



## Lessons from the CARES project - Remote emission sensing measurements in practice

**Yoann Bernard**  
International Council on Clean Transportation (ICCT)  
May 17<sup>th</sup>, 2023, CARES Webinar

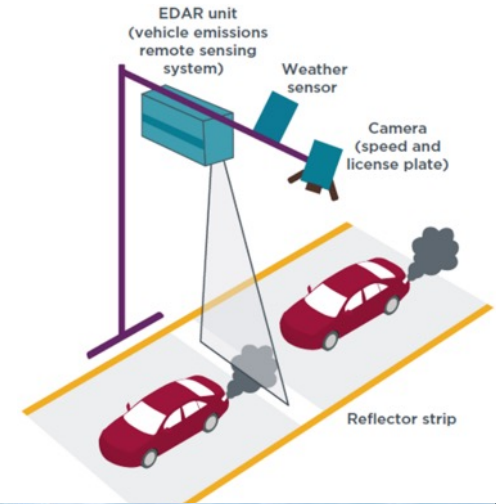
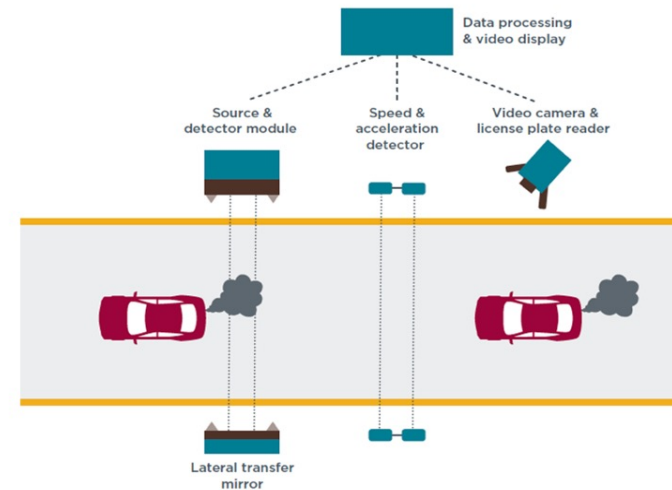
This project is receiving funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 814966



**CARES**  
CITY AIR REMOTE EMISSION SENSING

# Commercial optical remote sensing technology can measure real-world emissions of thousands vehicles per day

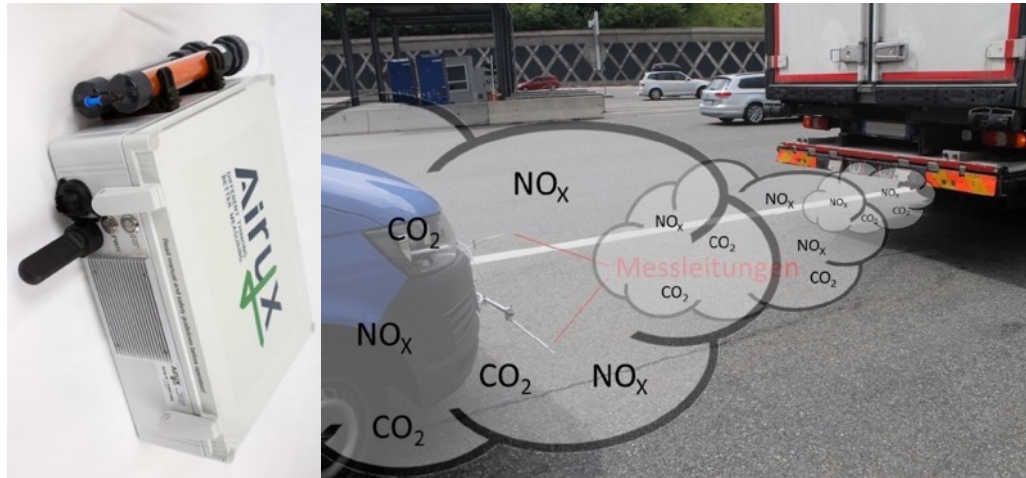
- Uses light beam to capture snapshots of the exhaust emissions from individual on-road vehicles
- Pollutants measured include NO, NO<sub>2</sub>, PM, CO, HC, NH<sub>3</sub> (OPUS)
- Combined with vehicle specific information (make, model, etc), to allow understanding of fleet emissions
- Up to 10,000 valid records per day



# Plume chasing and point sampling use lab-grade analyzers to study emissions from the plume

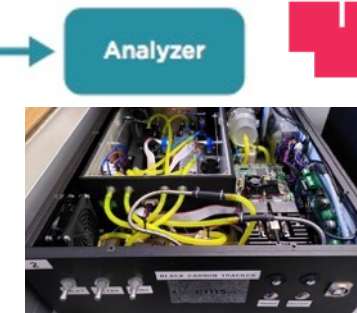
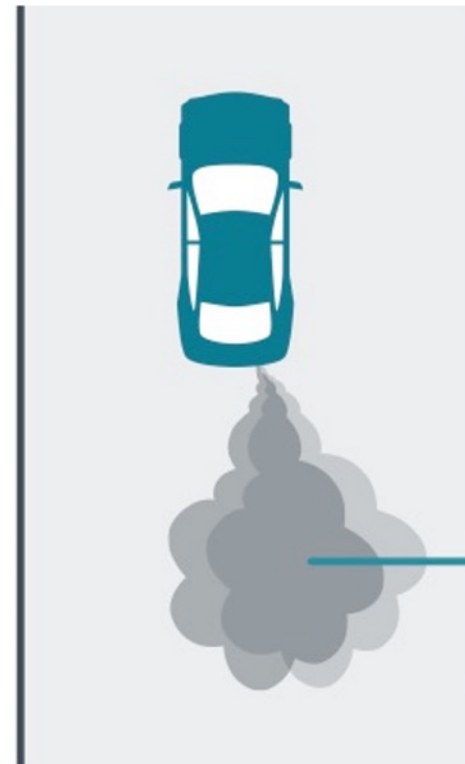
NO/NO<sub>2</sub>/NO<sub>x</sub>, BC, PN, CO<sub>2</sub>

## Plume chasing



Up to 200 vehicles sampled per day

## Point sampling



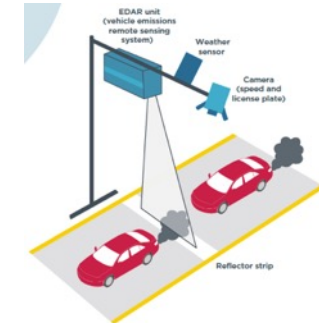
Up to 3,000 valid records per day

# Remote-sensing campaign in Milan

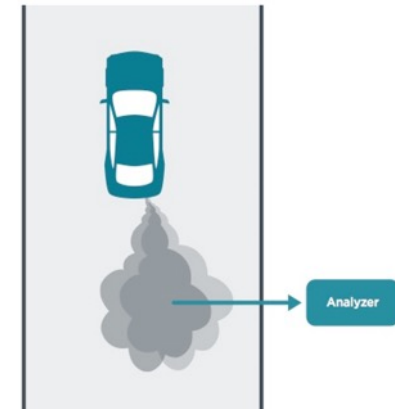


CARES remote emission sensing campaign in Milan completed

November 5, 2021  
News



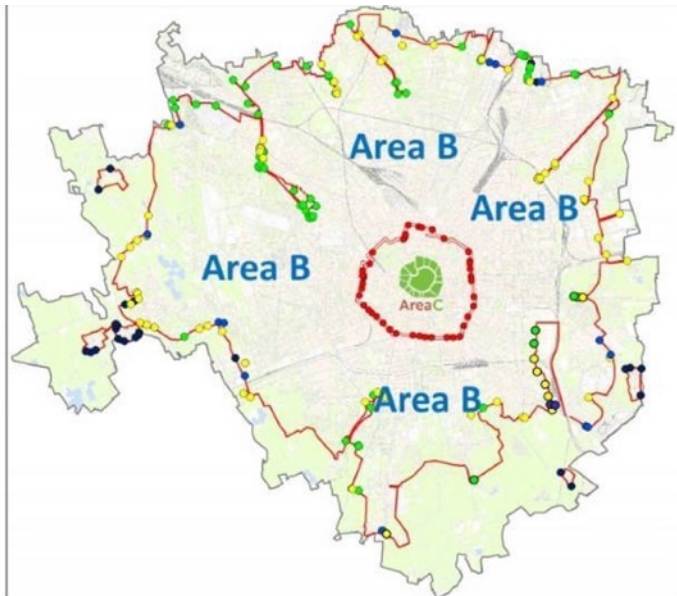
Schematic of top-down remote emission sensing device.



