Advanced I/M methods to identify PN and NOx high emitters

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DRAFT - preliminary and subject to changes

Outline

List of Results

Periodic Technical Inspection (PTI) Today

- The European Union methods of inspection and maintenance, Periodic Technical Inspection (PTI) for exhaust emissions are mostly regulated by Directive 2014/45/EU:
  - Correct performance of complex exhaust after-treatment systems are verified by visual inspection (leaks, etc.).
  - Different requirements for vehicle engine type:
    - Positive ignition engine emissions use a certified exhaust gas analyzer to determine:
      - Gaseous emissions (CO, CO_2, O_2, HC) do not exceed OEM or vehicle type specified thresholds,
      - Lambda coefficient not outside OEM specified range, or if not specified not outside 1±0.03,
      - OBD read-out does not indicate significant malfunction.
    - Compression ignition engine emissions use certified opacity meter and protocol to determine:
      - Opacity does not exceed OEM/ vehicle type specified thresholds.
- Directive 2014/45/EU is out of date:
  - Not referenced to regulatory thresholds and measurements defined for (RDE) type-testing, notably for NO_x and PN measurement/thresholds and CO or CO_2 thresholds,
  - Existing PTI equipment cannot meet the PN requirements, and existing equipment may have to be adjusted to measure NOx.

PTI Tomorrow

- Post Dieselgate, European emission measurement is progressing:
  - VERT (DPF manufacturers association) advocates PN measurement at EU and member state levels
  - EU has implemented PMP and RDE protocol for vehicle type-approval testing, with measurement of CO, NO_x, HC+NO_x, PM and, from EURO-5, measurement of PN
  - Some member states are introducing new PTI regulations in advance of EU regulation:
    - Netherlands, Germany, Belgium, and Switzerland for PN for some diesel vehicles
  - EU regulates OBM CO_2 monitoring for new vehicles from 2021
- CITA has a role to play to implement emissions measurement at PTI:
  - Particulate protocol, measurement & threshold as per modified NPTI/Dutch procedure to be tested
  - NOx protocol, measurement & threshold as per CITA experience, to be developed and tested
  - Advocating EU homogeneity and building future-proof systems

Overview of published PTI PN Test Campaigns

- Many studies have demonstrated that measuring particle number concentration at low idle correlates to the particle emission during legal homologation test cycles and provides sufficient reliability to determine the filtration quality of a DPF:
  1. Kadijk and Mayer (2017) NPTI White Paper.
  2. Burtscher et al. (2019) A New Periodic Technical Inspection for Particle Emissions of Vehicles.
  3. Giechaskiel et al. (2020) Comparisons of Laboratory and On-Road Type-Approval Cycles with Idling Emissions. Implications for Periodical Technical Inspection (PTI) Sensors.
- Gasoline engines with GPF can be tested similarly at idle but perhaps at higher RPM, and with some conditioning factors still being researched [VERT (2021) PTI by Particle Count PN at Low Idle[4]]

Overview of published PTI NOx Test Campaigns

- There have been recent efforts to trial methods to incorporate a NOx emissions test into the PTI schedule, as outlined in the CITA (2022) NOx position paper[5]:
  - Static idling load test[6] – deemed most promising in short term
  - Q_{NOx} Ratio – deemed more promising in long term
  - Speed acceleration/speed pumping
  - Short drive method (3DATX/Opus)
  - Driving cycle on test bench
  - Accelerated drive (start up)
  - OBD/diagnostic functions/OBM – deemed more promising in long term

Enhanced PTI Test Pilot – Opus Sweden

Aims and Objectives of the PTI Pilot Test Campaign

- PTI format:

Minimize Test Time | **Engine Conditioning** | **Repeatability** | **NOx Protocols** ***including NOx static idle protocol***

- Pollutant trends:

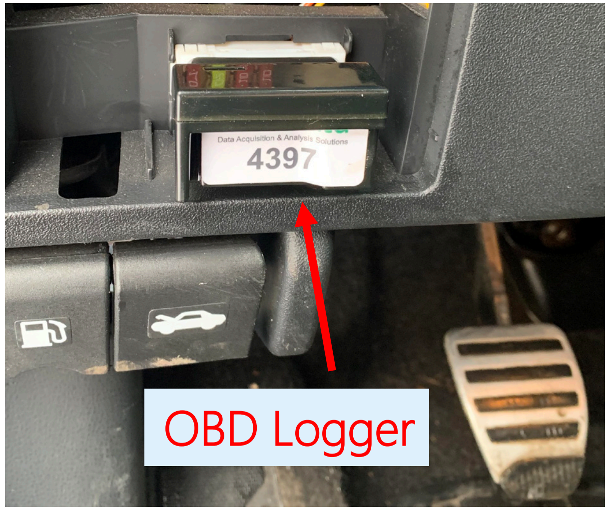
Comparison to Euro Standards | **Comparison to PTI Results**

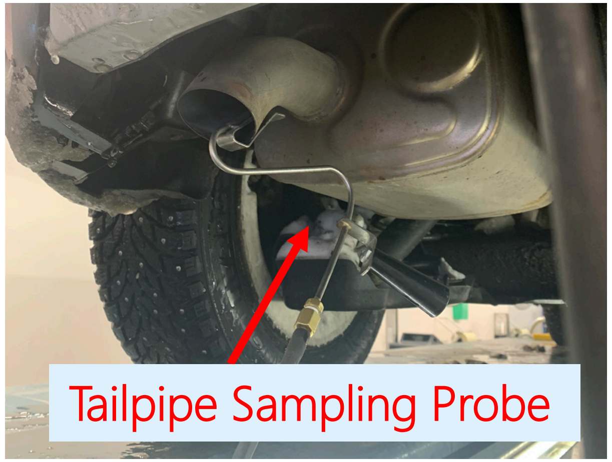
- Identification of high emitters

Introduction to the Borås Test Site

- Tests were conducted at the Borås Opus Bilprovning PTI Test Centre

parSYNC warmup and zeroing while vehicle is being prepared





Device used - The parSYNC iPEMS

- **Lightweight & Easy To Use**
  - Total System Weight: 6.7 kg (22.1 lb)
    - parSYNC® Weight: 4.1 kg (13.7 lb)
    - CUBE™ Weight (with one battery): 2.6 kg (8.4 lb)
- **Battery Life**
  - 4-5 hours typically
- **GasMOD™ Sensor Cartridge**
  - Electrochemical: NO (0-5000ppm) & NO_2 (0-300ppm)
  - NDIR: CO_2 (0-20%), CO (0-15%)
- **Particulates Sensor Cartridge**
  - PN/PM (10 to 10,000nm = 0.01 to 10µm)

The new parSYNC FLEX iPEMS

Gases – CO, CO_2, NO, NO_2 + **HC and O_2**

Particulates - Ionization, Scattering, and Opacity, **with advanced temperature control**

Diffusion charging-based particle number counter coming soon, to meet PTI requirements

