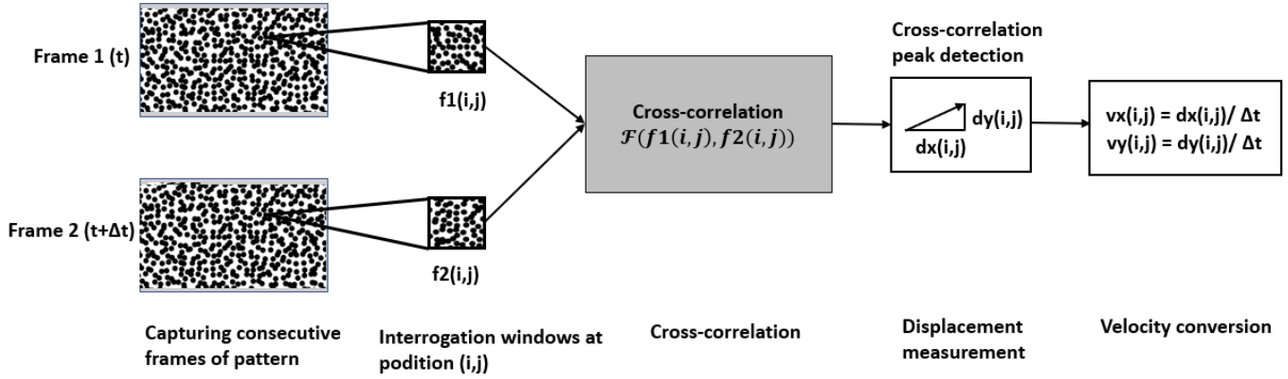
Remote Emission Sensing
Gas Imaging Technique



Gas Schlieren Imaging Sensor (GSIS)

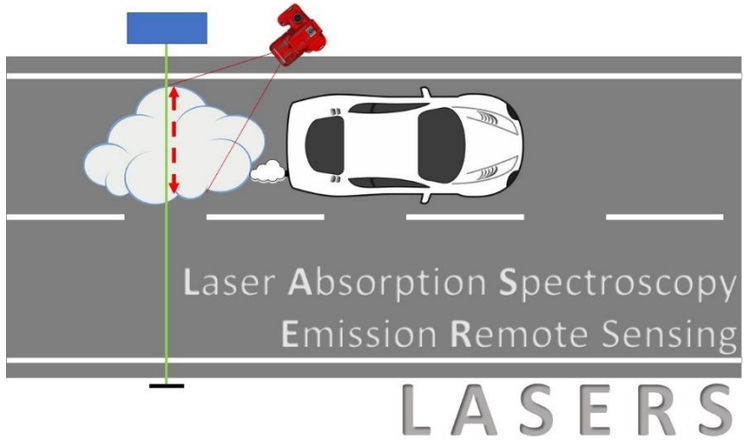
- Gases cause gradient in refractive index
- Subtract two consecutive images of structured background
- Image processing allows
  - visualization of distortion
  - determination of density field
  - estimation of geometric size





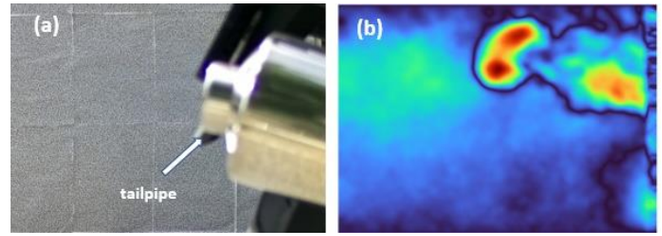
[Imtiaz, H. H.; Liu, Y.; Schaffer, P..; Kupper, M.; Bergmann, A. *Displacement and density fields construction of L-vehicles exhaust plumes using Windowed Fourier Transform based Graphical Phase Analysis and Optical Flow and comparison with state-of-the-art*, **SAE manuscript in preparation**]

Remote Emission Sensing
Gas Imaging Technique



Gas Schlieren Imaging Sensor (GSIS)

- Assessment by
  - evaluation of three algorithms with ground truth data
  - assign displacement to concentration
  - lab experiments compared to CFD



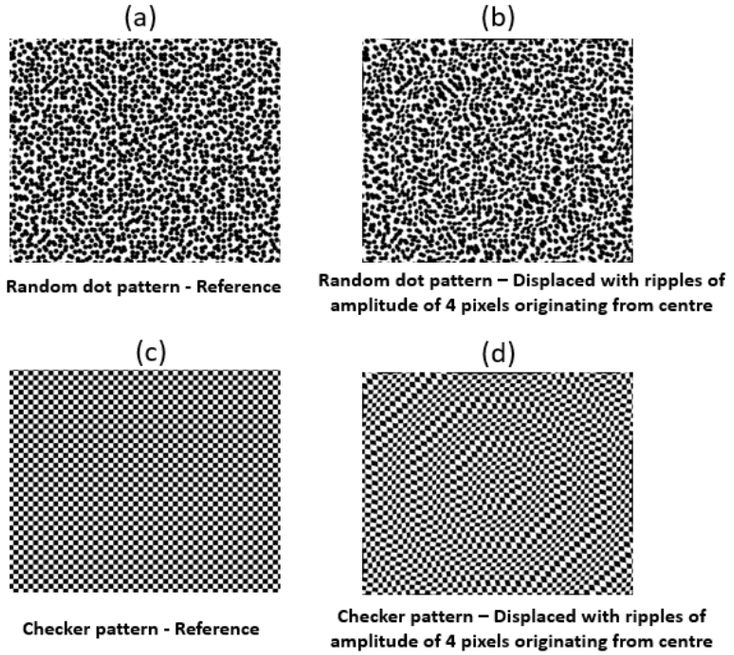
Publication soon

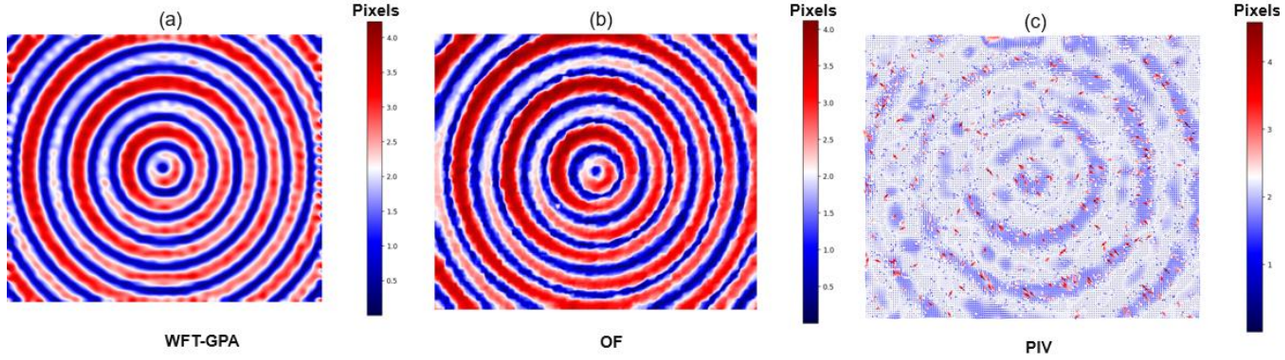
[Imtiaz, H. H.; Liu, Y.; Schaffer, P..; Kupper, M.; Bergmann, A. *Displacement and density fields construction of L-vehicles exhaust plumes using Windowed Fourier Transform based Graphical Phase Analysis and Optical Flow and comparison with state-of-the-art*, **SAE manuscript in preparation**]

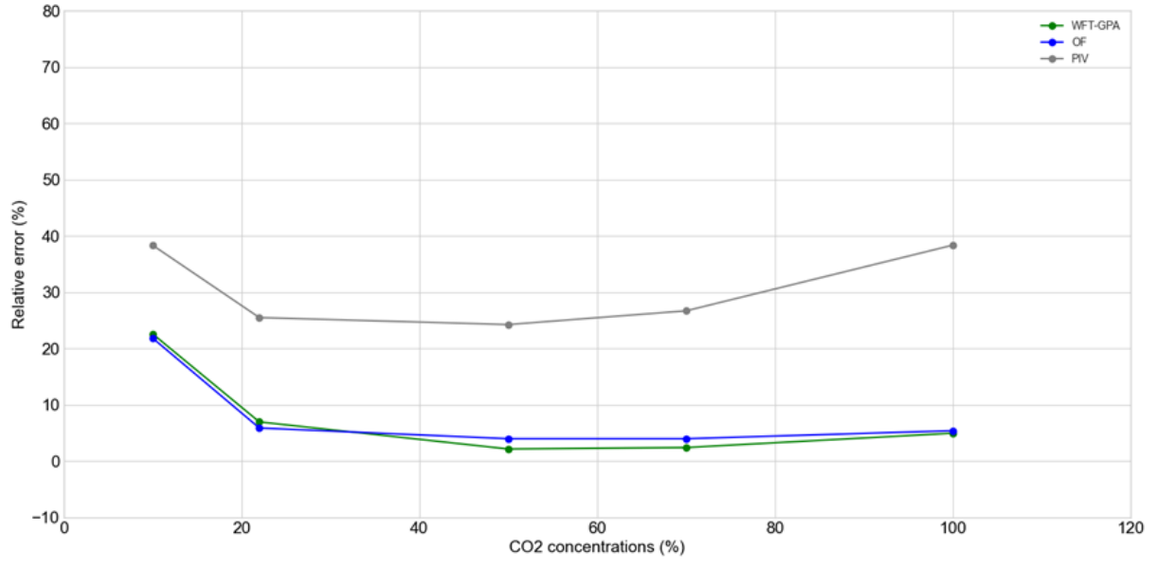
Remote Emission Sensing
Gas Imaging Technique

Gas Schlieren Imaging Sensor (GSIS)

- Assessment by
  - evaluation of three algorithms with ground truth data
  - assign displacement to concentration
  - lab experiments compared to CFD