CARES website: <https://cares-project.eu/cares-milan-res-complete/>

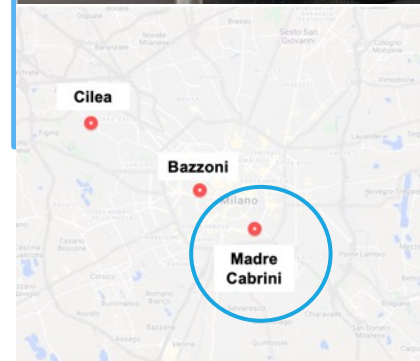
# Remote-sensing campaign in Milan

- Primary objective: track policy effectiveness of the Milan Low Emission Zone (LEZ)
- Second key objective: test and compare a variety of remote-sensing instruments in practice
- Third objective: comparison remote sensing measurements with PEMS in real-world
- Additionally: Volatile Organic Compounds (VOC) monitoring, advanced air monitoring stations
- Practical lessons from preparing the measurements (permissions, electricity access, safety, GDPR)



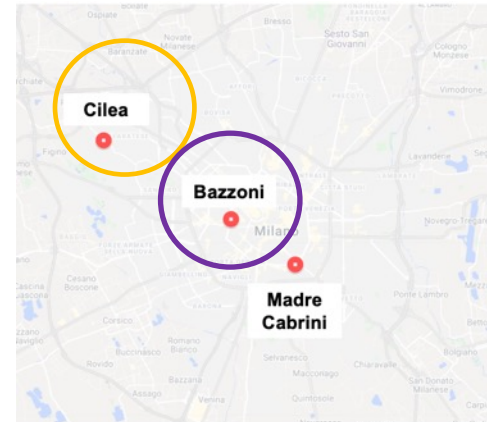
# Remote sensing testing in Milan

- Testing period: Fall 2021 (Sep – Oct)
- HEAT's EDAR remote sensing systems
  - Deployed in two sites: Via Cilea, Via Madre Cabrini
  - > 35,000 measurements
- Point sampling
  - Via Madre Cabrini, Via Bazzoni
  - Enable real-world measurements of particulate number (PN) and black carbon
- Concurrent portable emissions measurement system (PEMS) testing on certain vehicles



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- Concurrent portable emissions measurement system (PEMS) testing on certain vehicles
- Air quality monitoring instruments and advanced sensors
- Ambient ammonia concentration and resuspension particle measurements



Reference

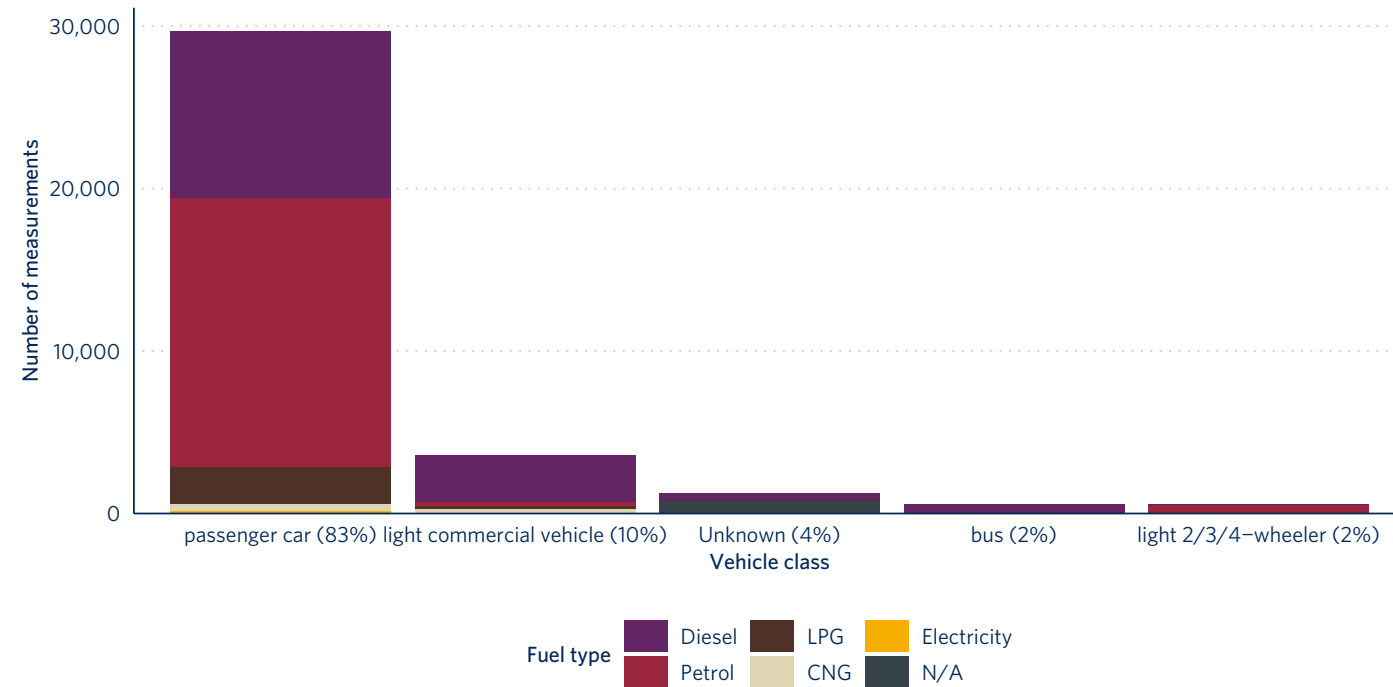


Advanced sensors



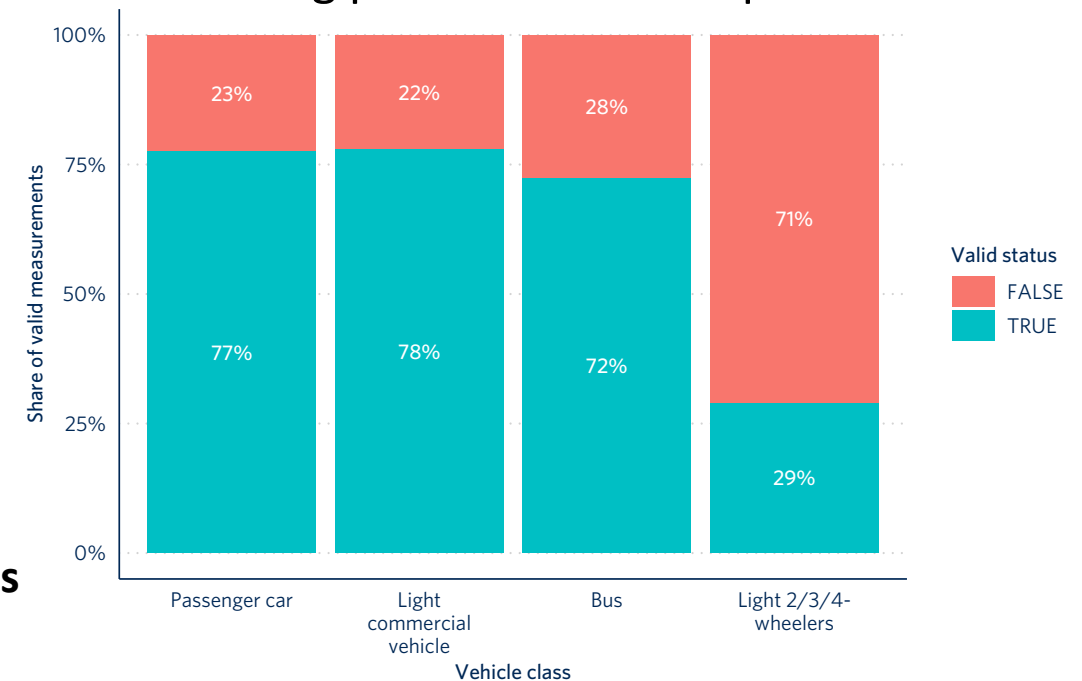
# Milan's RS measurements from commercial systems

## Fleet measurements



- Passenger car most commonly found
- Significant shares of LPG/CNG vehicles relative to other cities
- Lower share of valid emission measurements of scooters and motorcycles due to driving pattern and small plumes\*

## Emissions measurements



\*Milan is completely flat, which is sub-optimal to foster larger plumes during the measurement

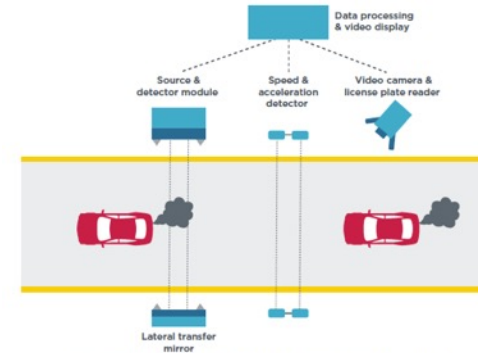
# Remote-sensing campaign in Krakow



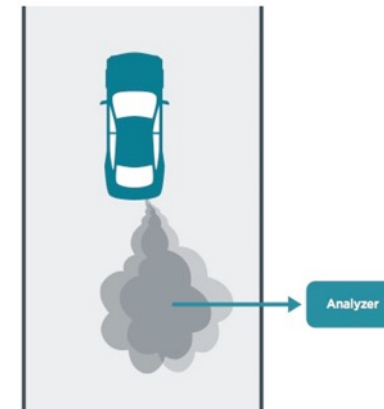
Krakow remote emission sensing measurement campaign successfully completed

December 17, 2021

News



Schematic of cross-road remote emission sensing device.