Enhanced chiller and volatile particle removal

Hot-swap Milwaukee Li-Ion batteries for full-day of testing

Onboard display and data storage + WiFi Access-point

Full CAN + support for external sensors

Integrated GPS and Ambient Pressure, Temperature, Humidity

Integrated wireless OBD reader for LD and HD

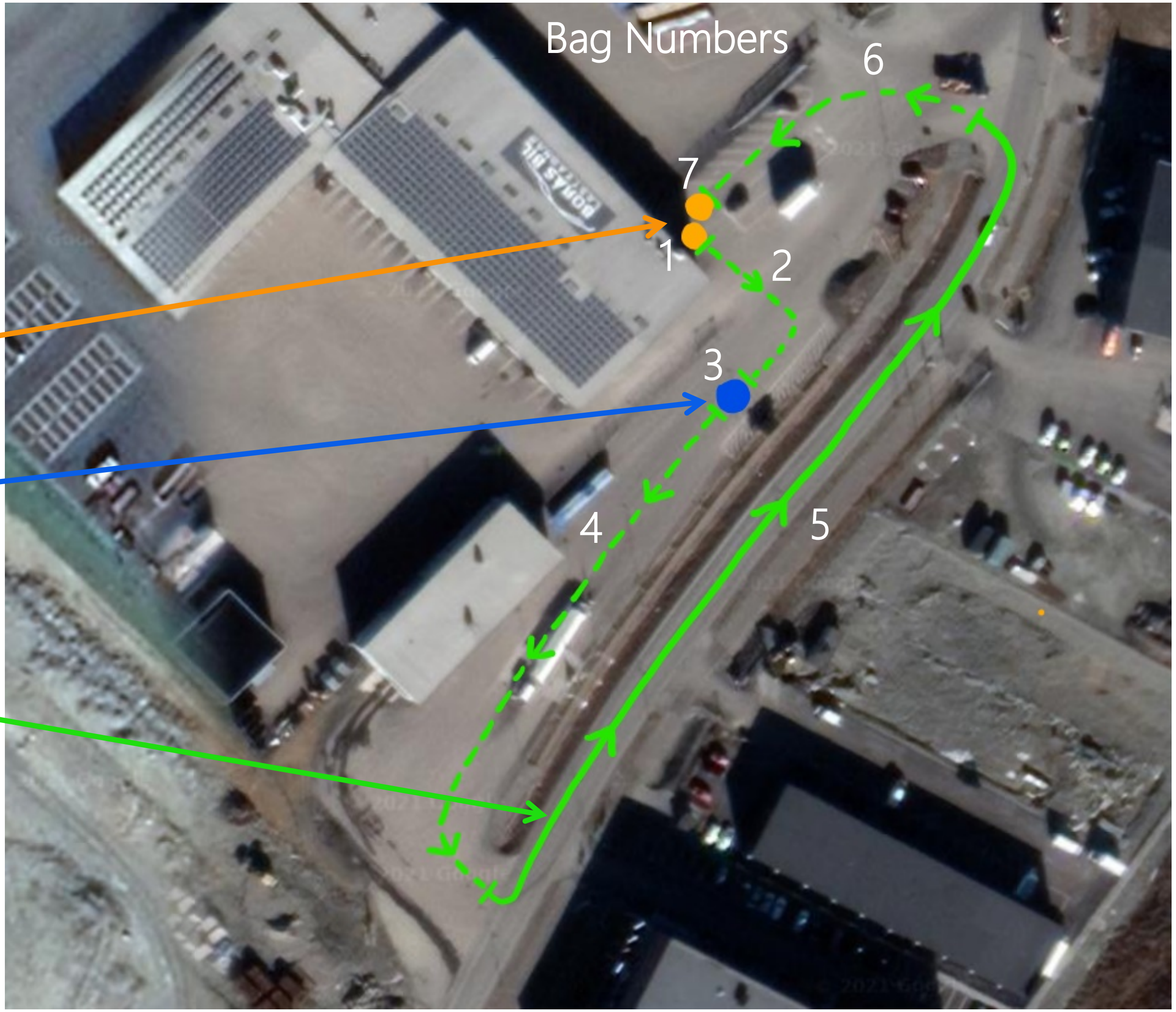
… and still light-weight (11 kg) and installs in minutes

Test Protocol V01/V02 – Extra 20 Minutes onto PTI

Bag No.	parSYNC Location	Description
	Bench	Warmup (or dry-out) the parSYNC using wall power while sampling clean ambient air (use HEPA filter if available)
0	Bench	Start test data file | Sample clean ambient air for ~60 seconds
Zeroing	Vehicle	Run the zeroing procedure while parSYNC is on the bench
0		With parSYNC running on battery power move it to the vehicle | Connect to tailpipe probe | Connect OBD reader to ECU port | Start the vehicle | Drive to parking lot position | Idle vehicle for 60 seconds
1-3	Vehicle	PN Idle – 30 seconds of idle | **Repeat 3 times**
4-6	Vehicle	NO_x High Idle – Idle → ~2500 RPM, hold for 5 seconds → return to Idle and hold for 10 seconds | **Repeat 3 times**
7	Vehicle	Idle for 60 seconds to allow NO_x emissions to stabilise
8-10	Vehicle	NO_x Acceleration – Stationary → 30 kph → Stationary | **Repeat 3 times**
11	Vehicle	Return vehicle to workshop/garage to uninstall | Disconnect parSYNC and place on bench and connect to wall power | Sample clean ambient air for 60 seconds
Zeroing	Bench	Run zeroing procedure with parSYNC on the bench

Test Protocol V03/V04 – Extra 5 Minutes onto PTI

Bag No.	parSYNC Location	Description
0	Bench	Sample clean air while parSYNC is on the bench.
Zeroing	Bench	Zero the parSYNC. Idle the vehicle.
0	Vehicle	Move parSYNC to vehicle. Sample exhaust gas for ~10 seconds.
1	Vehicle	PN Idle protocol – 60 seconds of idle – conducted while car is at garage
2	Vehicle	Drive to emissions shed
3	Vehicle	NOx High Idle – Follow standard PTI protocol for gasoline and diesel vehicles
4	Vehicle	Drive to NOx Acceleration test start point
5	Vehicle	NOx Acceleration – *Idle for 10 seconds*, then accelerate quickly to 30 kph, then brake normally (not hard) to a complete stop, *idle for 10 seconds*
6	Vehicle	Drive back to garage.
7	*Vehicle*	*PN Idle protocol – 60 seconds of idle*
8	Bench	Disconnect parSYNC. Sample clean air for at least 60 seconds.
Zeroing	*Bench*	*Zero the parSYNC.*