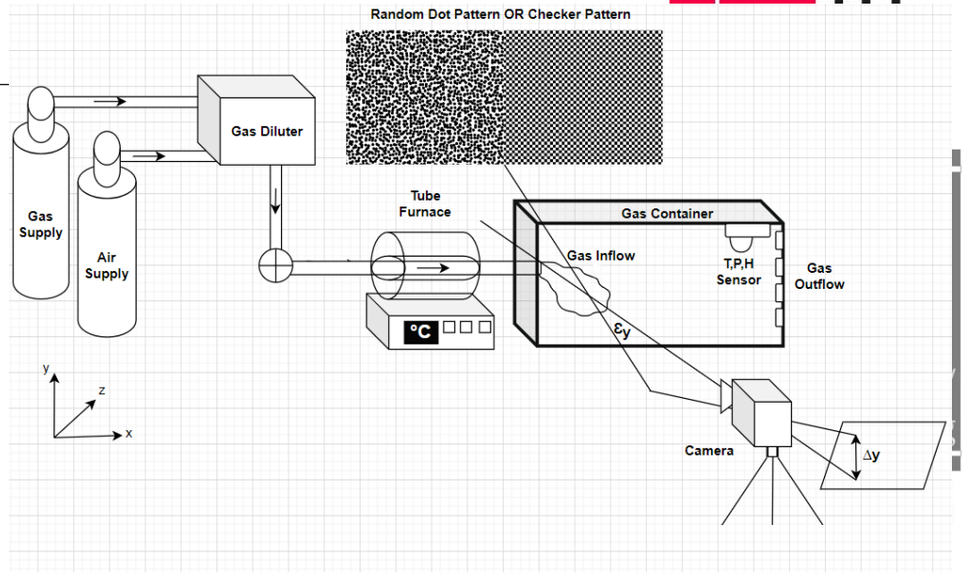




Publication soon

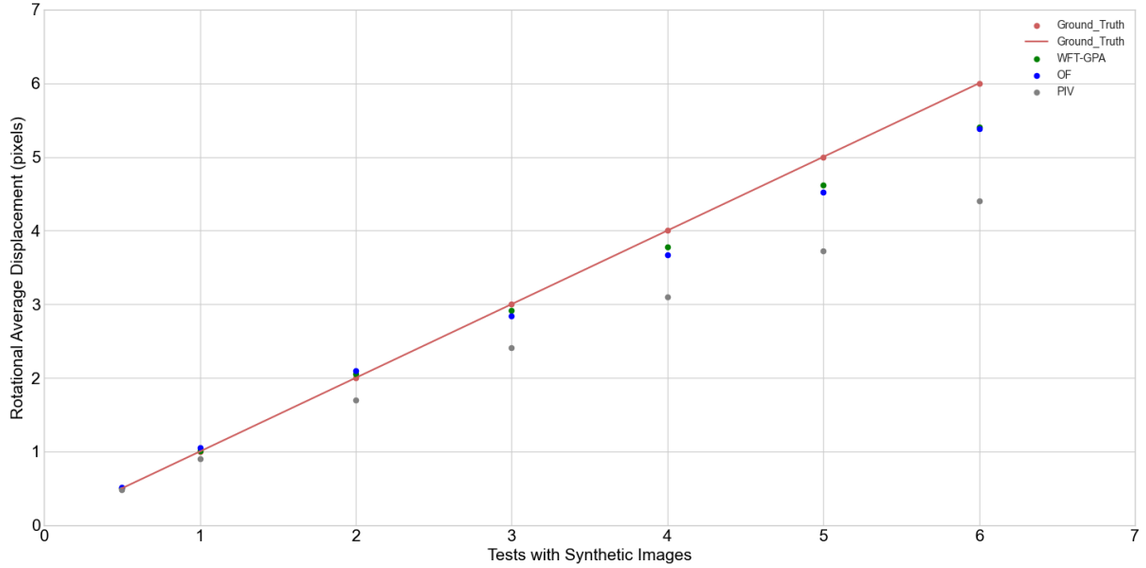
[Imtiaz, H. H.; Liu, Y.; Schaffer, P..; Kupper, M.; Bergmann, A. *Displacement and density fields construction of L-vehicles exhaust plumes using Windowed Fourier Transform based Graphical Phase Analysis and Optical Flow and comparison with state-of-the-art*, **SAE manuscript in preparation**]

Remote Emission Sensing
Gas Imaging Technique



Gas Schlieren Imaging Sensor (GSIS)

- Assessment by
  - evaluation of three algorithms with ground truth data
  - assign displacement to concentration
  - lab experiments compared to CFD

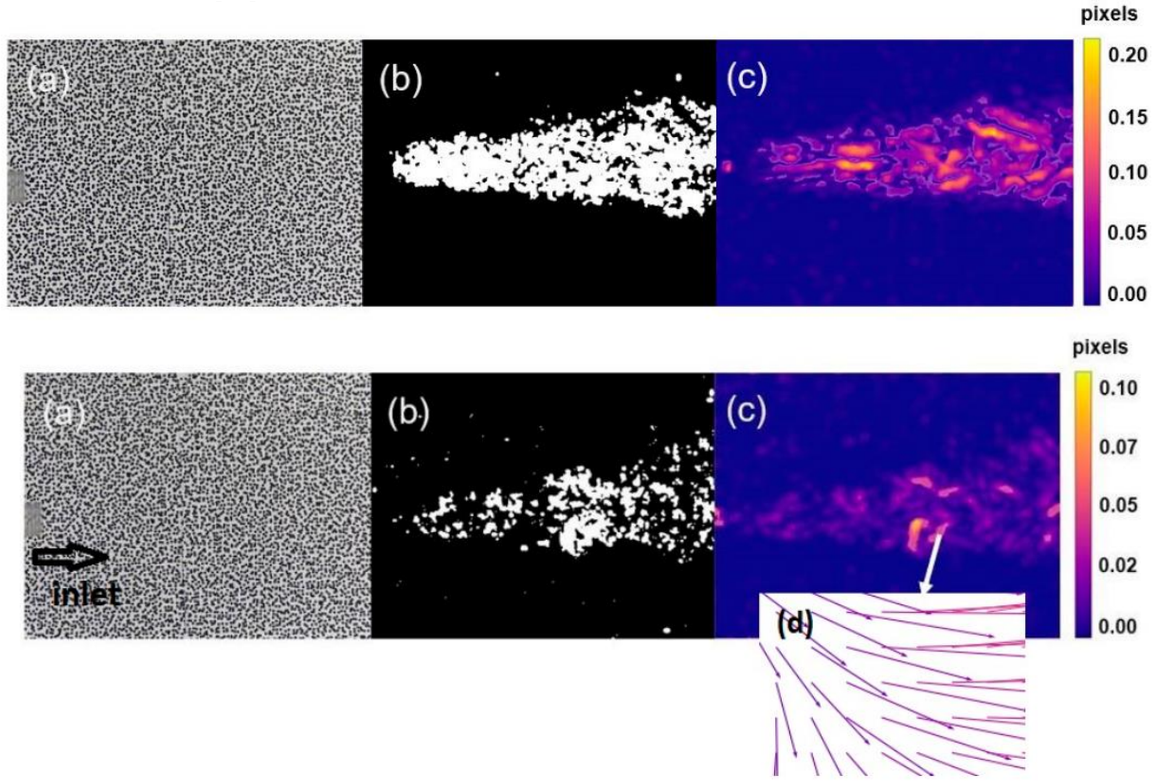


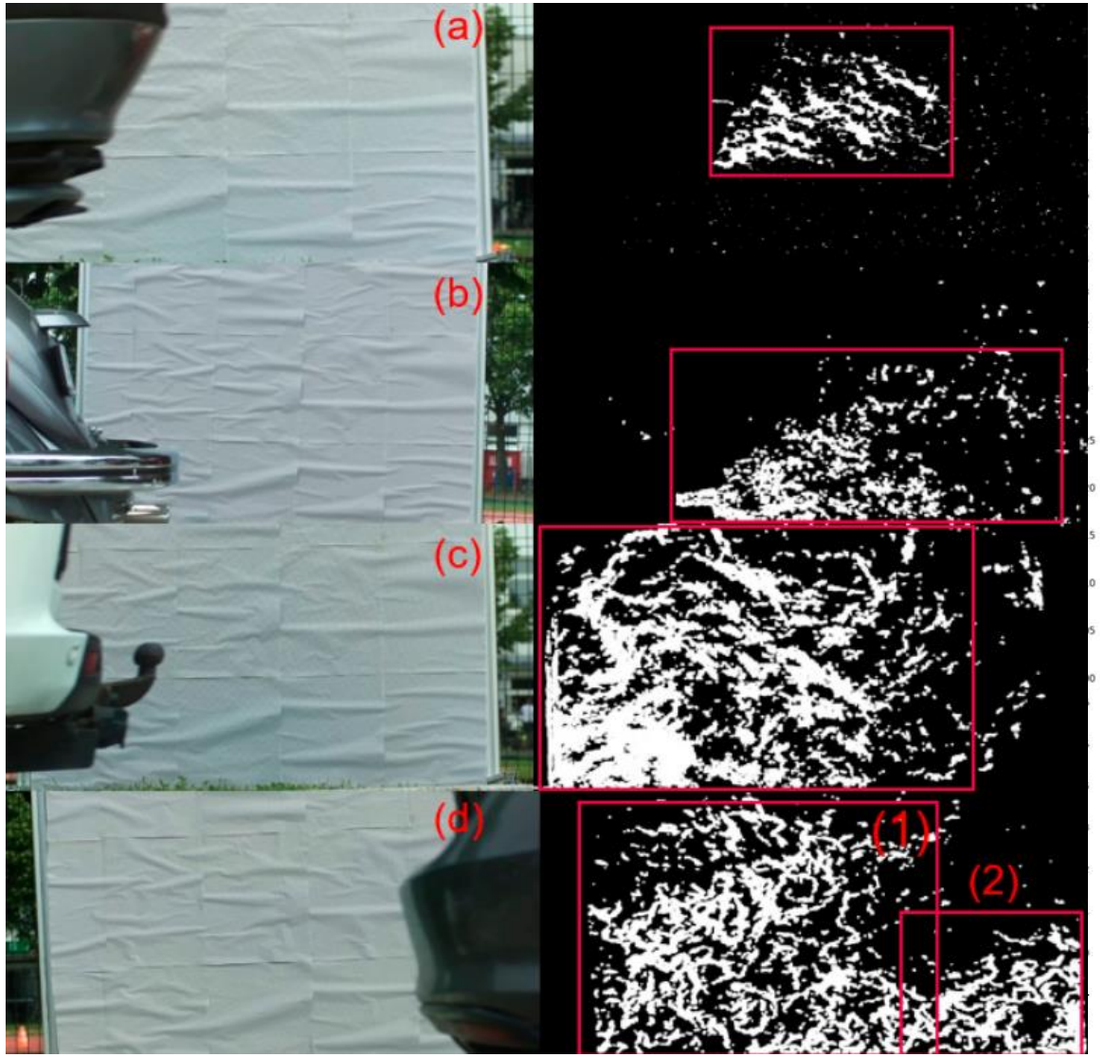
Publication soon

[Imtiaz, H. H.; Liu, Y.; Schaffer, P..; Kupper, M.; Bergmann, A. *Displacement and density fields construction of L-vehicles exhaust plumes using Windowed Fourier Transform based Graphical Phase Analysis and Optical Flow and comparison with state-of-the-art*, **SAE manuscript in preparation**]