# Krakow LEZ context

- Test LEZ in Krakow in 2019 led to introduce efficient national provisions on LEZs
- These new national provisions allows cities in Poland to implement LEZ, and distinguish by fuel type and euro standard
- Krakow announced the first LEZ in Eastern Europe which will be phased from July 2024 to 2026
- Remote sensing data is key to inform policymakers in charge of designing the upcoming LEZ
- Data collected in December 2021 were compared with May 2019 (first remote sensing campaign)

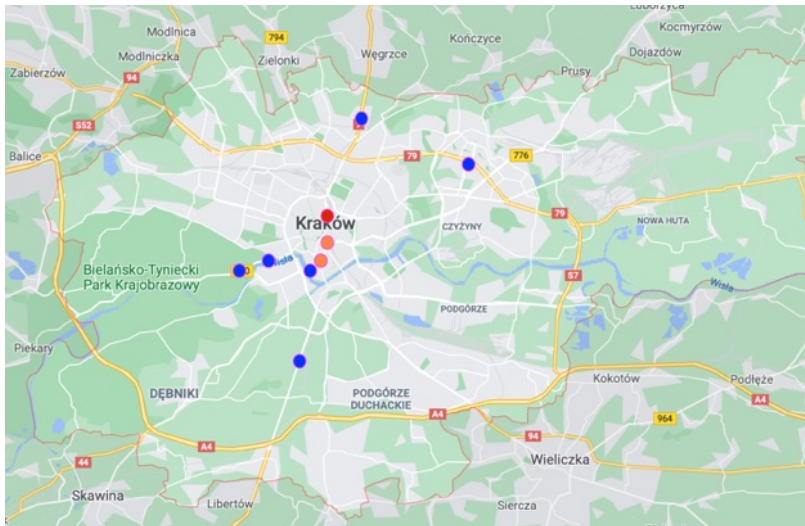


0 2000 m

— Drogi nieobjęte Strefą Czystego Transportu na terenie Miasta Krakowa

# Remote-sensing campaign in Krakow

- Primary objective: assist the preparations of the city for introducing a Low Emission Zone
- Secondary objective: validation of previous measurement campaign, using winter data
- Key learnings include measurements during winter time: snow-covered license plates, wet roads with dirt which covered plates, and worsened translucency of the commercial optical system.



Testing sites



Snow: no measurement

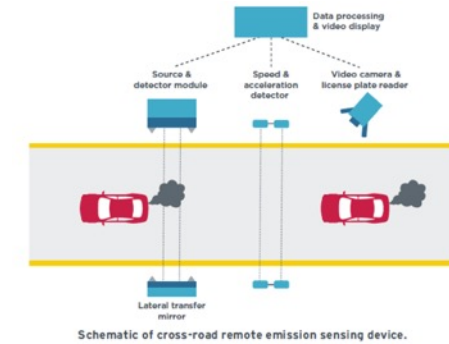


Collocation of instruments

# Remote-sensing campaign in Prague

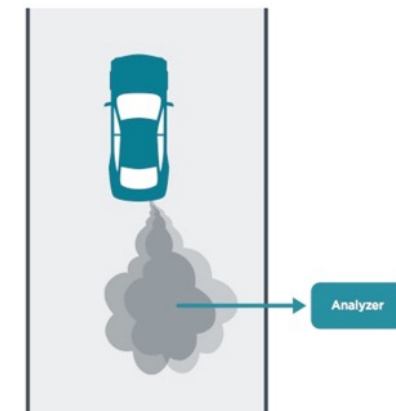


Prague, Czech Republic



CARES remote emission sensing campaign in Prague completed

October 7, 2022  
News



Yoann Bernard

# Remote sensing, point sampling and plume chasing campaign in Prague and Brno

The campaign focused on high-emitter identification:

- Point sampling and cross-road OPUS instruments were collocated
- Demonstration of plume chasing
  - “Simple” set up in a car equipped with NO, NO<sub>2</sub>, CO<sub>2</sub>
  - A van equipped with lab-grade analyzers and affordable PN-meters.
  - Investigation of the share of high-emitting HDV in the fleet
- Vehicle specifications from collected plates

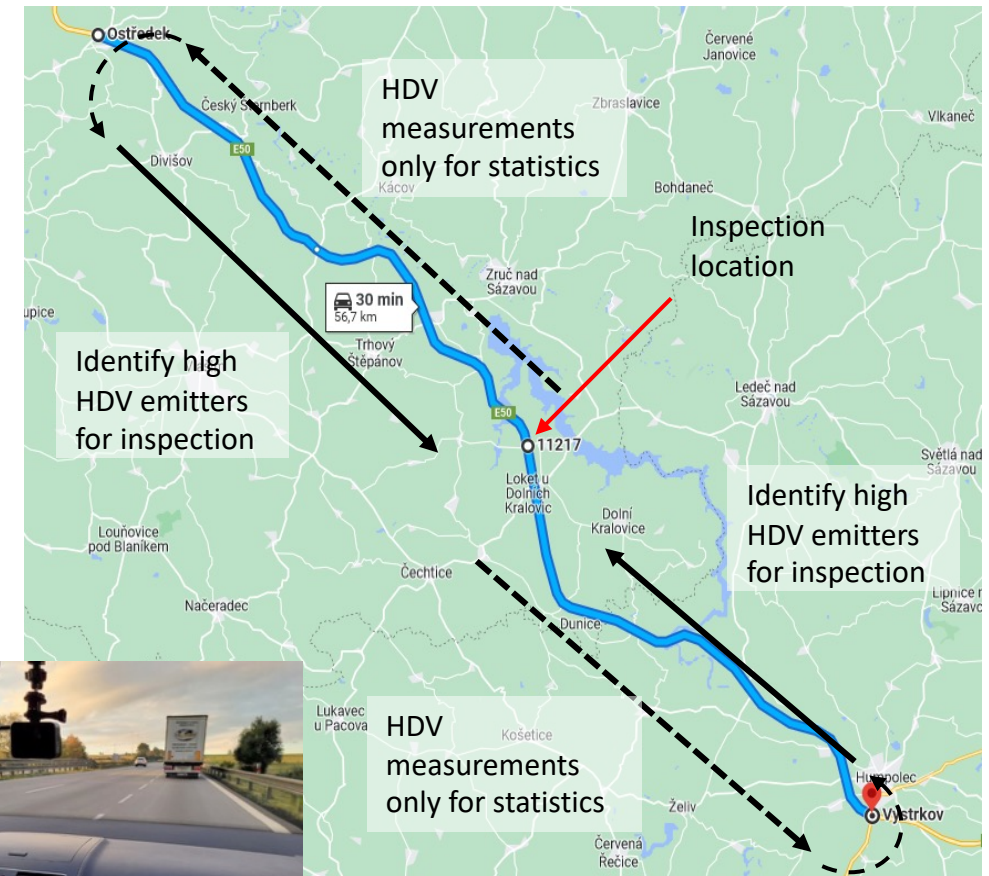


# Prague and Brno – Detection of HDV high-emitters

- Instrumentation: NO, NO<sub>2</sub>, PN, BC, CO<sub>2</sub>

Table 7: Used instruments during the Prague measurement campaign.

Instruments (scientific setup)	Instruments (simple setup)	Measured Species
ICAD	ICAD	NO <sub>x</sub> , NO <sub>2</sub> , CO <sub>2</sub>
Counter		PN (D <sub>50</sub> @ 23 nm)
SMPS		PN <sub>90nm</sub>
TEN		PN (D <sub>50</sub> @ 23 nm)
Black Carbon Tracker		BC, CO <sub>2</sub>
GPS	GPS	Location, Speed



# Plume chasing for HDV NO<sub>x</sub> emission screening and enforcement

Involvement of the Traffic Police Service Department and OBD expert from “NO<sub>x</sub> consulting”, TUV Nord CZ, partially funded by TU Dresden

- Commercial instruments available for NO<sub>x</sub>, and already in use by the Danish Police
- Can analyze emission over several kilometers and thus limit false positive (e.g. high emission due to cold start cold start)
- Over 1,000 HDV measured with plume chasing
- Cases of manipulation, defects, and suspicious engine software issues were discovered





# Major practical lesson learned

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- Optical, point sampling and plume chasing can be successfully deployed in cities
- Challenges were related to access to electricity, testing authorization, safety, GDPR and access to vehicles registration data (1 to 5 months). Winter conditions proved to lead to testing difficulties for emissions (for optical systems) and license plate capturing
- Cross-road and overhead commercial instruments, point sampling, and plume chasing were compared with reference instruments such as PEMS but it led to the need for compromise on testing locations
- Plume chasing can detect high-emitting vehicles but an enforcement campaign needs to be done in conjunction with the police and tampering experts.