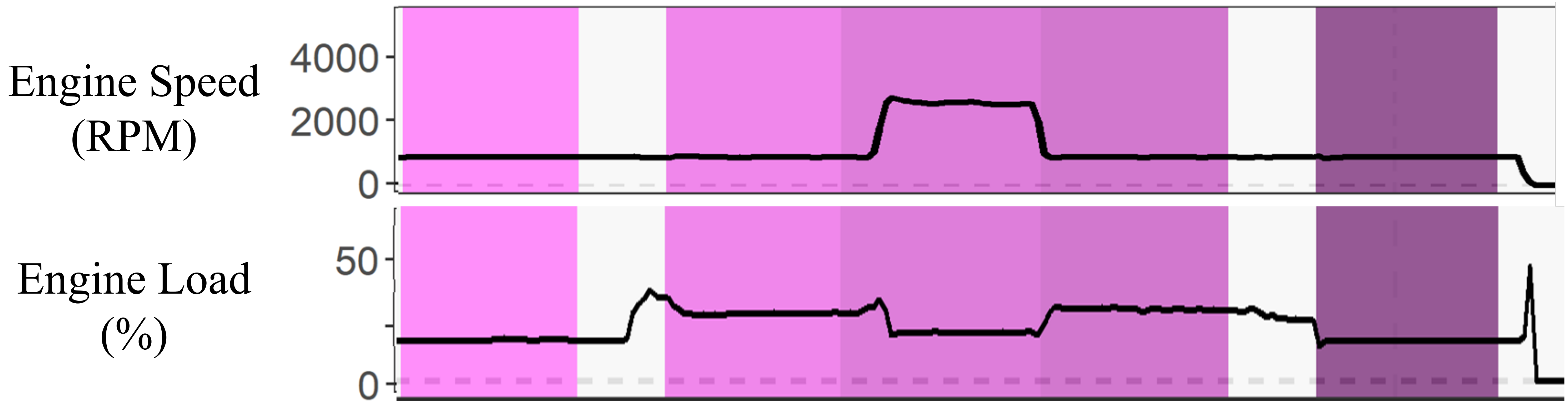


Test Protocol V05– Extra 7 Minutes onto PTI

Bag No.	parSYNC Location	Description
0	Bench	Sample clean air while parSYNC is on the bench.
Zeroing	Bench	Zero the parSYNC. Idle the vehicle.
0	Vehicle	Move parSYNC to vehicle. Sample exhaust gas for ~10 seconds.
1	Vehicle	PN Idle protocol – 60 seconds of idle – conducted while car is at garage
2	Vehicle	Drive to emissions shed
3	Vehicle	NOx High Idle – Follow standard PTI protocol for gasoline and diesel vehicles
4	Vehicle	Drive to NOx Acceleration test start point
5	Vehicle	NOx Acceleration – *Idle for 10 seconds*, then accelerate quickly to 30 kph, then brake normally (not hard) to a complete stop, *idle for 10 seconds*
6	Vehicle	Drive back to garage.
7	*Vehicle*	PN Idle protocol – 30 seconds of idle
8	Vehicle	Turn off any auxiliary equipment (A/C, lighting/signalling and rear window heater system)
9	Vehicle	Unloaded idle – 30s with A/C, lighting and signalling and rear window heater system off
10	Vehicle	Turn on A/C, lighting and signalling and rear window heater system (in that order)
11	Vehicle	Loaded idle – 30s with A/C, lighting and signalling and rear window heater system on
12	Vehicle	Loaded and accelerated – 30s with A/C, lighting and signalling and rear window heater system on, at 2500±500 rpm
13	Vehicle	Loaded idle – 30s with A/C, lighting and signalling and rear window heater system on
14	Vehicle	Turn off rear window heater system , lighting and signalling and A/C (in that order)
15	Vehicle	Unloaded idle – 30s with A/C, lighting and signalling and rear window heater system off
16	Bench	Disconnect parSYNC. Sample clean air for at least 60 seconds.
Zeroing	*Bench*	*Zero the parSYNC*

Test Protocol V05 – Static Idling Test Section

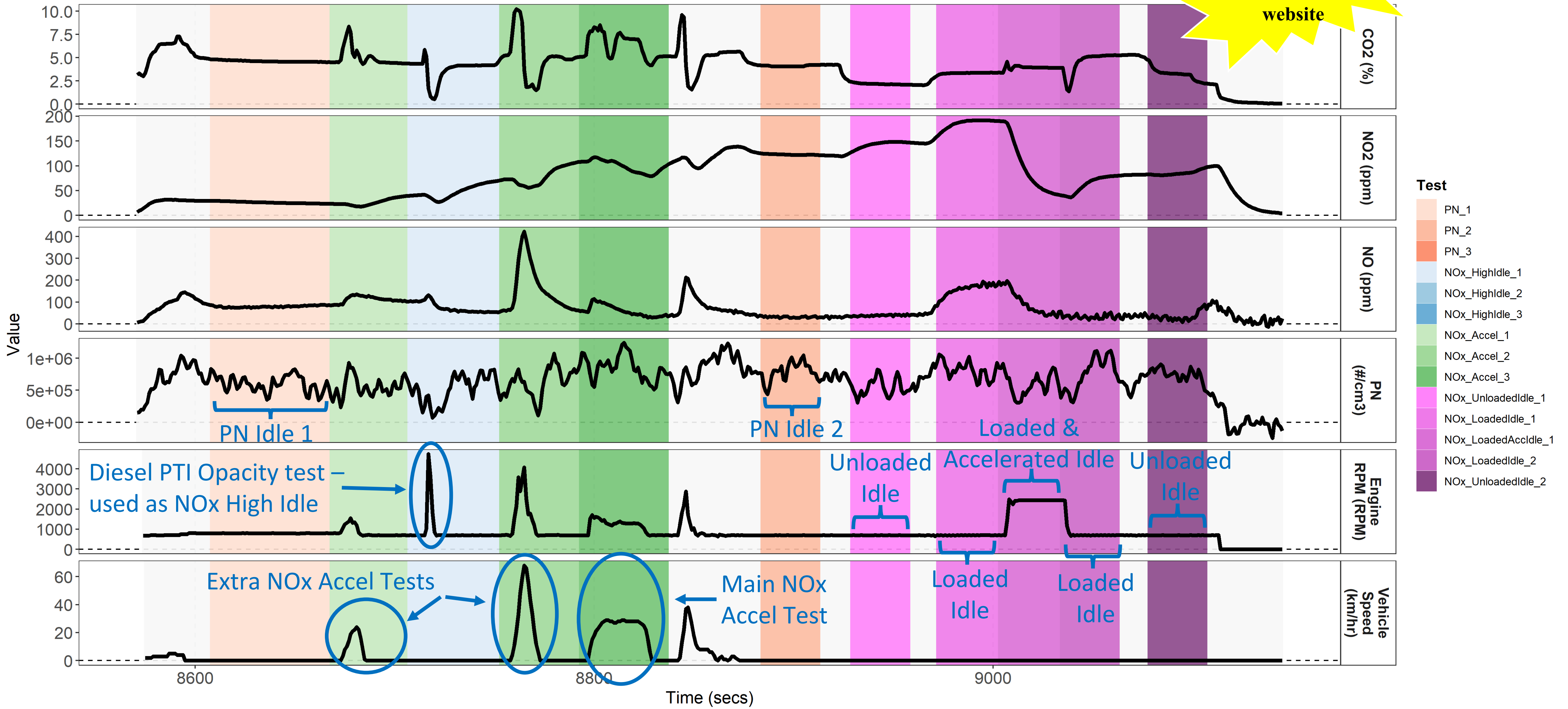
	Stage 1: Unloaded		Stage 2: Loaded	Stage 3: Loaded & Accelerated	Stage 4: Loaded		Stage 5: Unloaded	
Engine state	On		On	On	On		On	
Engine rotation speed	Natural idle speed		Natural idle speed	2000 < rpm < 3000	Natural idle speed		Natural idle speed	
Vehicle extra load equipment	Disconnected		Connected	Connected	Connected		Disconnected	
% Engine load value	<25% *		>25% *	Irrelevant	>25% *		<25% *	