Remote Emission Sensing Gas Imaging Technique

- GSIS application in traffic

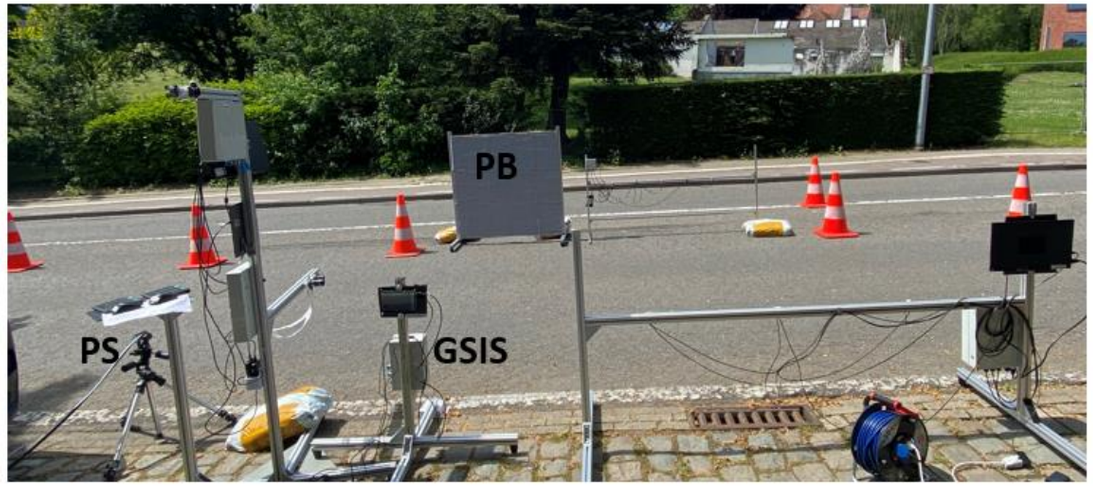


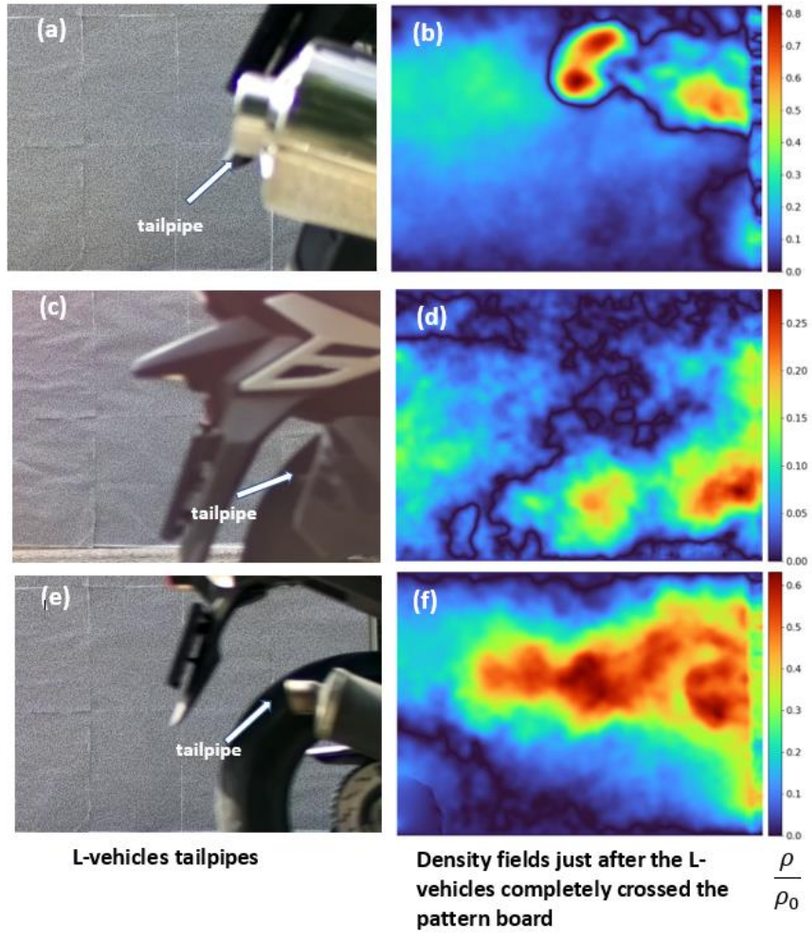


[Imtiaz, H. H., Schaffer, P., Liu, Y., Hesse, P., Bergmann, A., & Kupper, M. (2024). Qualitative and Quantitative Analyses of Automotive Exhaust Plumes for Remote Emission Sensing Application Using Gas Schlieren Imaging Sensor System. *Atmosphere*, *15*(9), 1023. https://doi.org/10.3390/atmos15091023]

Remote Emission Sensing Gas Imaging Technique

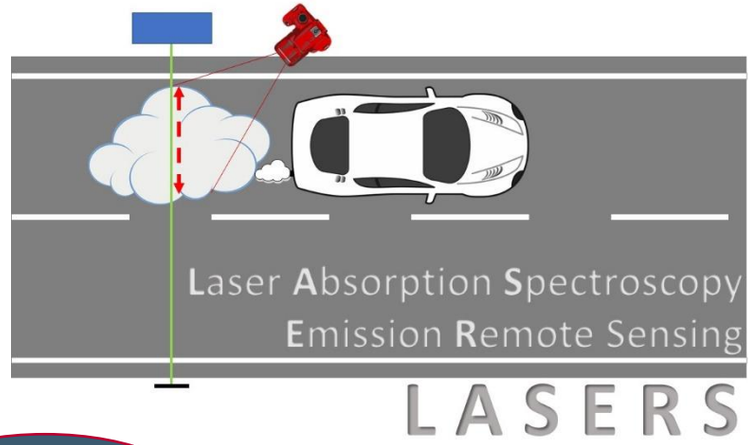
- GSIS application in traffic
  - Data collected in LENS campaigns
  - Analysis ongoing – only preliminary statement
  - Technique feasible for L-vehicles

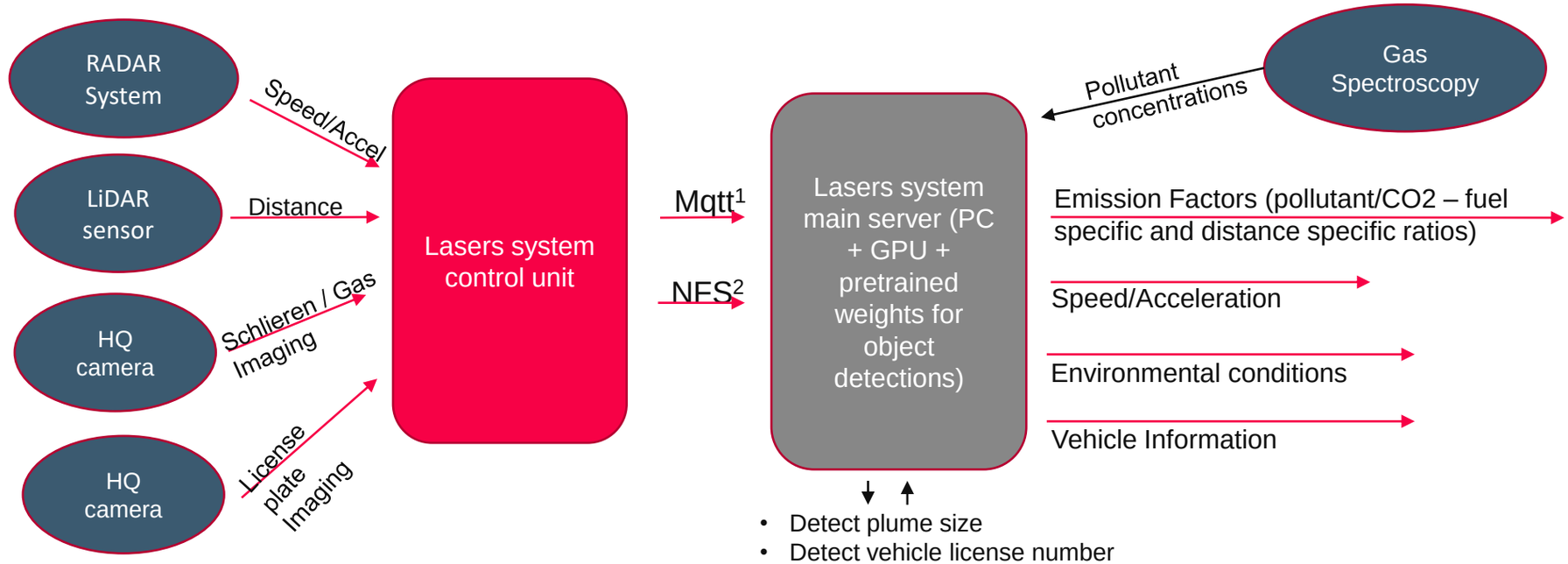




[Imtiaz, H. H., Schaffer, P., Liu, Y., Hesse, P., Bergmann, A., & Kupper, M. (2024). Qualitative and Quantitative Analyses of Automotive Exhaust Plumes for Remote Emission Sensing Application Using Gas Schlieren Imaging Sensor System. *Atmosphere*, *15*(9), 1023. https://doi.org/10.3390/atmos15091023]

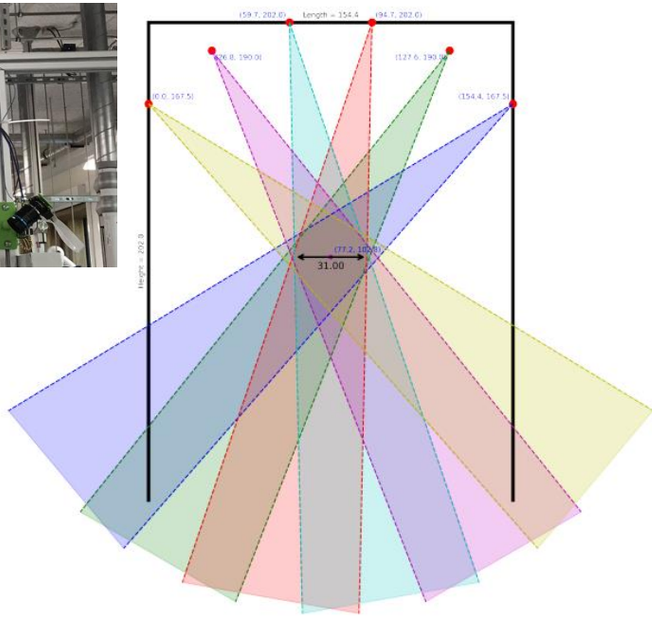
Remote Emission Sensing
LASERS System



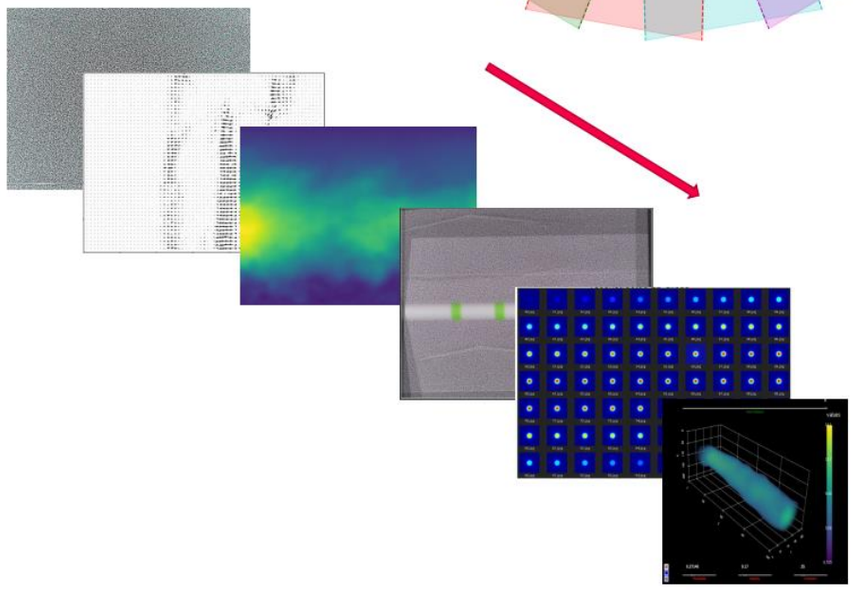


1. Sensors values with timestamps
2. Images with timestamps

LASERS “spin-off” Tomographic Schlieren



- Array of 6 cameras
- 3D-reconstruction of density field
- Study of turbulent flows in the lab
- Method technically functional, validation in work