## Lessons from the CARES project - Assessing real-world emissions from vehicle fleets

**Kaylin Lee**

International Council on Clean Transportation (ICCT)  
May 17<sup>th</sup>, 2023, CARES Webinar

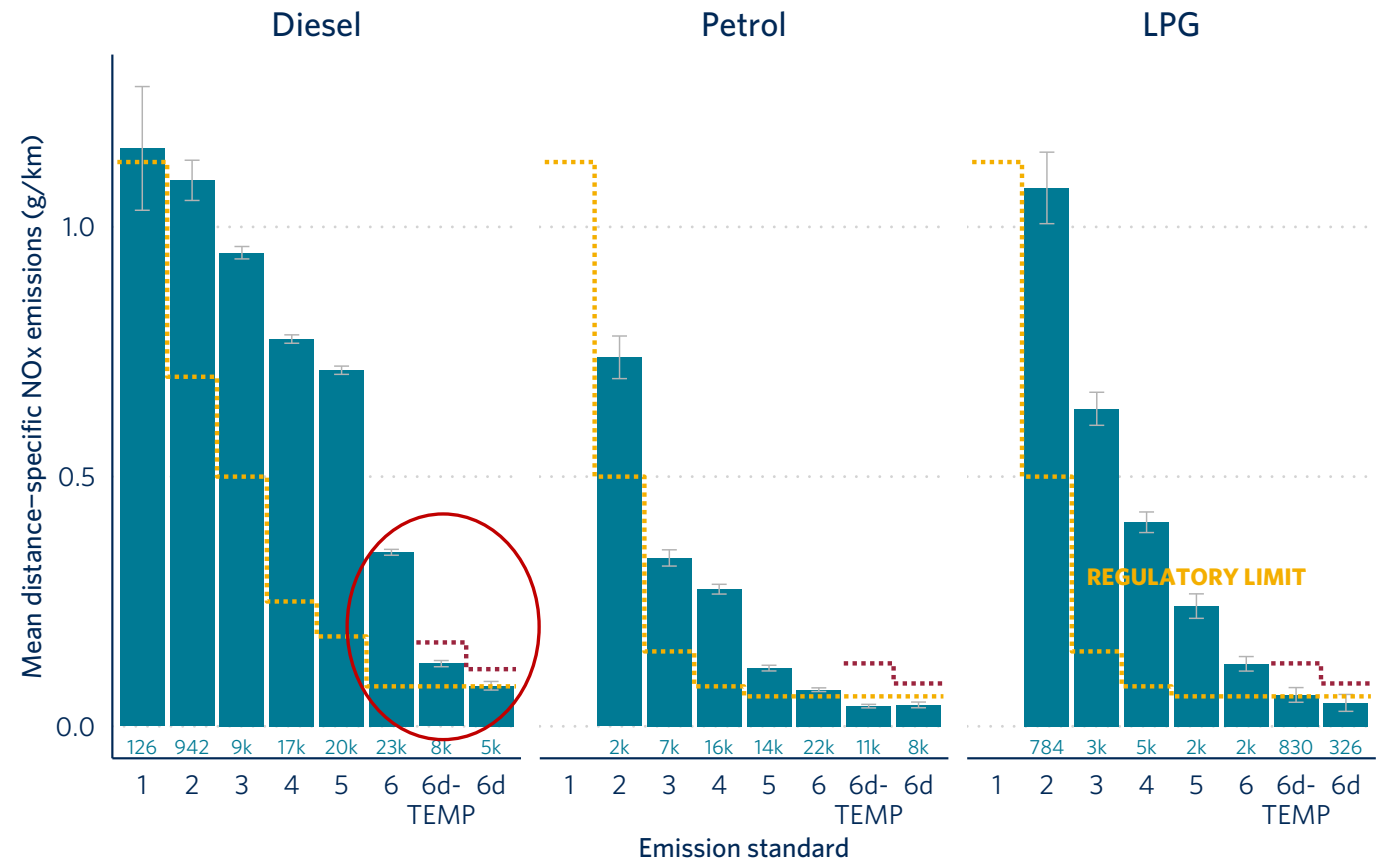
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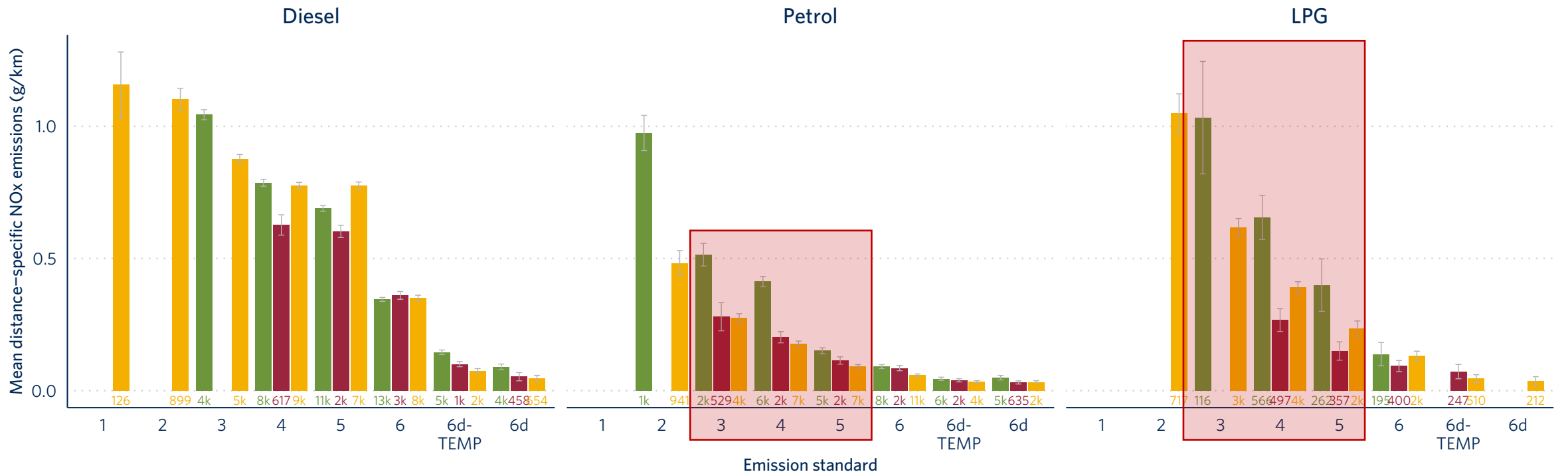
**CARES**  
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# Significant reduction in NO<sub>x</sub> emissions seen for new diesel vehicles but LPG vehicles not as clean as previously thought

- **Diesel:**
  - Little improvement before Euro 6
  - Emissions from Euro 6d-TEMP and Euro 6d comparable to those from new petrol vehicles
- **Petrol:**
  - Steady improvement with newer standards
- **LPG:**
  - Around 30% higher NO<sub>x</sub> than petrol vehicles of the same standards



# Campaign-specific results add city-specific contexts to the NO<sub>x</sub> emission performance of certain vehicle fleet.