Example of V05 PTI Test Protocol - Diesel

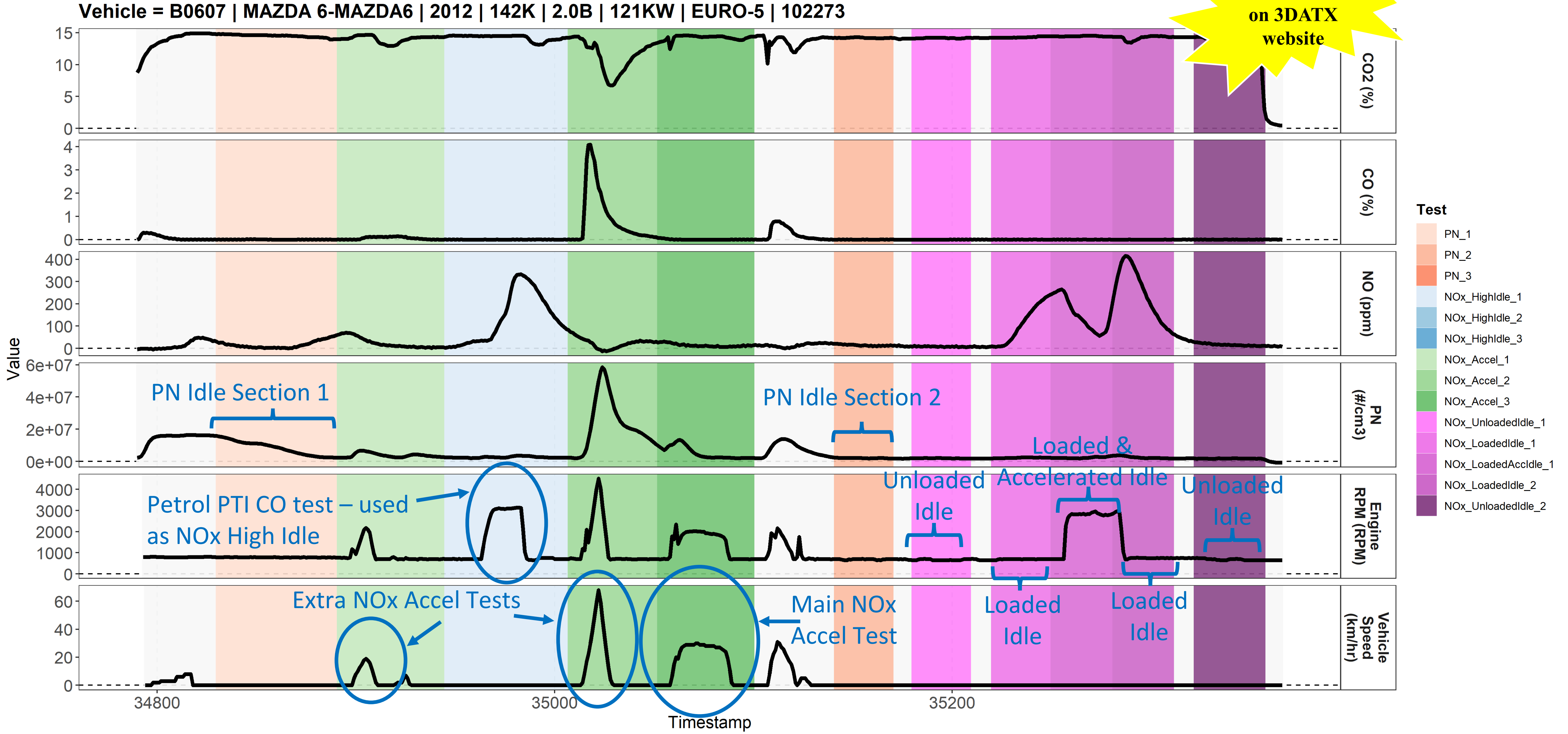
Full timeseries on 3DATX website

Vehicle = B0600 | VOLVO V70 | 2010 | 346K | 2.4D | 129KW | EURO-4 | 151360



Example of V05 PTI Test Protocol - Petrol

Full timeseries on 3DATX website

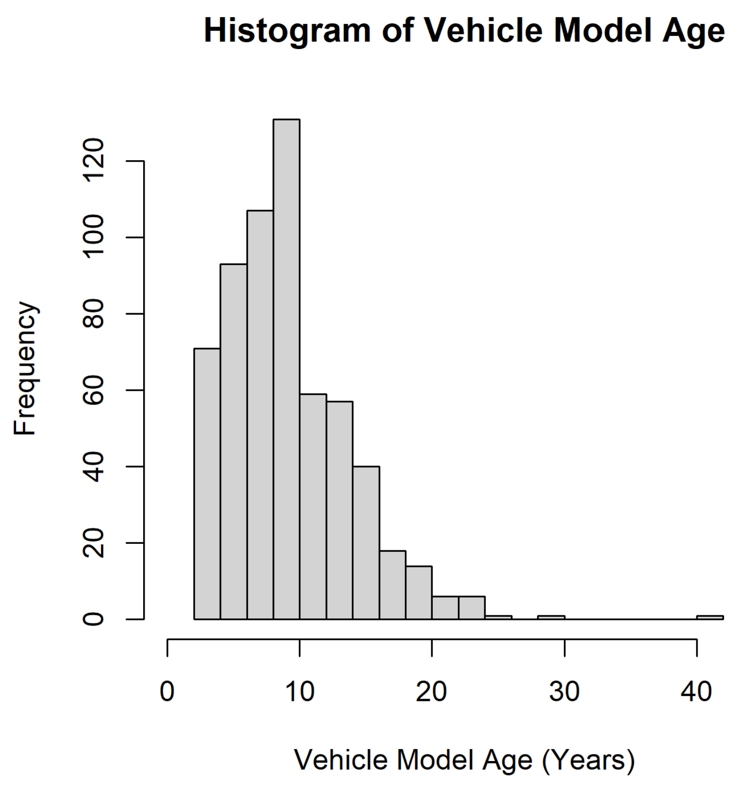


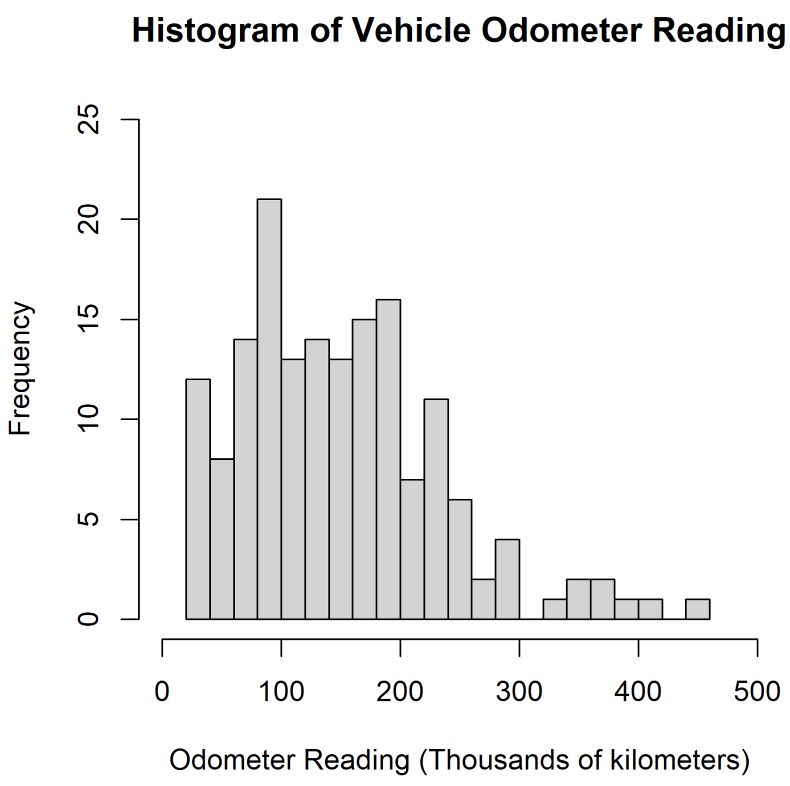