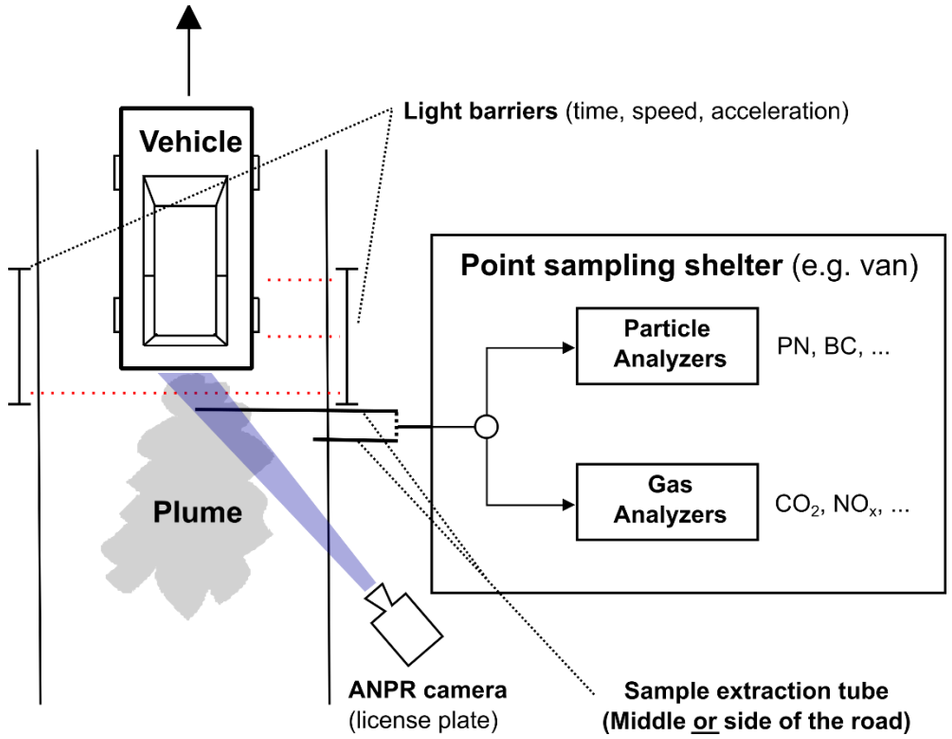


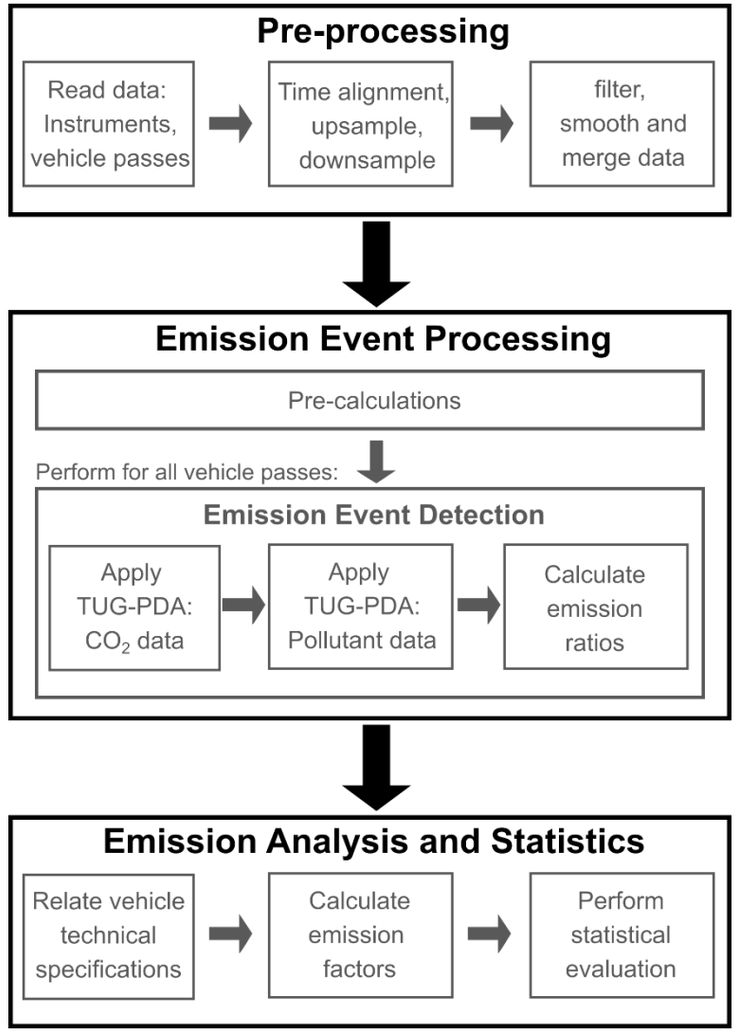
- Current work
  - Comparison od results to simulated data
  - Test series using hot turbulent air

[Master’s Thesis Thomas Forstinger – ongoing]

Point Sampling

Point Sampling

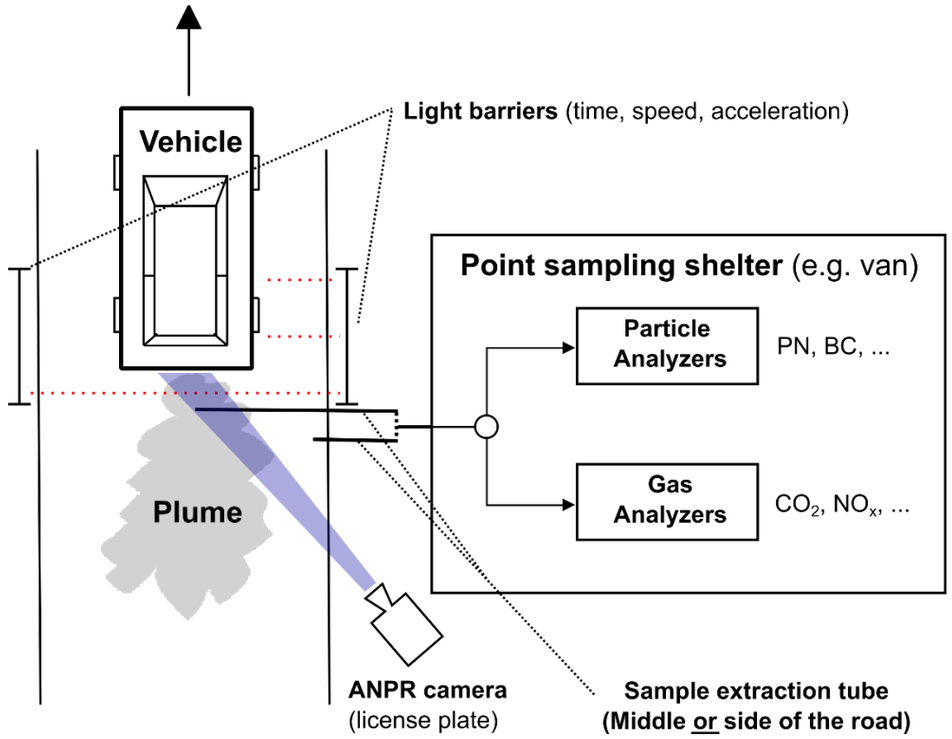


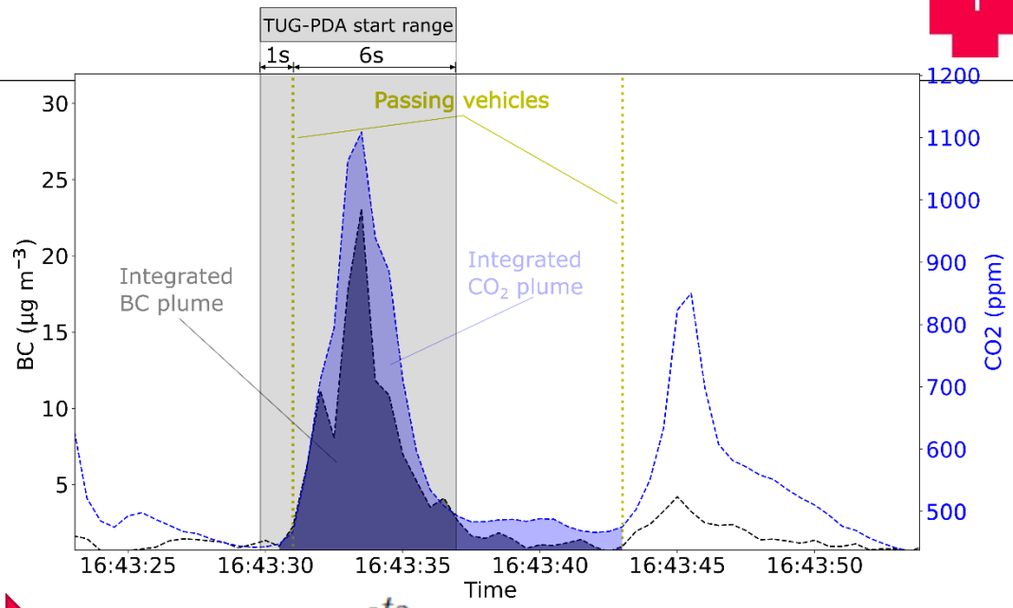


Allows 24/7 emission screening
Automated post-processing
Quantification of gases and particle metrics