Campaign ■ Prague 2022 ■ Milan 2021 ■ Krakow 2021

# Successful reduction of PM emissions from diesel vehicles with diesel particulate filters & uncertain PM emission performance of LPG vehicles

- **Diesel:**

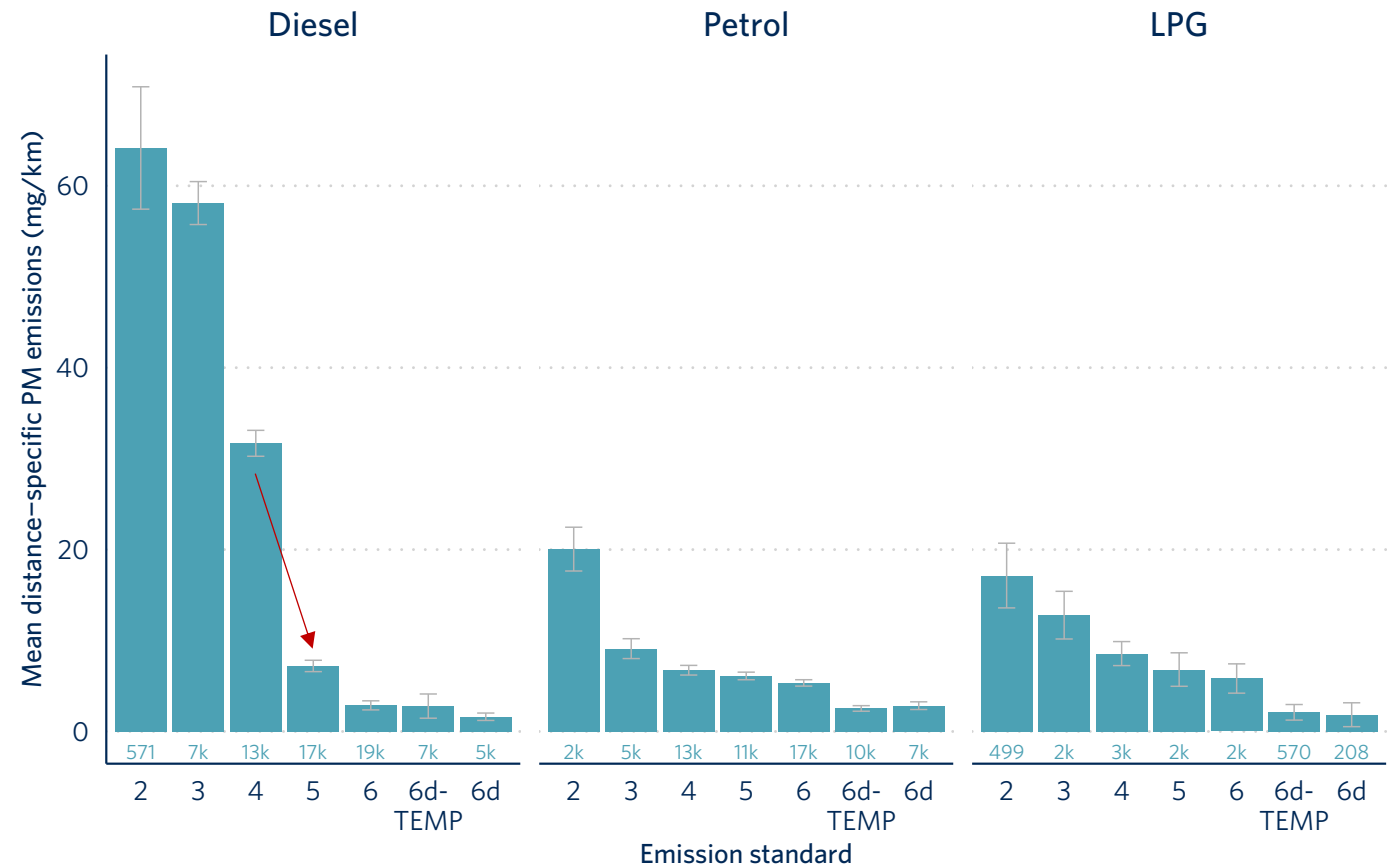
- A significant decrease in PM emissions with the introduction of diesel particulate filters (DPF)
- Euro 6 and above halved PM emissions from Euro 5

- **Petrol:**

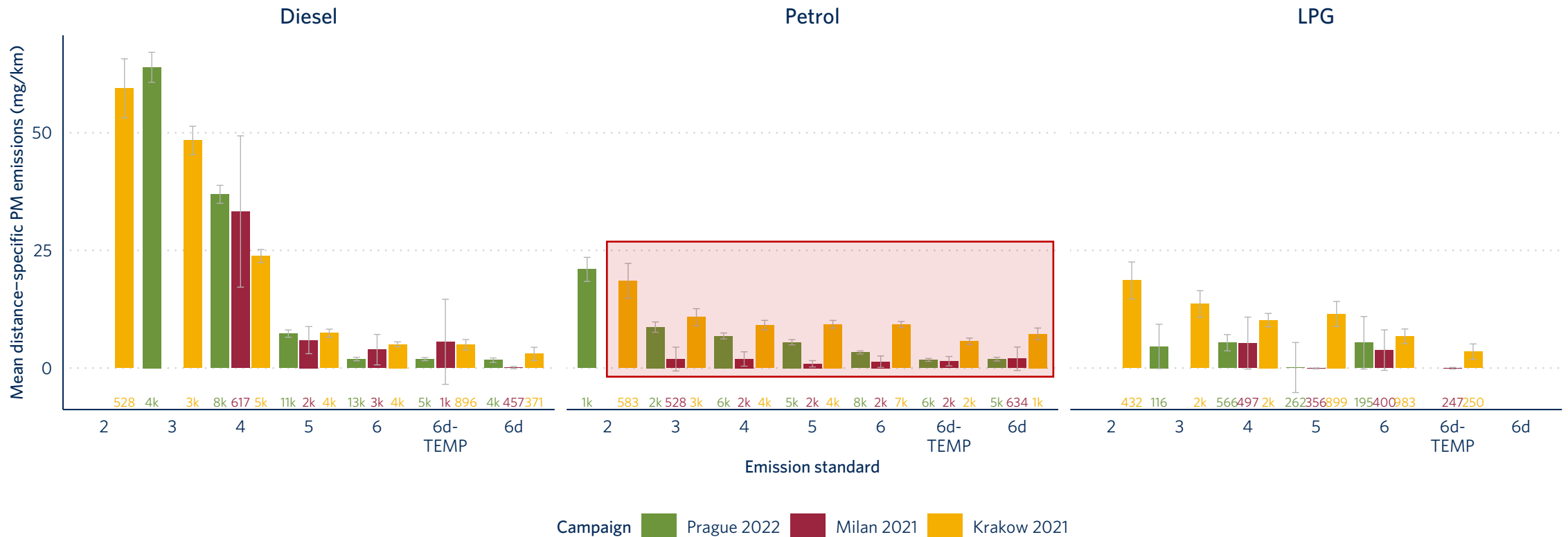
- 20-40% levels of diesel vehicles of the same standards before Euro 4

- **LPG:**

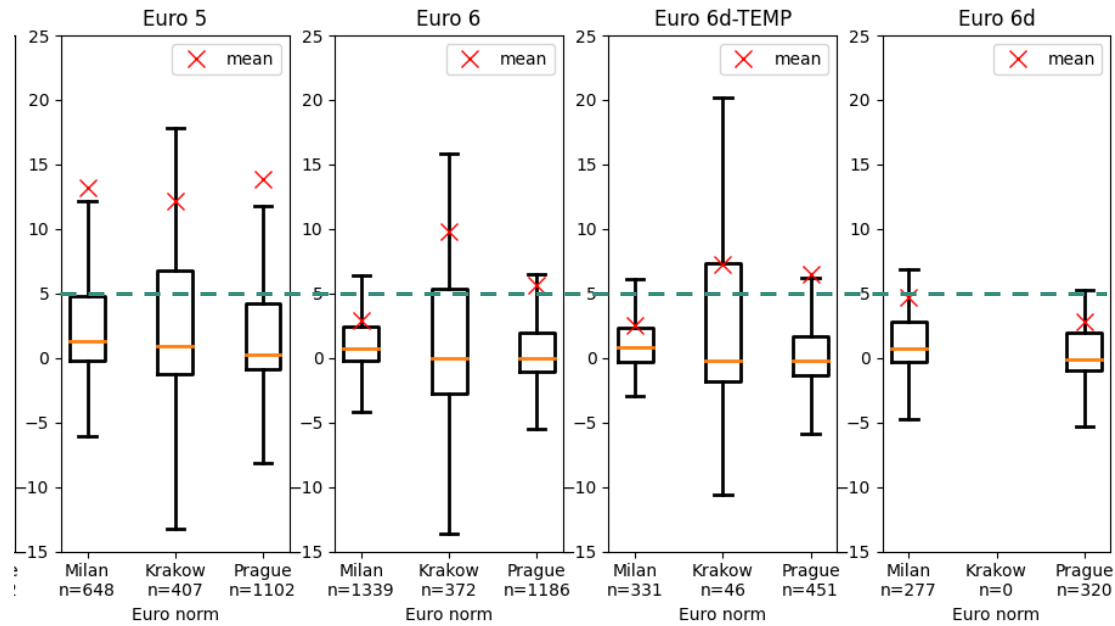
- No significant PM benefits from LPG vehicles compared to petrol vehicles



# Campaign-specific results show the influence of driving conditions on PM emission performance.



# Point sampling data show similar trends, indicating that average BC emissions from diesel Euro 5 and above exceed type-approval limits