Characteristics of the Test Fleet

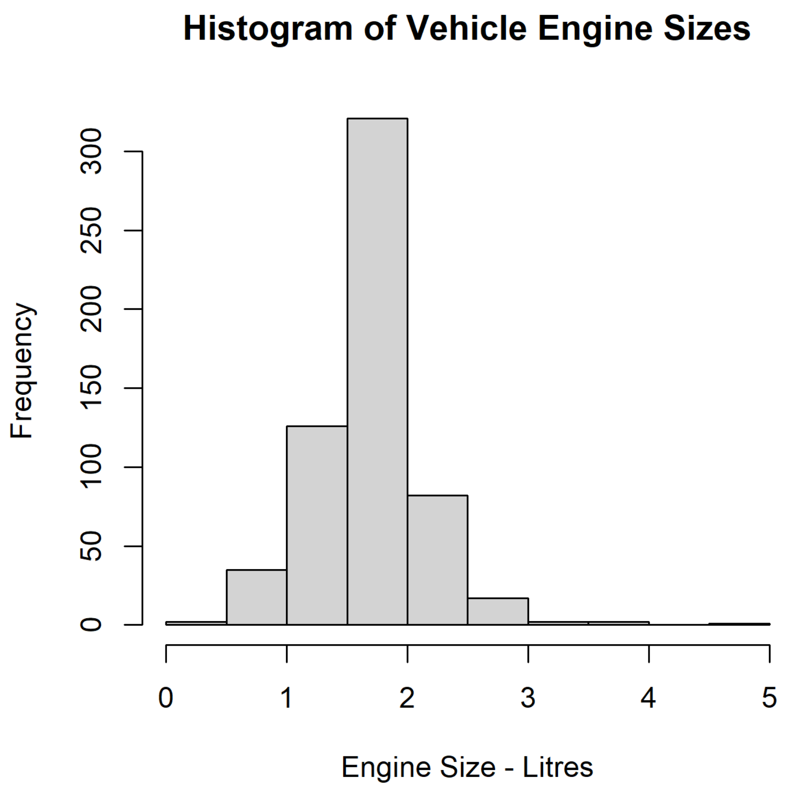
Age, Mileage, Engine Size, Fuel, Euro Std

Fleet Composition – Vehicle and Engine Information

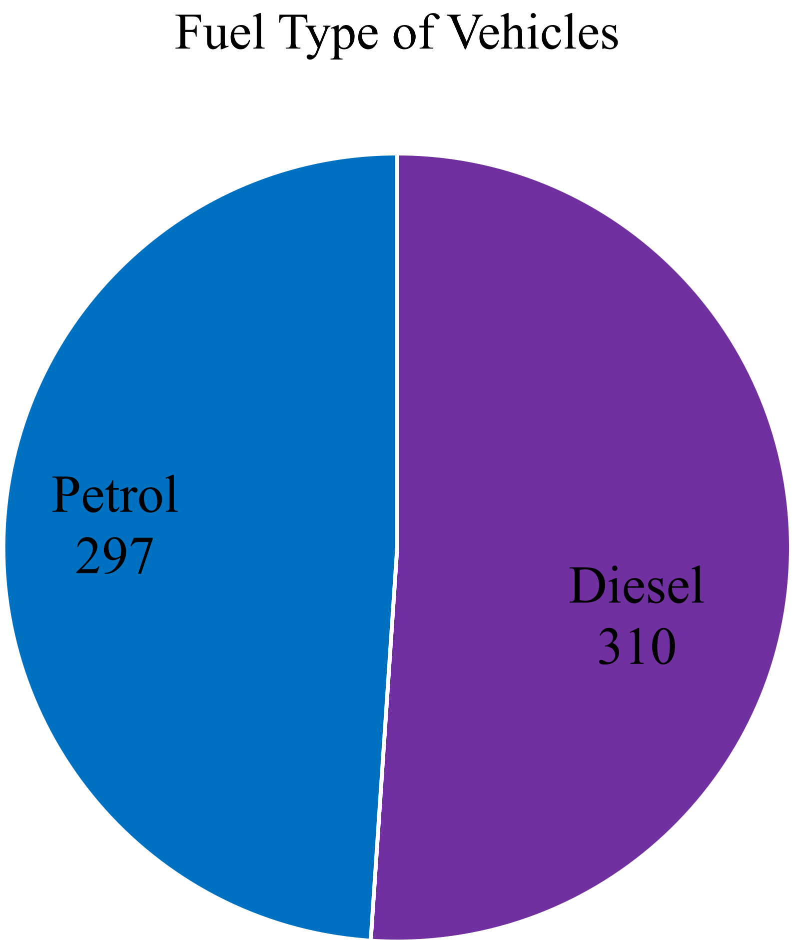
607 vehicles underwent enhanced PTI testing at the Borås Opus Bilprovning PTI Test Centre during January 2021 – June 2022