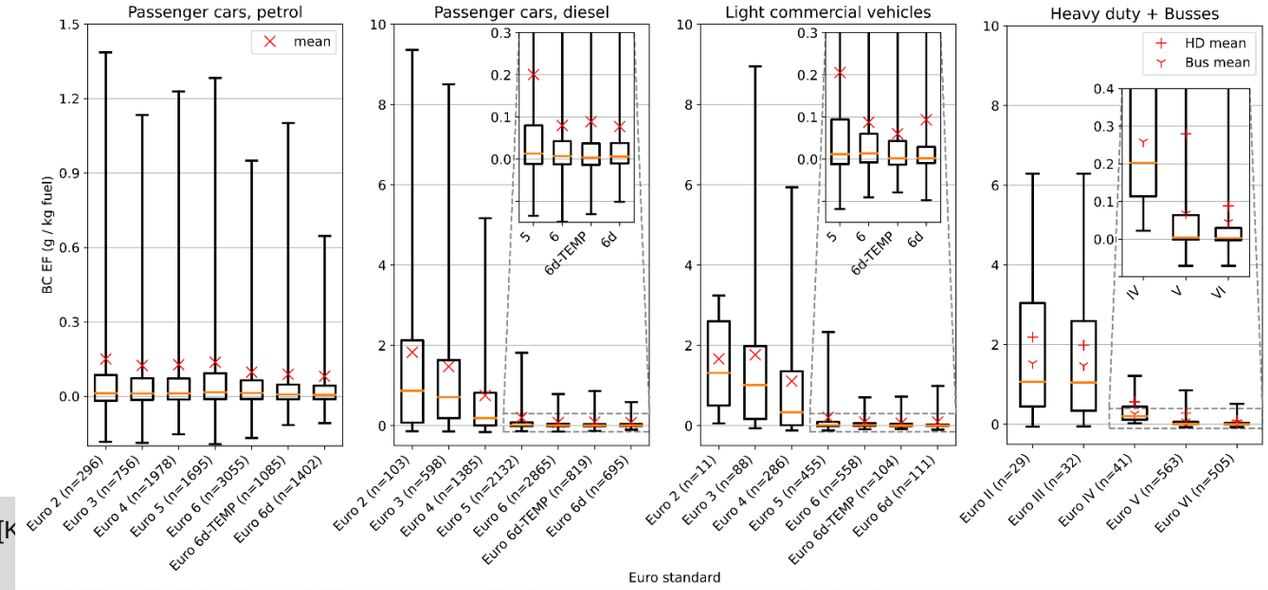
[Knoll, M., Penz, M., Juchem, H., Schmidt, C., Pöhler, D., & Bergmann, A. (2024). Large-scale automated emission measurement of individual vehicles with point sampling. *Atmospheric Measurement Techniques*, *17*(8), 2481–2505. https://doi.org/10.5194/amt-17-2481-2024]

Point Sampling





$$ER = \frac{\int_{t_1}^{t_2}([P]_t - [P]_{t_0})dt}{\int_{t_1}^{t_2}([CO_2]_t - [CO_2]_{t_0})dt}$$

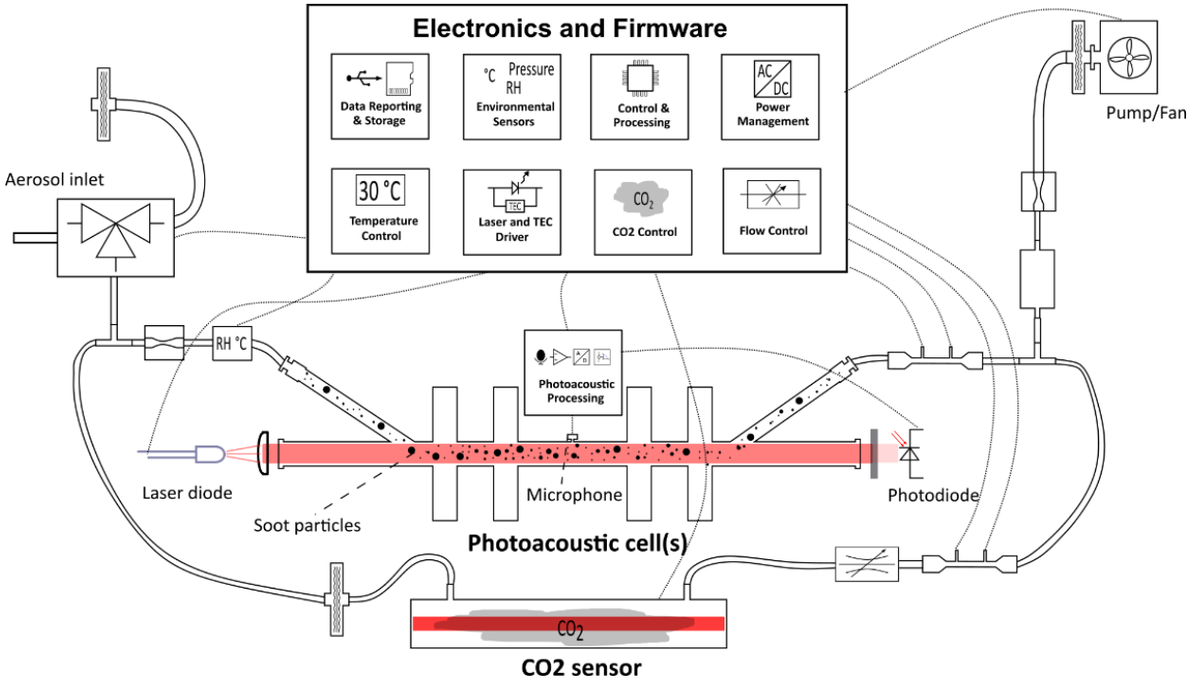


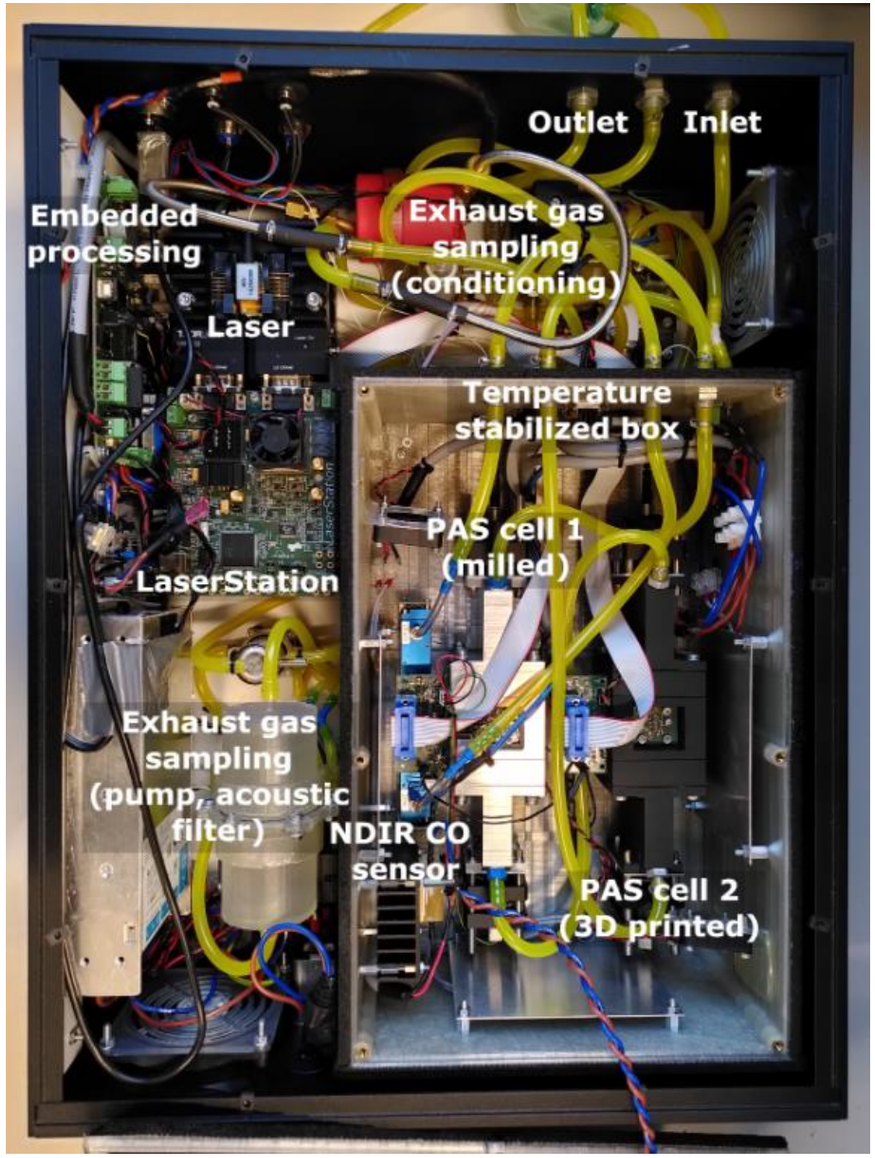
Allows 24/7 emission screening
Automated post-processing
Quantification of gases and particle metrics

[K
Measurement Techniques, 17(6), 2461–2505. https://doi.org/10.5194/amt-17-2461-2024]

Point Sampling Instrumentation
PM – Black Carbon Tracker

- BC: custom-made photoacoustic cell
- CO2: commercial NDIR sensor

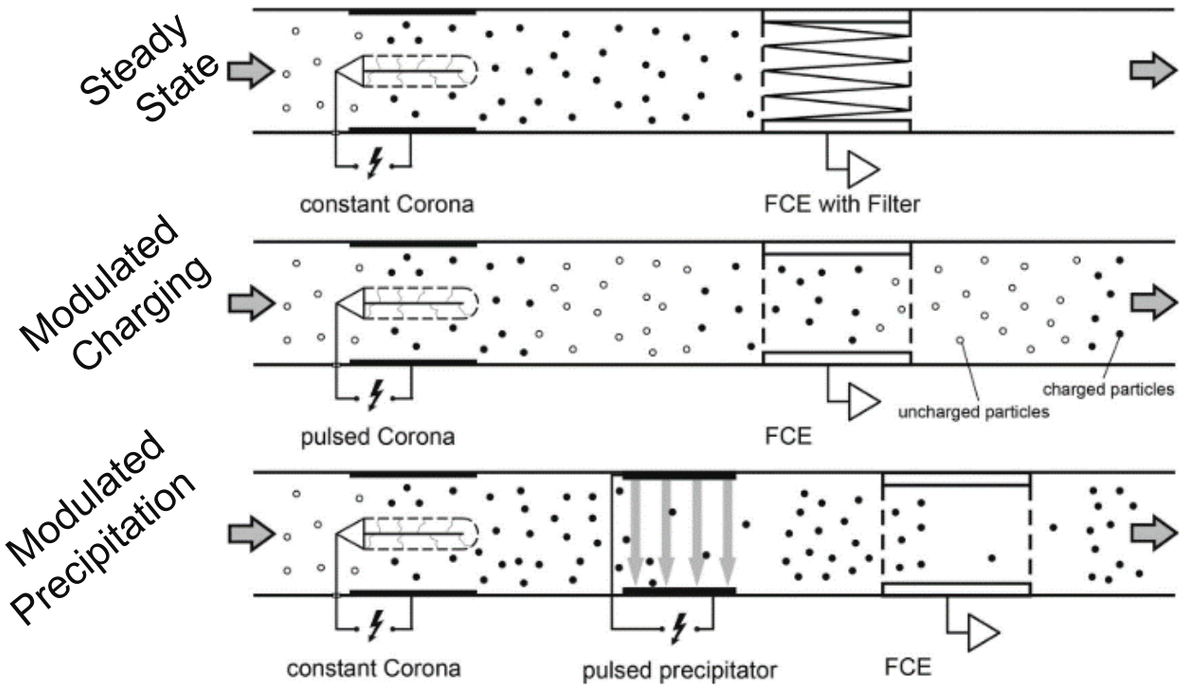




The development of the BCT and all work of TU Graz in the CARES project was done by Markus Knoll within his PhD-Thesis. [Knoll, Markus Franz. *Point Sampling as Remote Emission Sensing Method to Screen Particulate Matter Emissions*. 2024.]