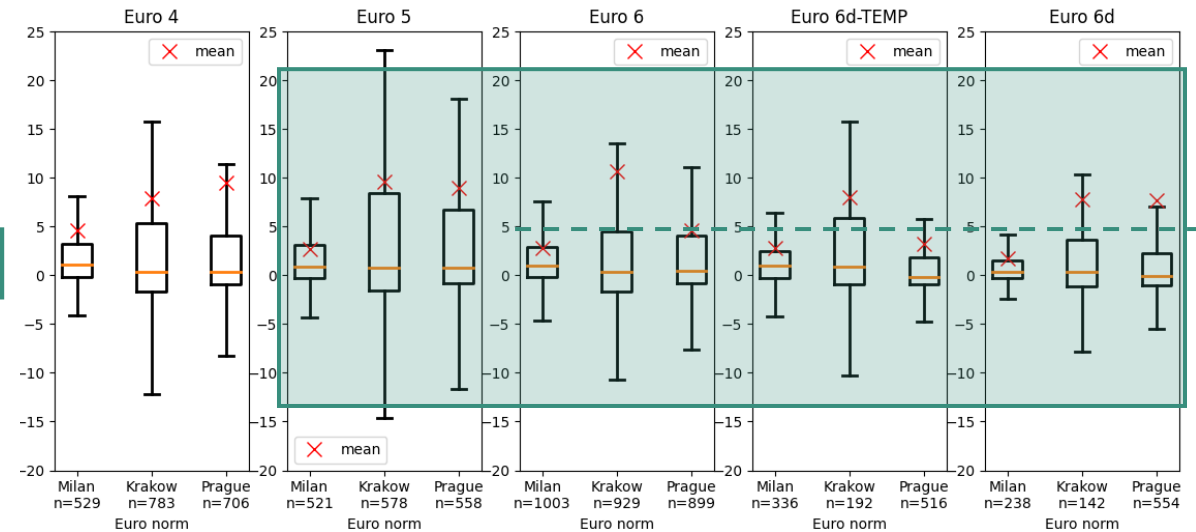


## Diesel passenger cars

- Mean BC emissions from Euro 5 and above exceed 5mg/km type-approval limit
- Presence of a small fraction of high-emitting vehicles (mean > median)

## Petrol passenger cars

- Highly elevated BC emissions from Krakow vehicles
  - Euro 6 and above exceed 5mg/km type approval limits
  - Mean > median



# Remote sensing measurements can also support the planning and assessment of low emission zone policies.

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- Milan's low emission zone (2019 - ):

- Zone B (i.e. Via Cilea):
  - At least Euro 2 for petrol vehicles
  - At least Euro 3 for diesel vehicles (with diesel particulate filters)
- Zone C (i.e. Via Madre Cabrini):
  - At least Euro 2 for petrol vehicles
  - At least Euro 4 diesel vehicles (with diesel particulate filters)

- Exemptions include:
  - LPG, CNG powered vehicles,
  - 2 wheelers, such as motorcycles and mopeds

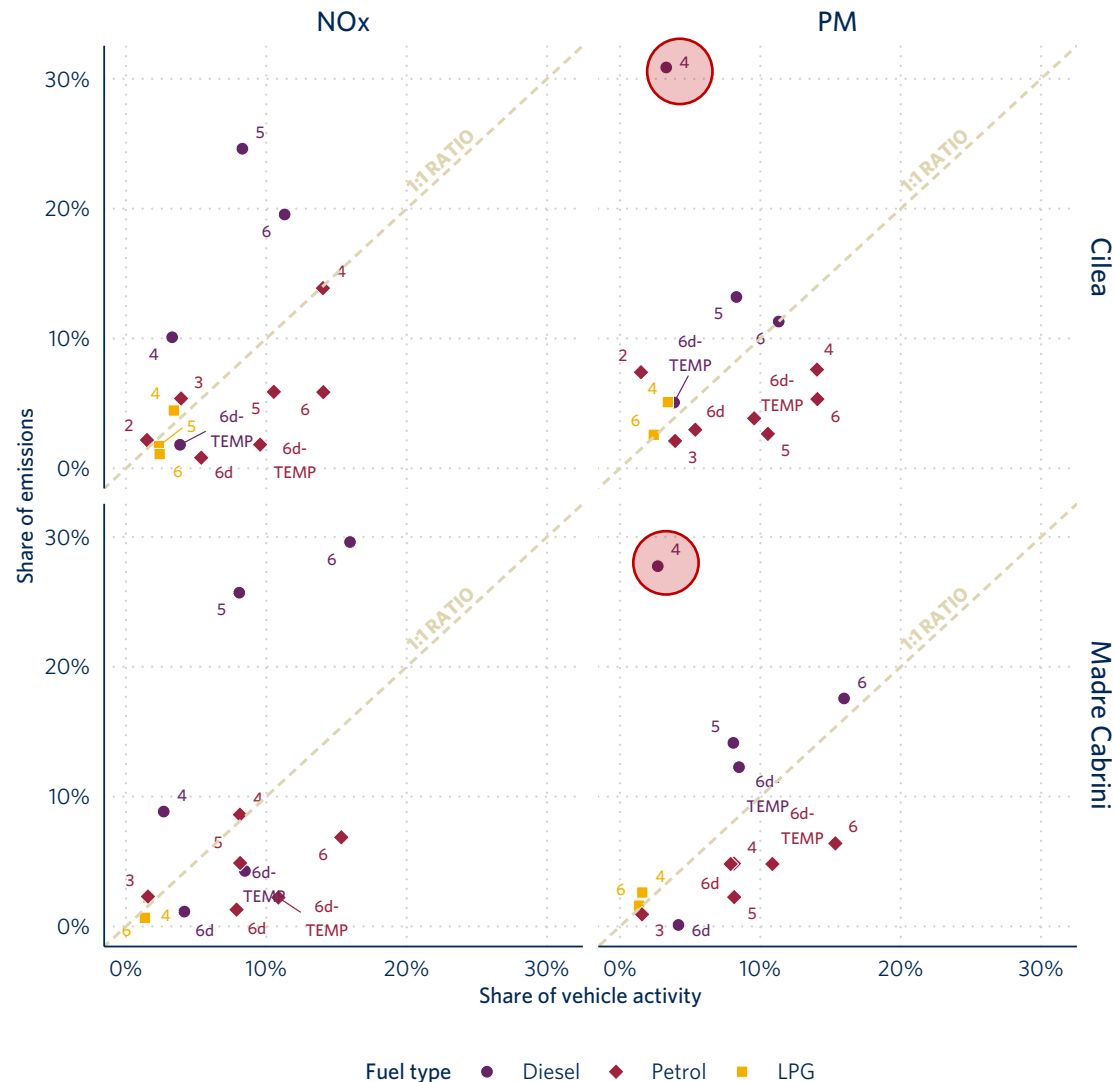
- Next step of restrictions delayed due to COVID

- Krakow's low emission zone:

- Starting 2024 for vehicles registered before 2023:
  - Petrol and LPG vehicles certified to Euro 1 or later
  - Diesel vehicles certified to Euro 2 or later
- Starting 2024 for vehicles registered after 2023 & 2026 for all vehicles:
  - Petrol and LPG vehicles certified to Euro 3 or later
  - Diesel vehicles certified to Euro 5 or later



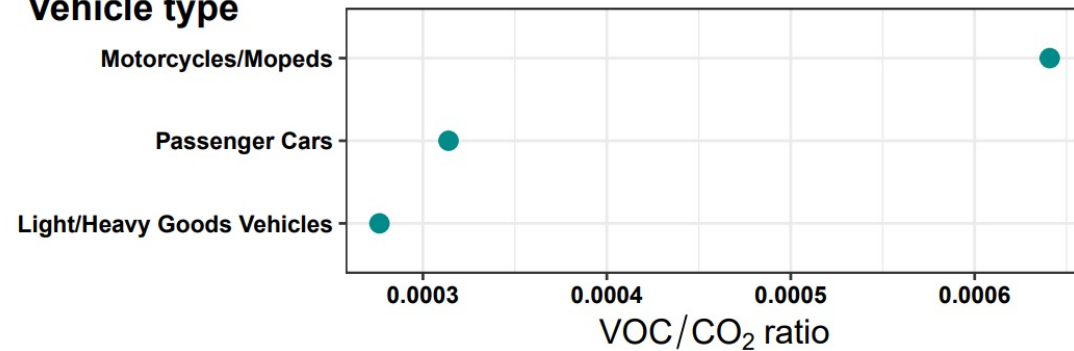
# Milan's low emission zone's need for limiting exemptions to vehicles powered by LPG and CNG and motorcycles and mopeds for greater emissions benefits