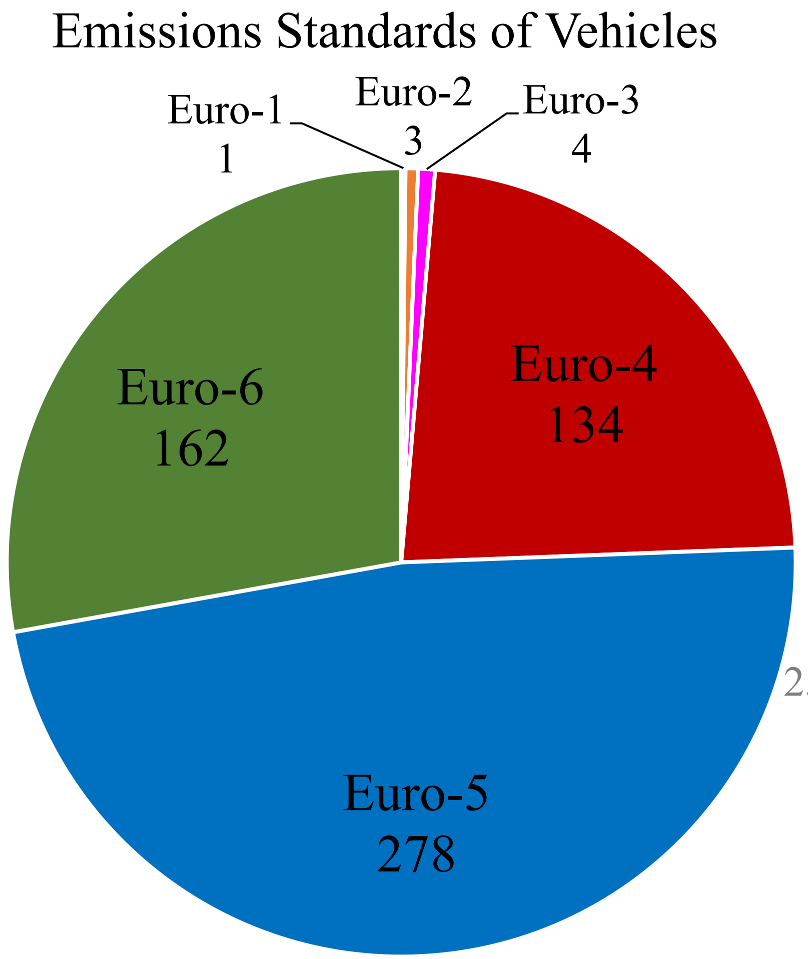






Fleet Composition – Fuel Types and Emission Standards





EURO	MY
1	1993
2	1997
3	2001
4	2006
5	2011
6	2015

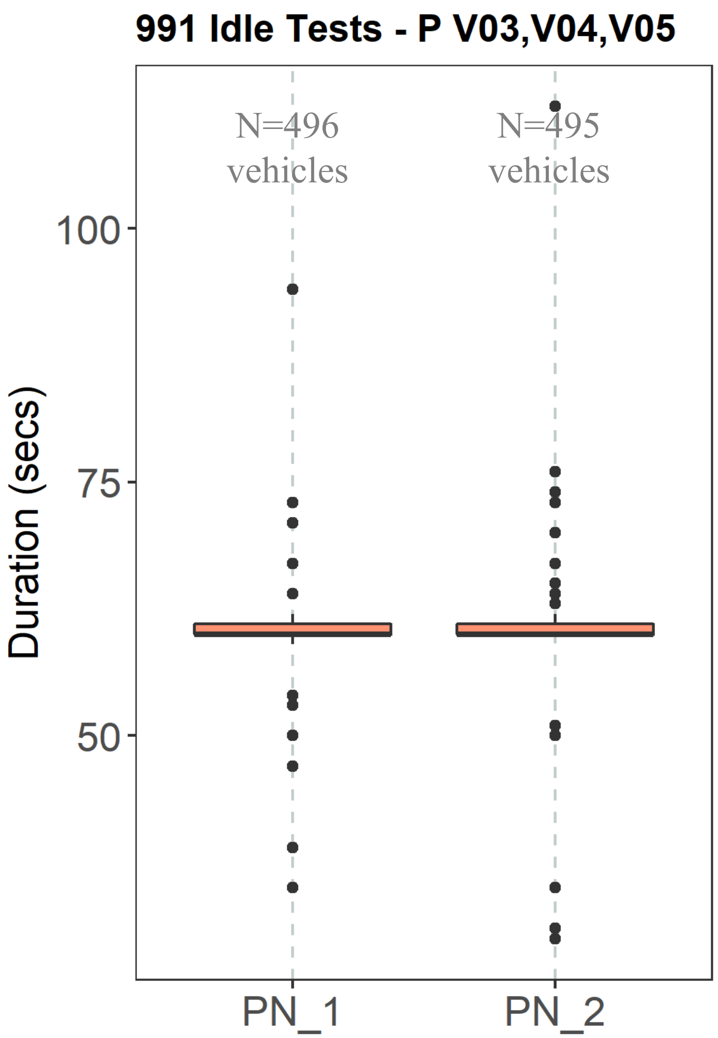
25 vehicles were of pre-Euro or unknown Euro standard

Characteristics of the Test Protocol

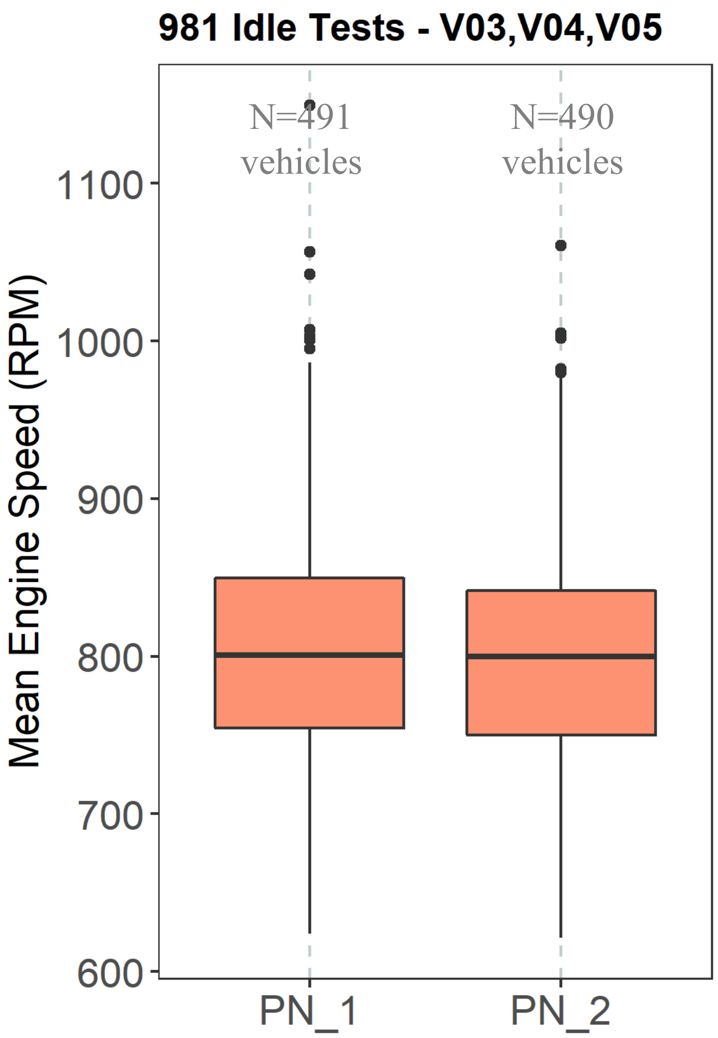
Inter-Vehicle Comparison, Operator Consistency

Idle Tests 1 and 2 – How Consistent?