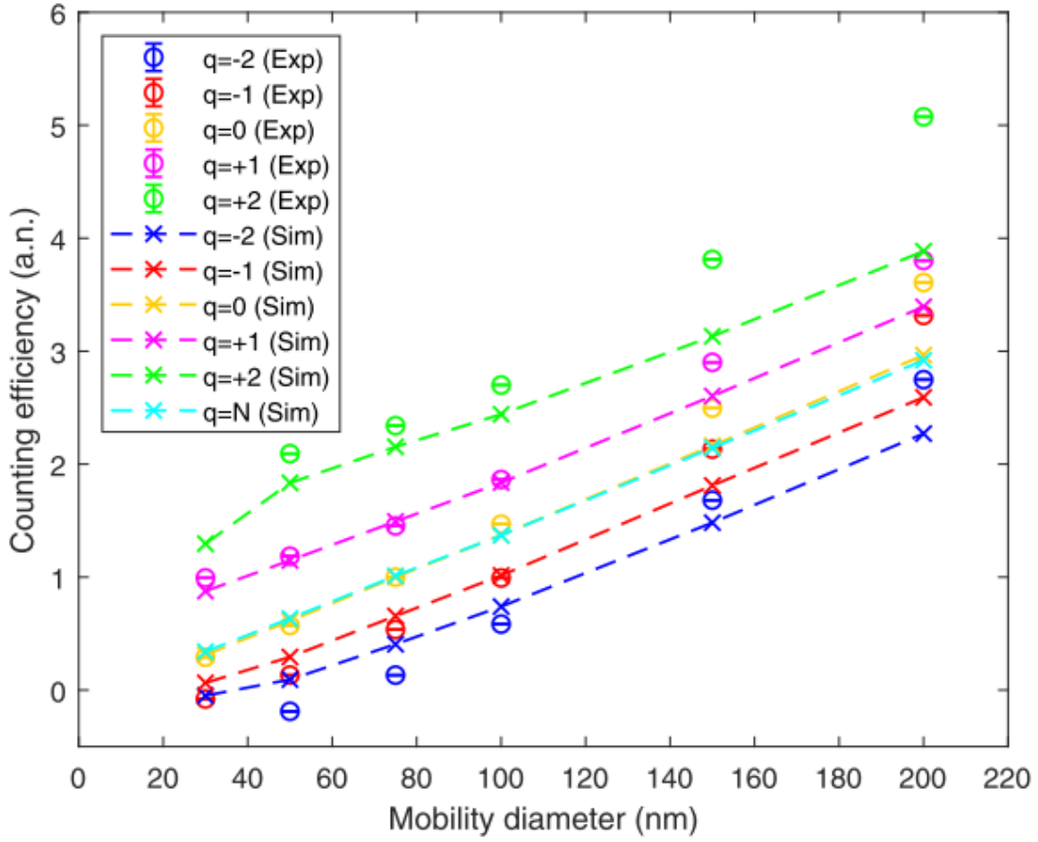
Point Sampling Instrumentation
PN – Diffusion Charger

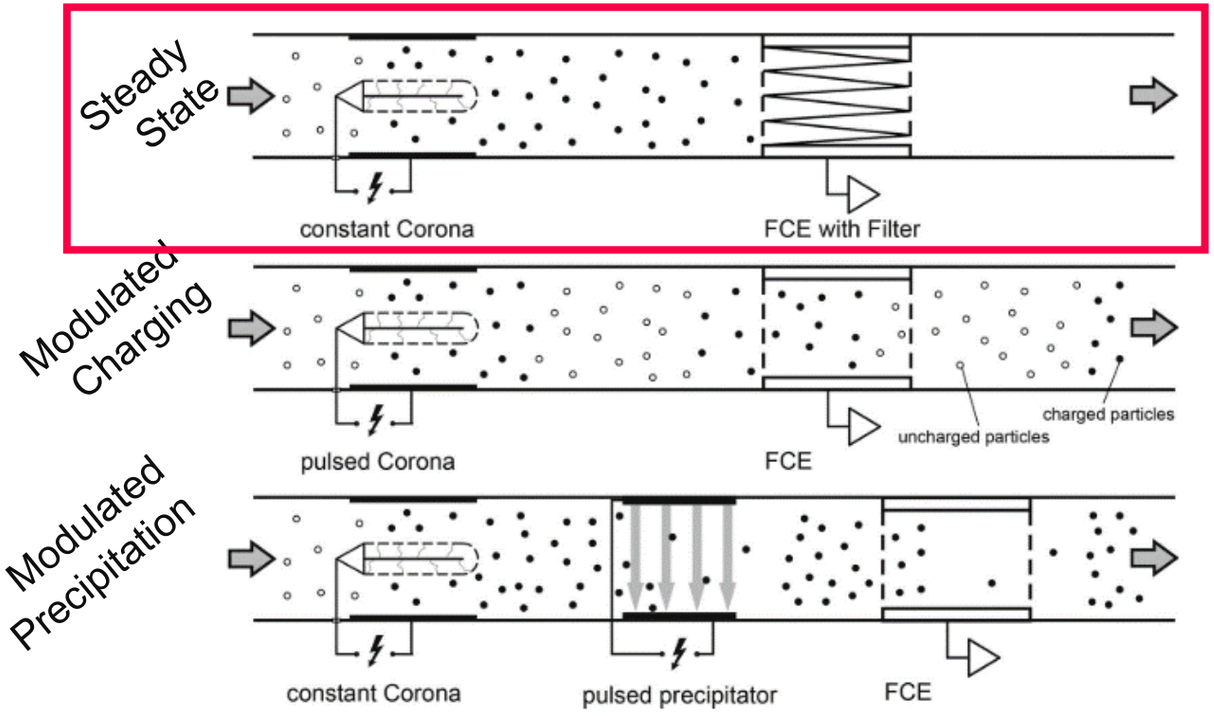
- Soot in exhaust carries charges (“pre-charged”)
- Exhaust particle measurement by DC requires dedicated approach
  - Variation of DC setup
  - Minimization of pre-charge influence
  - Reduction of particle size infuence



[Knoll, M., Schriefl, M. A., Nishida, R. T., & Bergmann, A. (2021). Impact of pre-charged particles on steady state and pulsed modes of unipolar diffusion chargers. *Aerosol Science and Technology*, *55*(5), 512–525. https://doi.org/10.1080/02786826.2021.1873910]

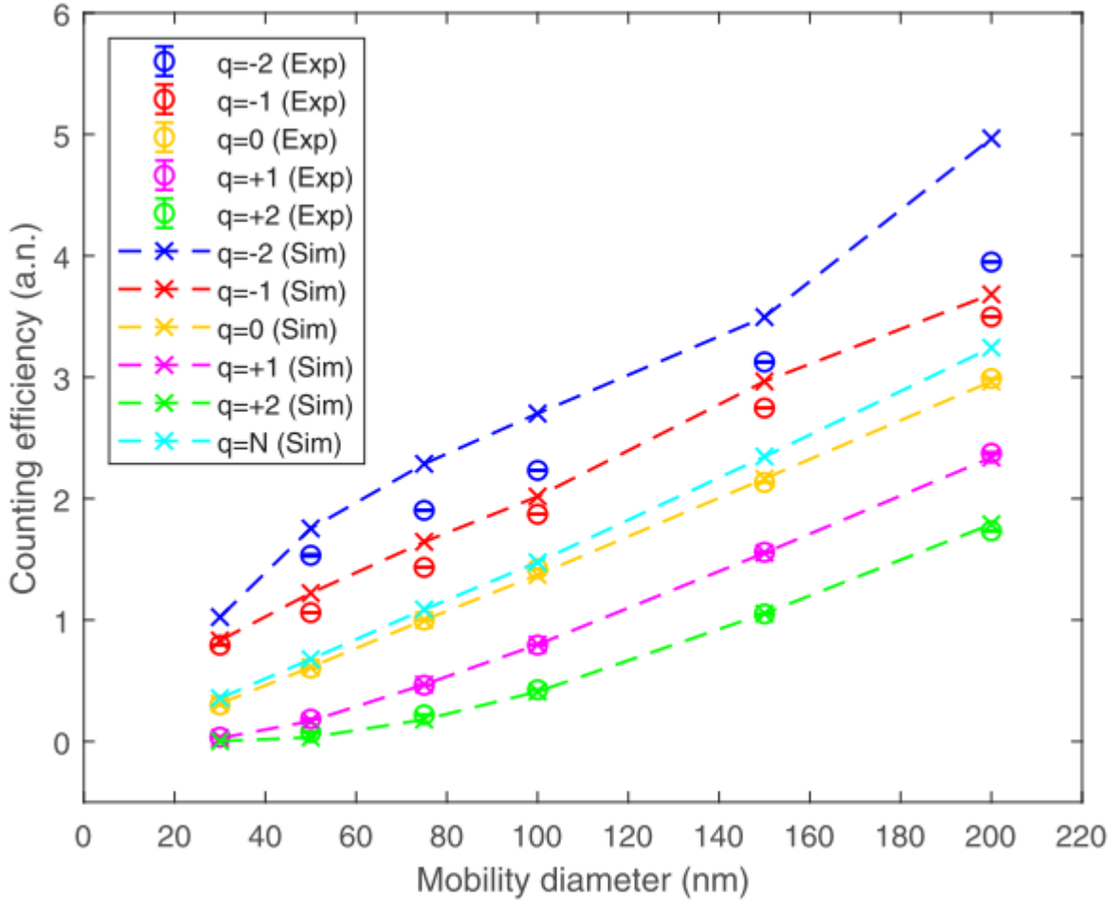
Point Sampling Instrumentation
PN – Diffusion Charger