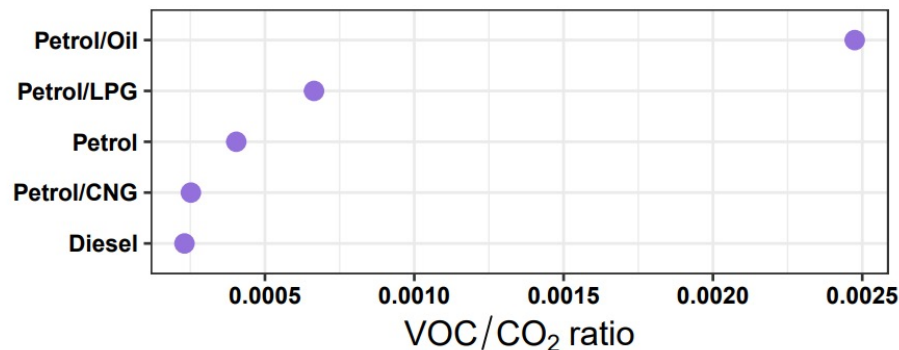
- RS measurements provide evidence supporting targeting diesel vehicles:
  - Pre- RDE Euro 6 have NO<sub>x</sub> emissions multiple times those from petrol, LPG, or CNG
  - Cilea: Euro 4 (no DPF) account for 30% of PM with only 3% of activity
  - Madre Cabrini: mostly Euro 4 with DPF but still largest contribution to PM due to exempted days
- Current LEZ exempts LPG/CNG vehicles and motorcycles and mopeds:
  - LPG make up a fair share in Milan (15% in Cilea) while emitting more NO<sub>x</sub> emissions than petrol vehicles
  - LPG responsible for carbon monoxide emissions and CNG methane emissions
  - They are important VOC (volatile organic compounds) sources

# Milan's low emission zone's need for limiting exemptions to vehicles powered by LPG and CNG and motorcycles and mopeds for greater emissions benefits

## Vehicle type

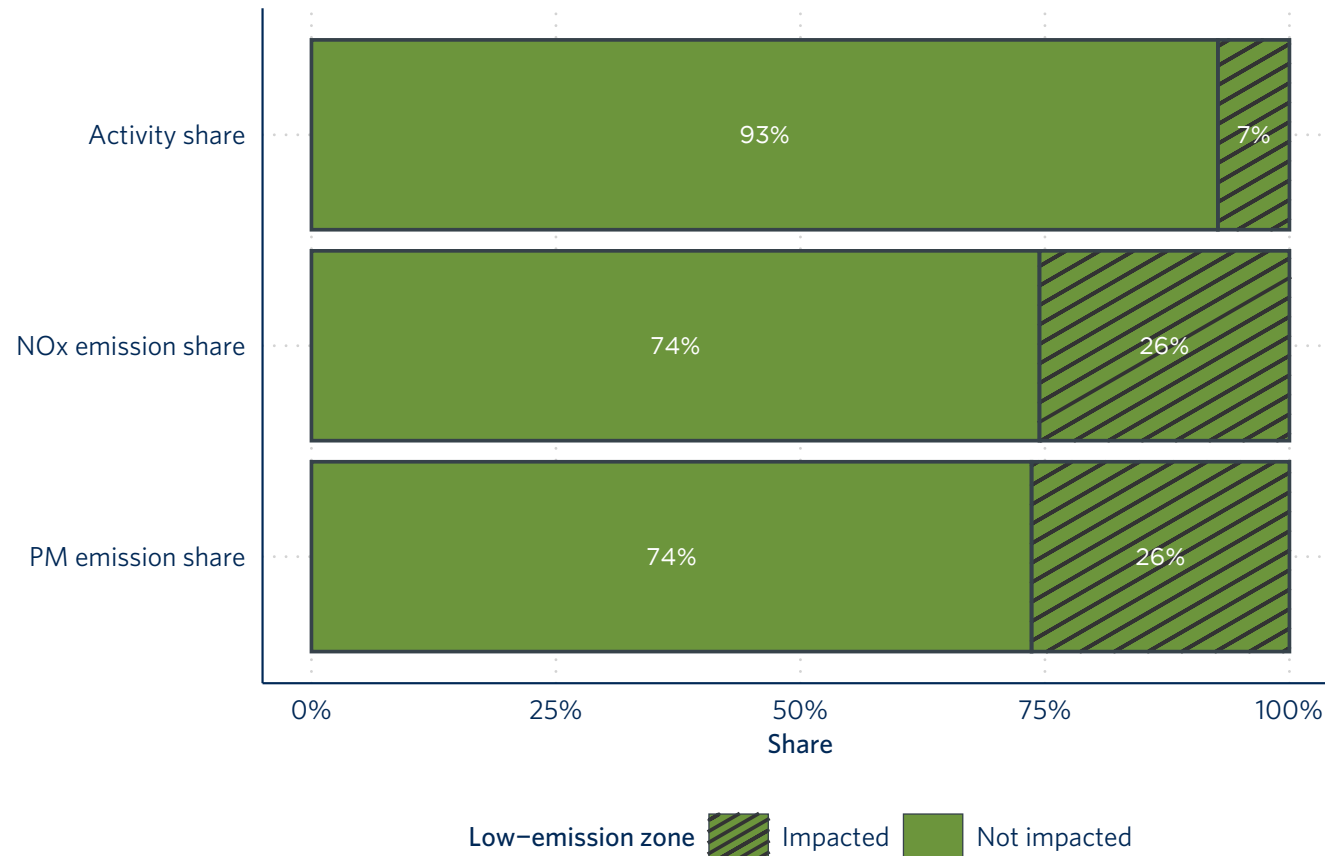


## Fuel type



- RS measurements provide evidence supporting targetting diesel vehicles:
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# Krakov's low emission zone would bring about disproportionate emissions benefits without affecting too many vehicle owners.



- Fleet composition in 2026
  - Increase in the shares of Euro 6d – 7
  - Affected share of vehicle activity down to 7% from 21% in 2021
- LEZ restrictions on diesel vehicles up to Euro 5 and gasoline vehicles up to Euro 2
  - Responsible for over a quarter of NO<sub>x</sub> and PM emissions

# Suspicious NO<sub>x</sub> high-emitters detected using plume chasing on a Prague highway

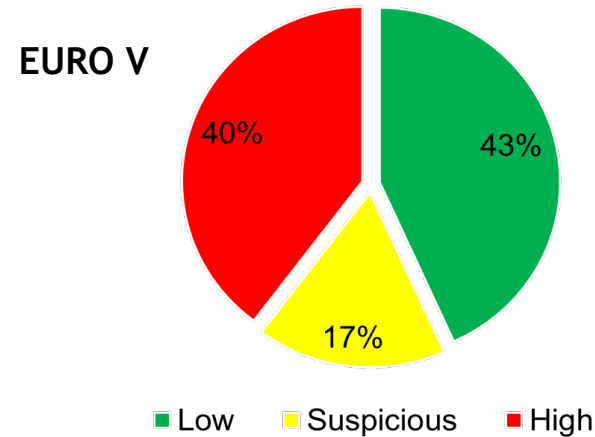
Auto-classification thresholds (≥ 60secs)

	Euro V	Euro VI
Classification	mg/kWh	mg/kWh
low (up to)	< 2500	< 1200
suspicious (up to)	> 2500	> 1200
high (above)	> 3500	>2200

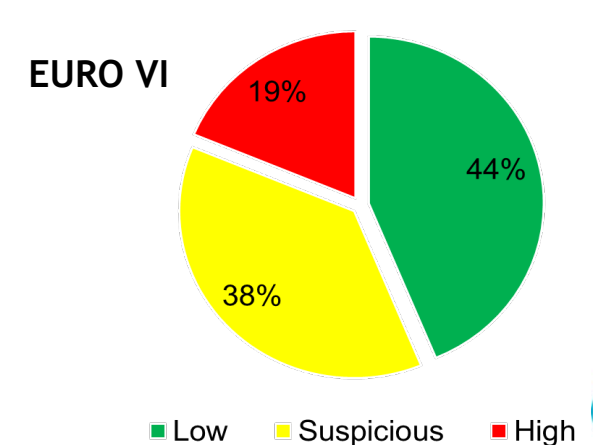
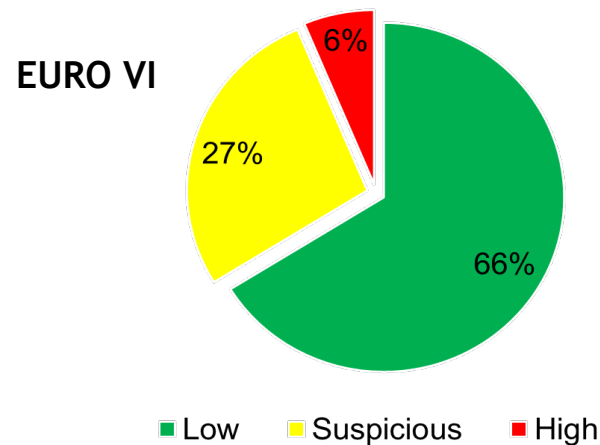
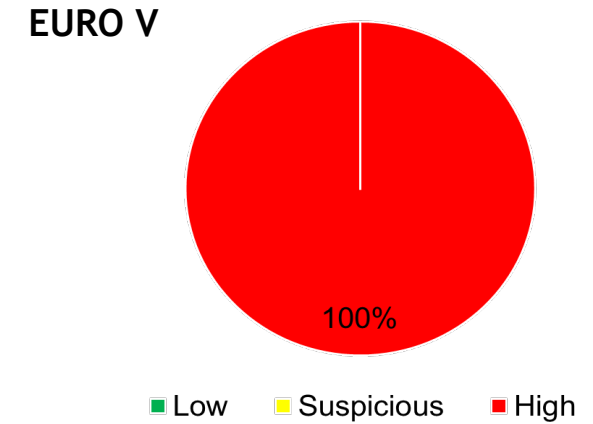
\* Reference thresholds