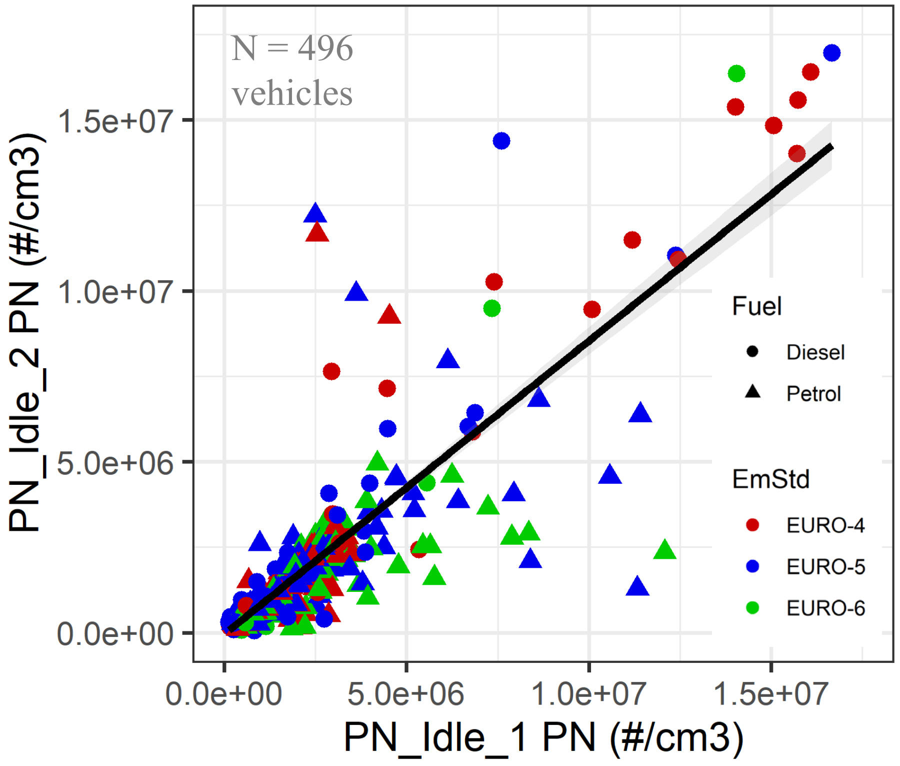
Duration



Engine RPM



First and second Idle tests are well correlated except some outliers (mainly petrol vehicles with anomalous emission trends)



High Idle Test – How Consistent?