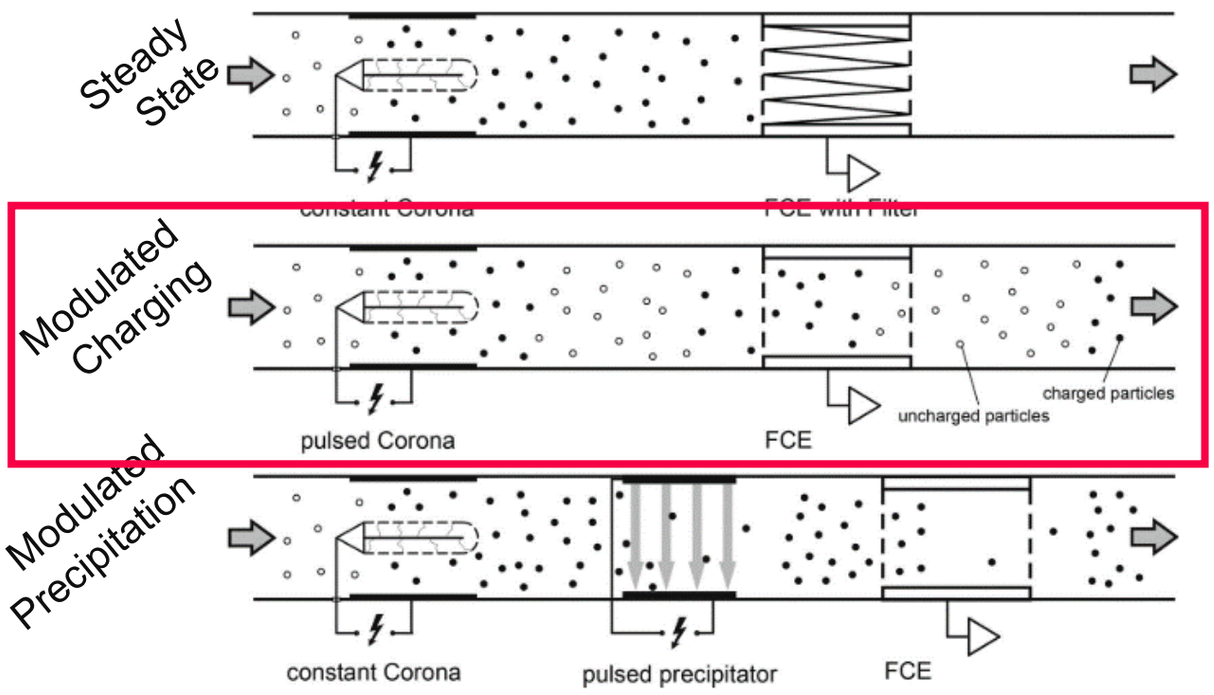




[Knoll, M., Schriefl, M. A., Nishida, R. T., & Bergmann, A. (2021). Impact of pre-charged particles on steady state and pulsed modes of unipolar diffusion chargers. *Aerosol Science and Technology*, *55*(5), 512–525. https://doi.org/10.1080/02786826.2021.1873910]

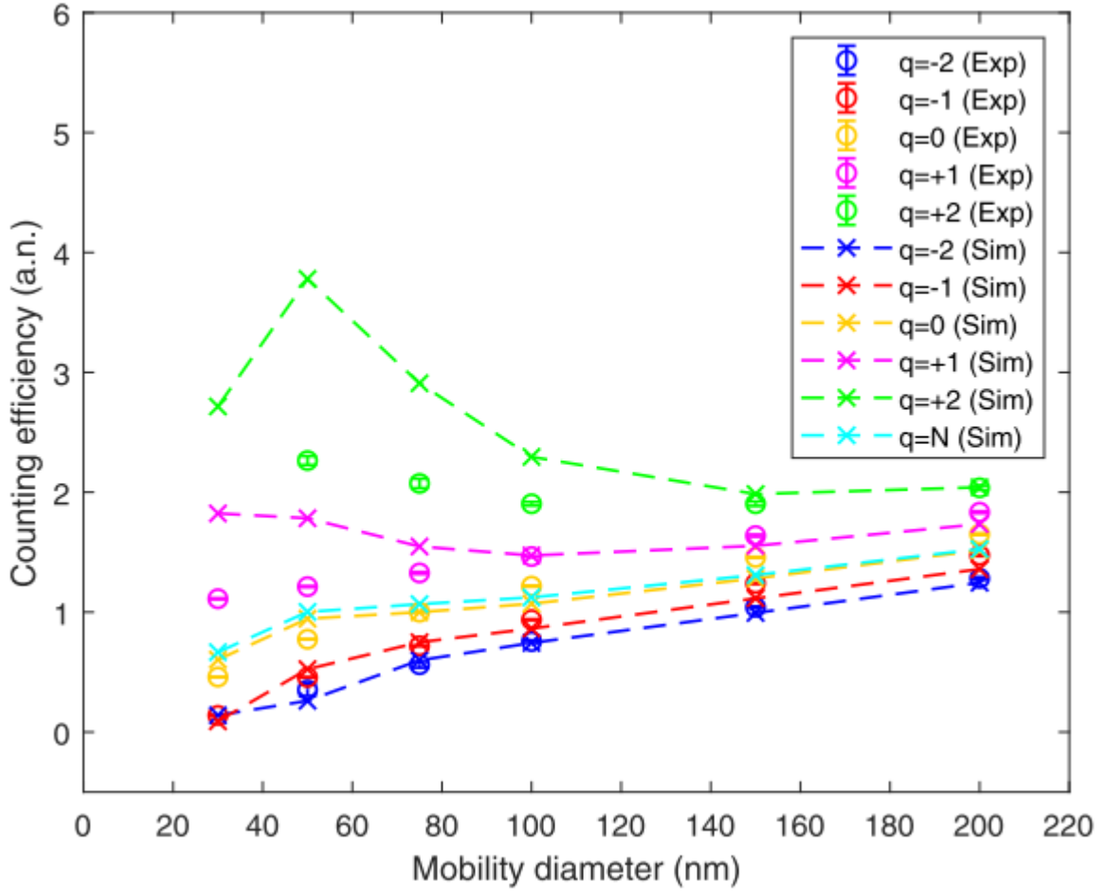
Point Sampling Instrumentation
PN – Diffusion Charger

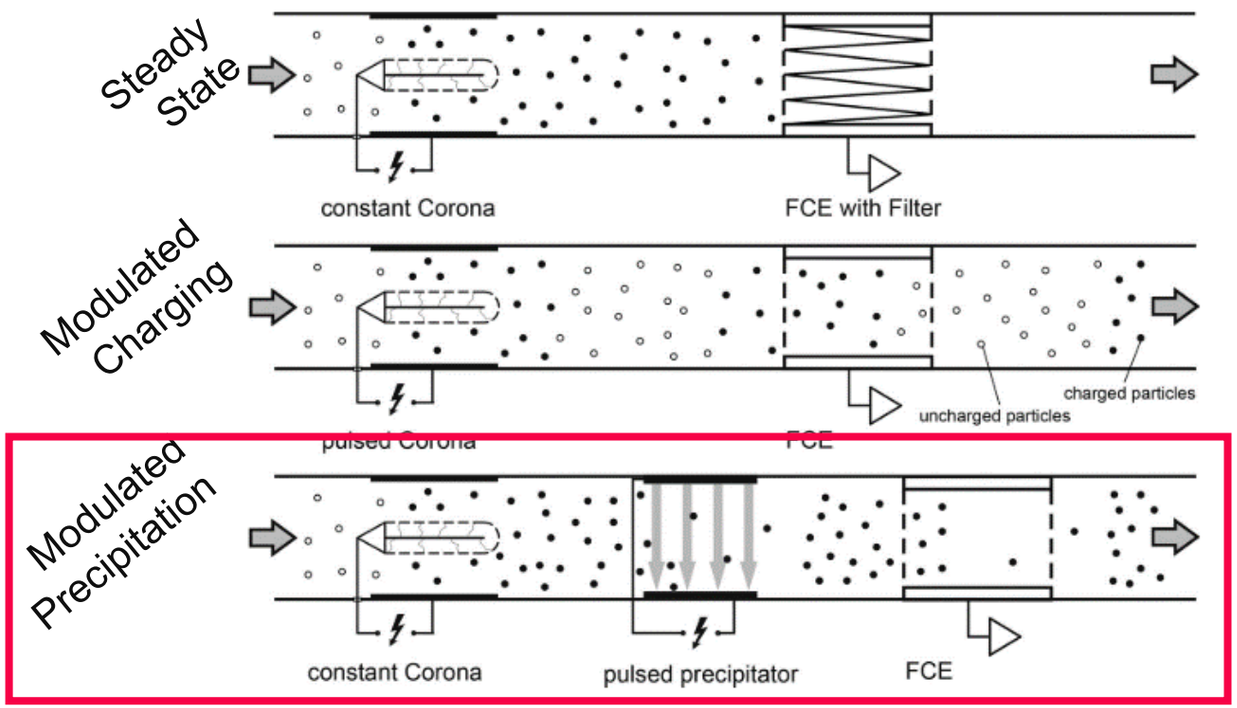




[Knoll, M., Schriefl, M. A., Nishida, R. T., & Bergmann, A. (2021). Impact of pre-charged particles on steady state and pulsed modes of unipolar diffusion chargers. *Aerosol Science and Technology*, *55*(5), 512–525. https://doi.org/10.1080/02786826.2021.1873910]

Point Sampling Instrumentation
PN – Diffusion Charger

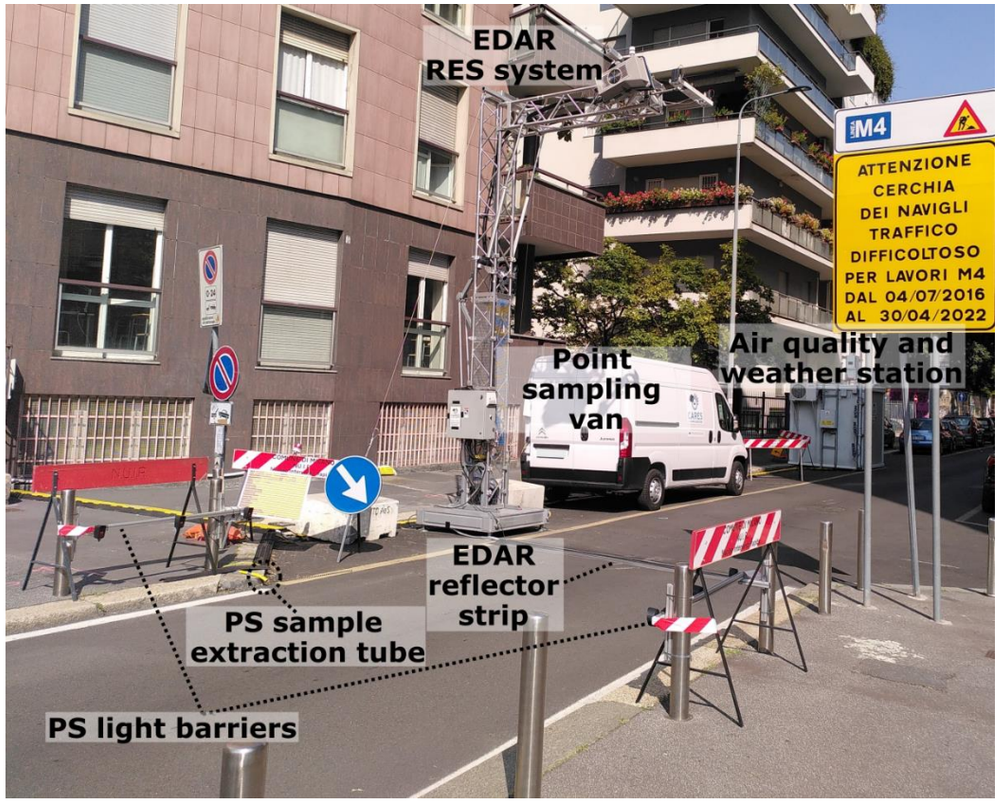




[Knoll, M., Schriefl, M. A., Nishida, R. T., & Bergmann, A. (2021). Impact of pre-charged particles on steady state and pulsed modes of unipolar diffusion chargers. *Aerosol Science and Technology*, *55*(5), 512–525. https://doi.org/10.1080/02786826.2021.1873910]