	Euro V	Euro VI
Classification	mg/kWh	mg/kWh
Euro emission limit	<2000	<460
ISC limit		< 690

Daytime measurements

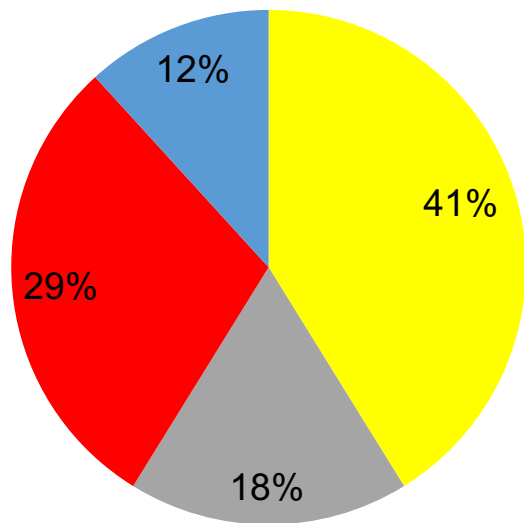


Nighttime measurements



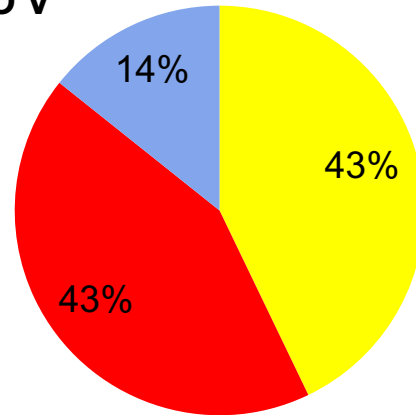
# Roadside inspection identified the causes of high emissions as defect, manipulation, and software issues

All inspected vehicles (n = 17)

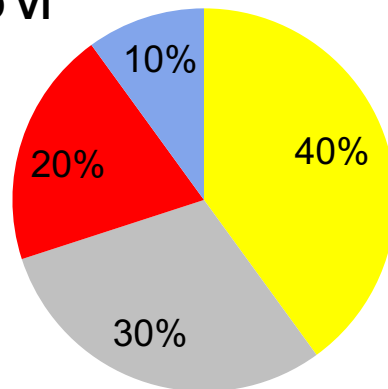


- No Error
- Defect / Error
- Software issues
- Manipulated
- Cold SCR

EURO V

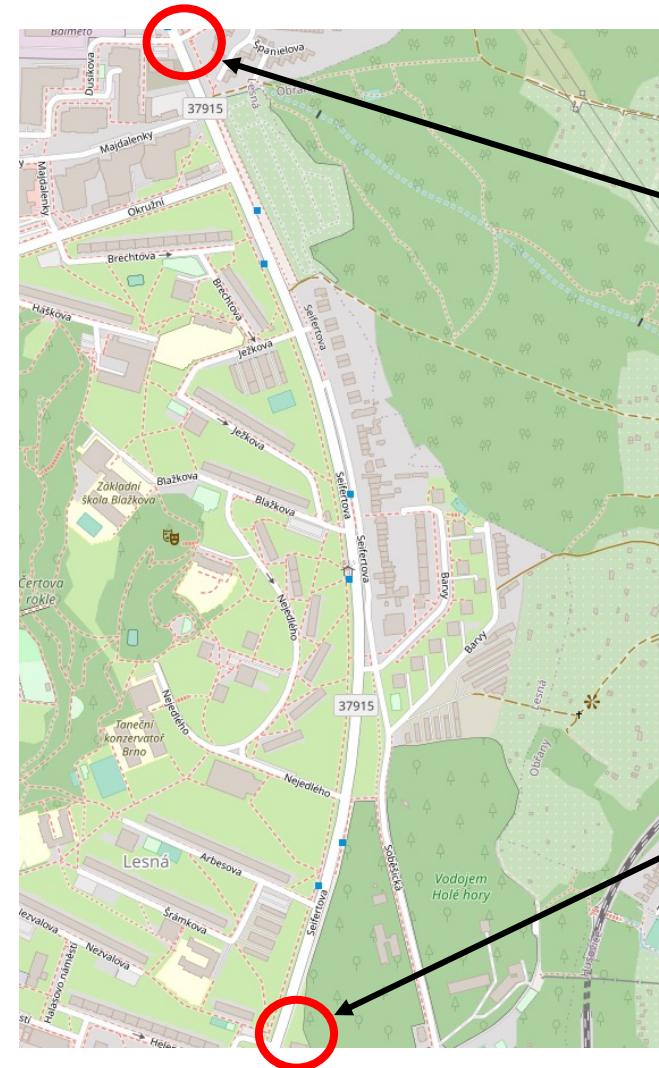


EURO VI



# PM high-emitters identified using point sampling

- Information of suspicious vehicles identified using PN counter passed to inspectors
  - Tentative Point Sampling PN threshold:  $> 1 \cdot 10^{14}$  # per kg fuel
- 13 out of 17 inspected vehicles identified as PM high-emitters
- Caveats:
  - Live identification by looking at the immediate graphs – needs software
  - Looking parallel at data and license plates and forwarding the information



Police and technical inspections

Forwarded by telephone potential high emitters

PS location

Vehicle	Reg. Year	Fuel type	TAILPIPE			Inspection comment
			PS BC (g/kg)	PS PN (10 <sup>14</sup> /kg)	INSPECTION PN (#/cm <sup>3</sup> )	
<b>FORD Transit</b>	2008	Diesel	-	-	3,00E+06	Missing ANPR detection
<b>MAN TGL 12.250</b>	2011	Diesel	-	-	9,00E+07	Missing license plate information
<b>FIAT Doblo</b>	2014	Diesel	0,43	77	9,00E+06	Expired technical inspection
<b>FORD Transit</b>	tbd	Diesel	0,65	62	3,00E+07	
FORD Galaxy	2012	Diesel	2,99	36	-	393k mileage, no working DPF according to inspection, no PN inspection
SKODA Octavia	tbd	Diesel	-	-	3,00E+06	Missing ANPR detection
PEUGEOT 407	2008	Diesel	1,8	39	2,00E+06	
SKODA Superb	tbd	Diesel	-	-	2,30E+06	Vehicles too close for proper plume separation
<b>IVECO Daily</b>	2011	Diesel	-	-	5,00E+06	Missing ANPR detection
<b>VW Transporter</b>	2009	Diesel	1,38	109	1,35E+07	
AUDI A3	tbd	Diesel	-	-	1,40E+07	Missing ANPR detection
MERCEDES BENZ	2001	Diesel	19,51	386	-	Visible smoke during acceleration, no PN inspection
DACIA Logan	2015	Petrol	0,37	4,9	-	No tailipe PN inspection
SKODA Octavia	2007	Diesel	0,17	12,4	-	No tailipe PN inspection
FORD S-Max	2006	Diesel	2,78	63,2	-	No tailipe PN inspection
HYUNDAI i30	tbd	Petrol	-	-	4,50E+04	No high emitter, vehicles too close for proper plume separation

# Major findings and conclusions

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- Highest NO<sub>x</sub> and PM emissions from pre-Euro 5 diesel light-duty vehicles but latest emission standards showing significant improvements
- Significantly elevated PM emissions from petrol vehicles in winter ambient temperatures (Krakow)
- Higher pollutant emissions from LPG-compatible vehicles than their petrol equivalents
- A small share of vehicles responsible for high average pollutant emissions (e.g due to malfunctioning or tampering of DPF, SCR)
- RS measurements can be used to quantify benefits and shortcomings of low emission zone policies and help make the case for their development and implementation
- RES techniques offer promising solutions to identify high-emitting vehicles or groups of vehicles and to develop effective policies for reducing emissions from transport
- RES could complement periodical technical inspection of vehicles in the European Union, by providing a efficient, contactless and undetectable method of screening emissions





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# Thank you for your attention!



This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 814966