Point Sampling
CARES Results

- Two characterization champaigns
  - EDAR Heat Remote Sensing
  - Point Sampling
  - PEMS
- Three in-field campaigns: Milano, Krakow, Prague
  - ~161.000 valid vehicle passes
  - 34.323 valid PS data (capture rate ~21 %)
  - OPUS Remote Sensing Device (RSD)
  - Heat EDAR
  - TU Graz Point Sampling



Point Sampling
CARES Results and Conclusion

CARES
CITY AIR REMOTE EMISSION SENSING

PS validation measurements

- Particles: Good agreement between PS and PEMS
- NO_x: Statistical very good agreement between PS, EDAR and PEMS

PS compared to EDAR (HEAT)

- Particles: Large differences
- NO_x: Statistically very good agreement

PS compared to RSD (OPUS)

- Particles: Similar range, good agreement for „old“ Diesel
- NO_x: Statistical good agreement
- Large differences for petrol vehicles

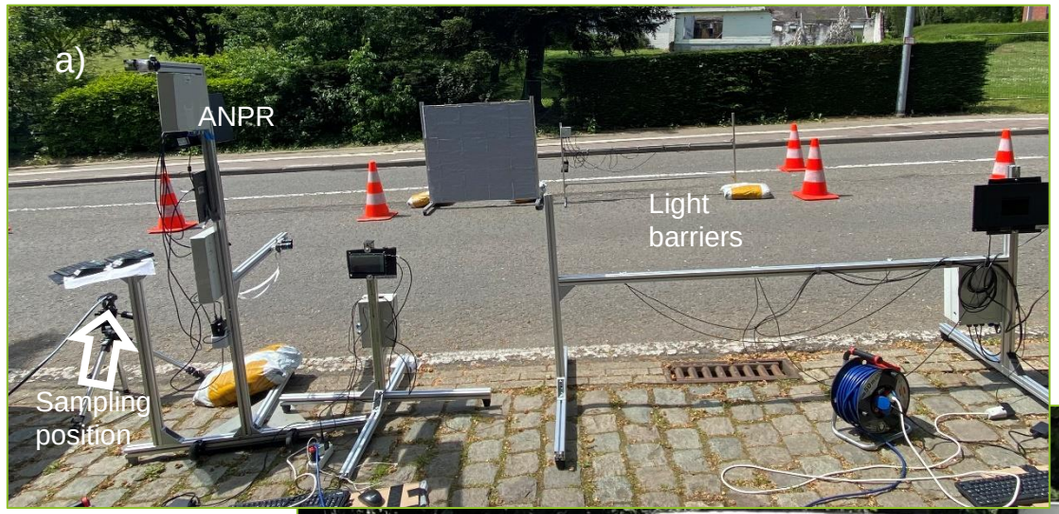
Please see publication for data

[Knoll, M., Penz, M., Juchem, H., Schmidt, C., Pöhler, D., & Bergmann, A. (2024). Large-scale automated emission measurement of individual vehicles with point sampling. *Atmospheric Measurement Techniques*, *17*(8), 2481–2505. https://doi.org/10.5194/amt-17-2481-2024]

Point Sampling
LENS preliminary results

L-vehicles Emissions and Noise mitigation Solutions

- Three in-field campaigns:
  - Leuven (BE)
  - Paris (FR)
  - Barcelona (ES)
- OPUS RSD
- TU Graz Point Sampling
- Schlieren Imaging



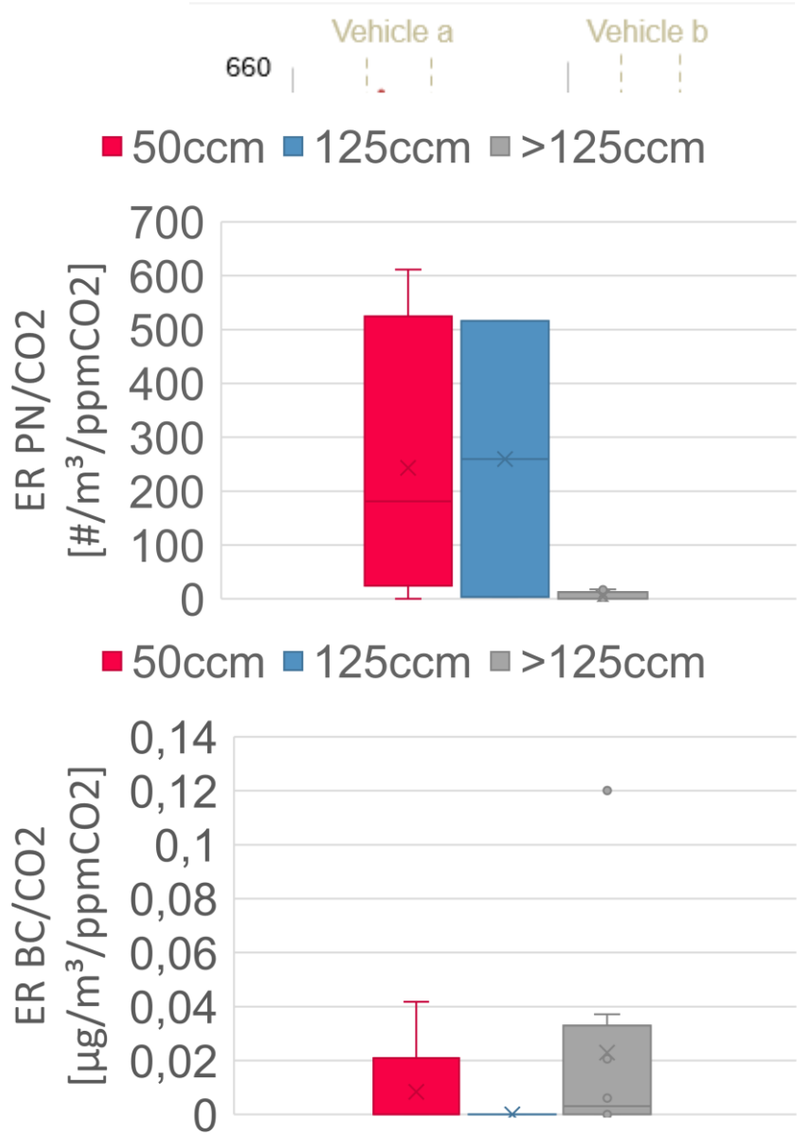
https://www.lens-horizoneurope.eu

Point Sampling
LENS preliminary results Leuven

- BC level overall very low
- PN concentration for lager motorbikes lower

- PS for L-vehicles very challenging
  - Capture rate ~ 10,5 % (compared to OPUS RSD)
  - Evaluation only possible with valid CO2 data
- Measured concentration levels by PS are very low

- More valid data from Paris and Barcelona
  - Data analysis ongoing

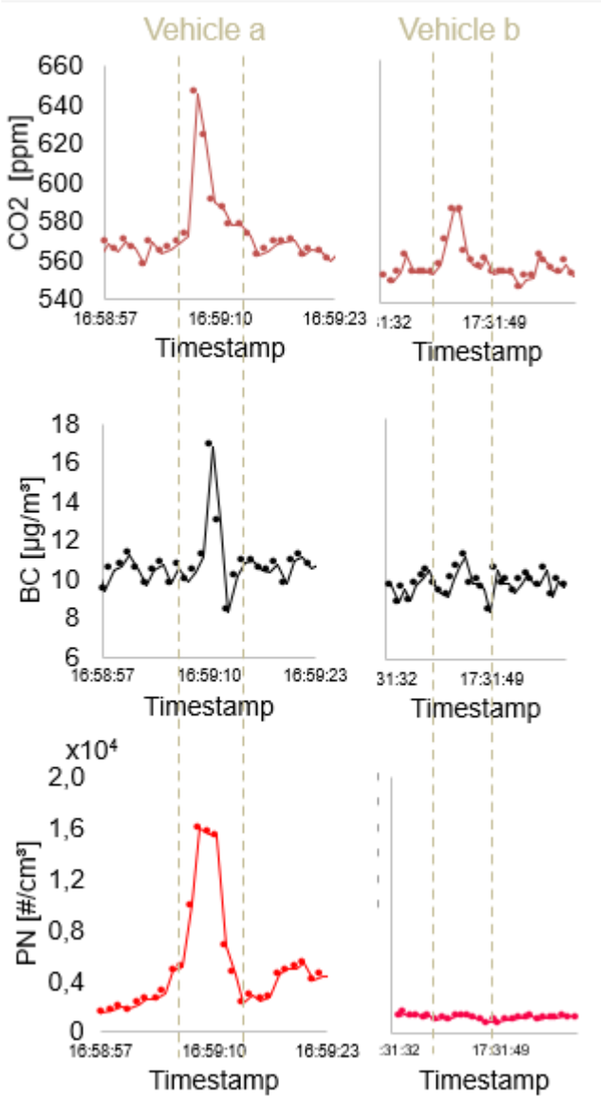


Point Sampling
LENS preliminary results Leuven

- BC level overall very low
- PN concentration for lager motorbikes lower

- PS for L-vehicles very challenging
  - Capture rate ~ 10,5 % (compared to OPUS RSD)
  - Evaluation only possible with valid CO2 data
- Measured concentration levels by PS are very low

- More valid data from Paris and Barcelona
  - Data analysis ongoing



SCIENCE
PASSION
TECHNOLOGY

Thank you for your attention

Martin Kupper | ERMES Plenary 2024

13.11.2024

www.ems.tugraz.at | martin.kupper@tugraz.at