Petrol Vehicles

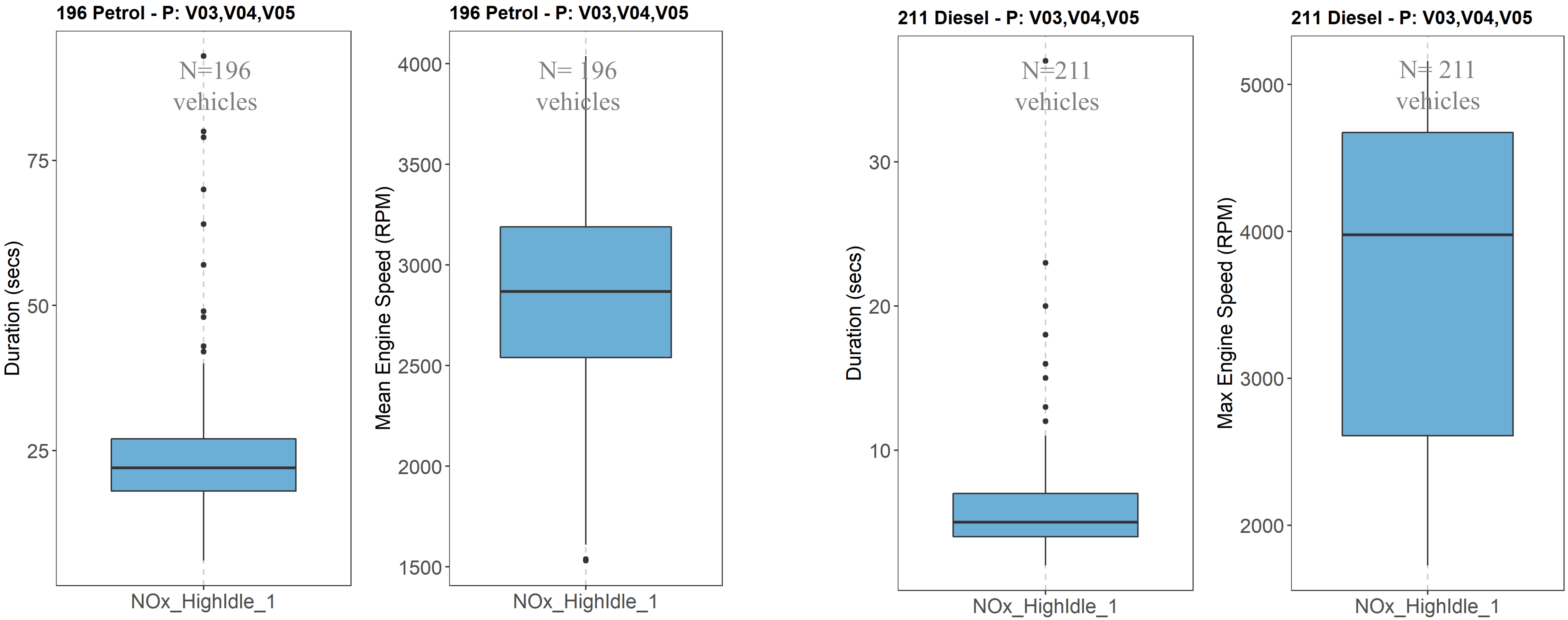
Duration

Mean Engine Speed

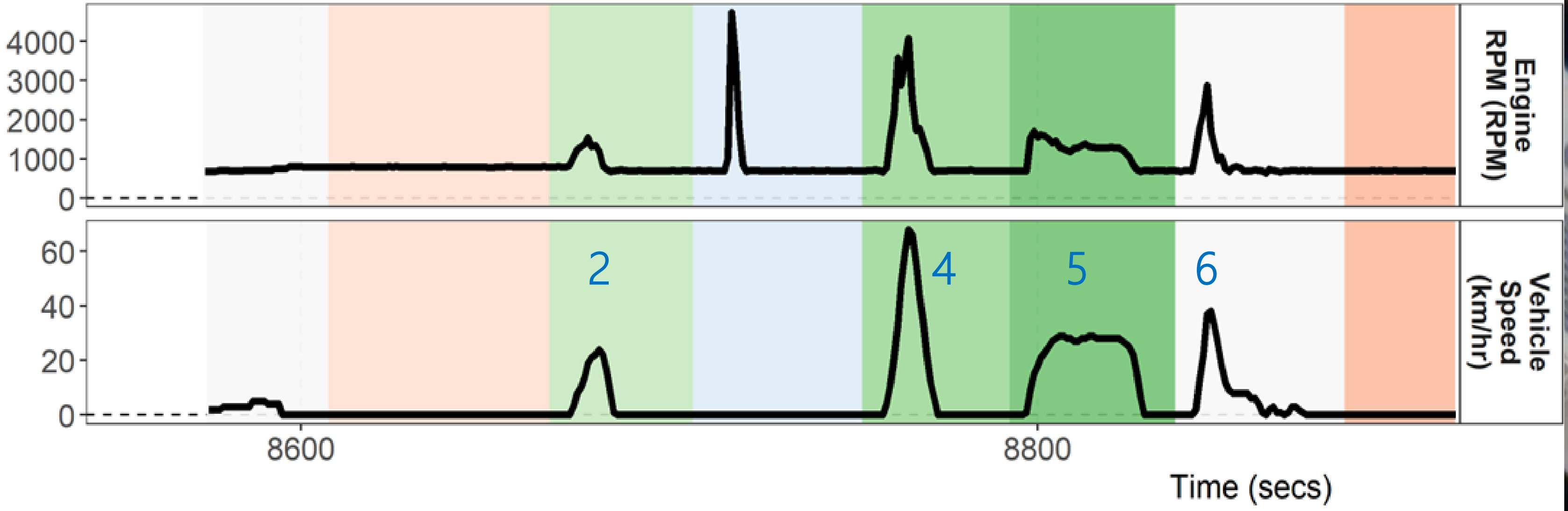
Diesel Vehicles

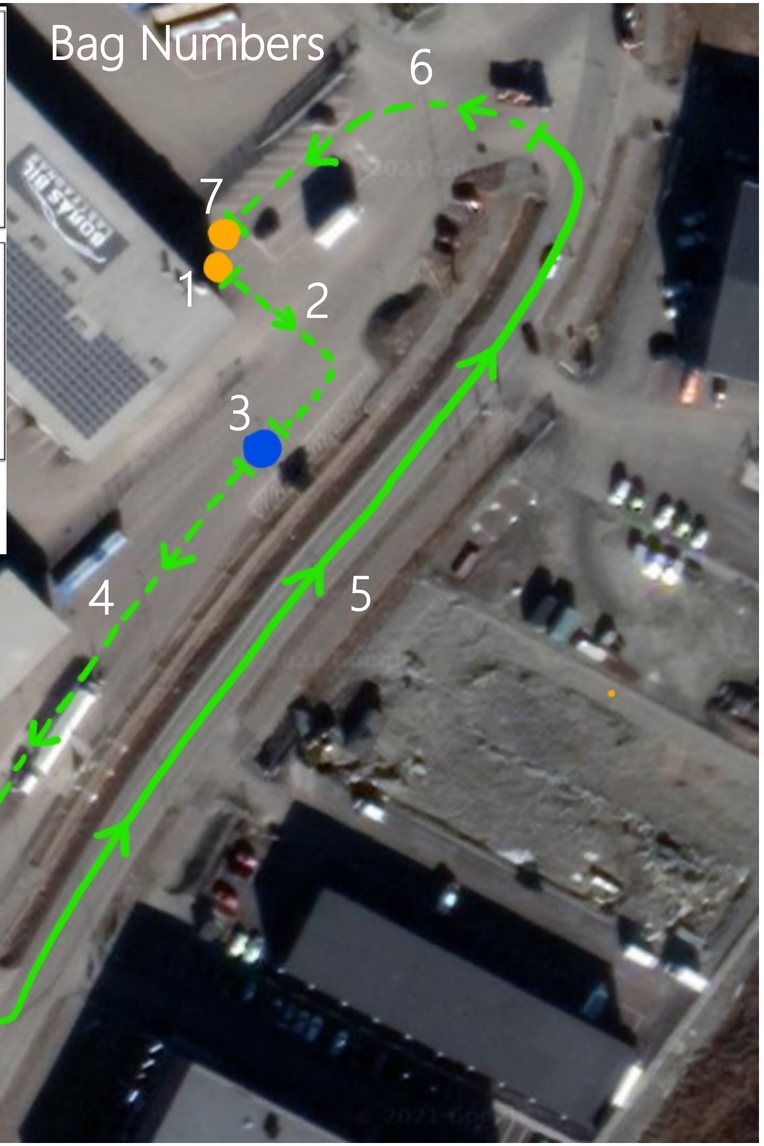
Duration

Max Engine Speed



Dynamic Acceleration tests



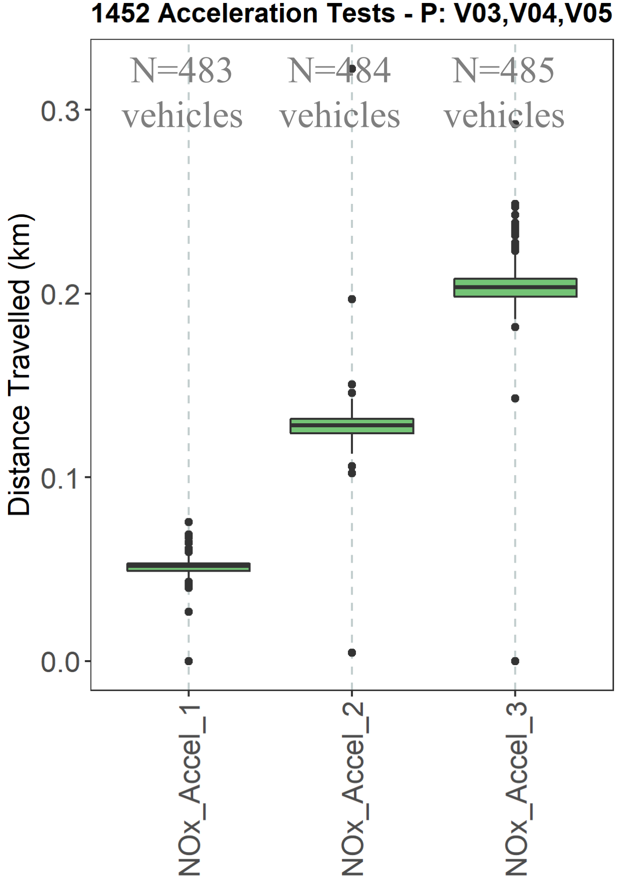


There are four driving sections in the protocol – labelled as 2, 4, 5, and 6.

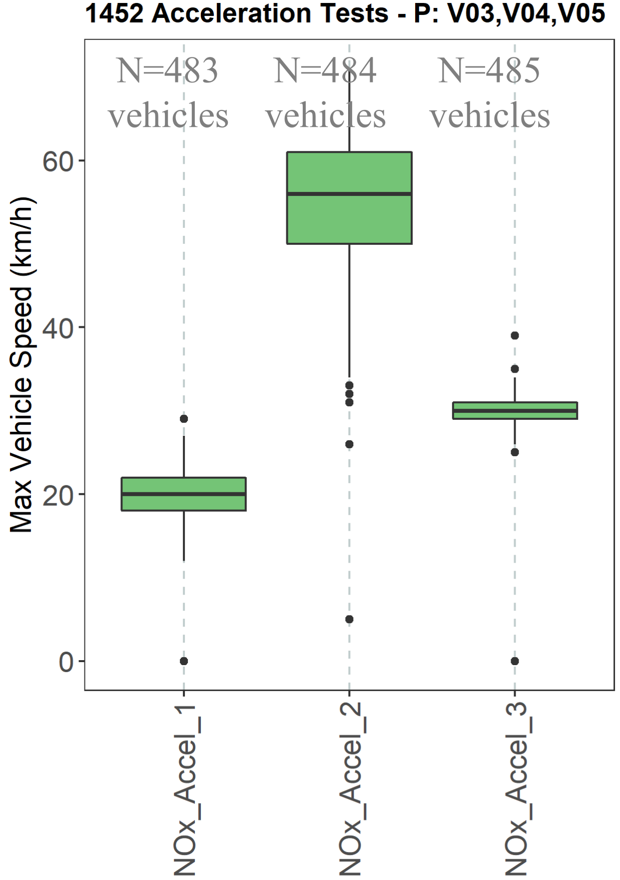
Sections 2, 4, and 5 have been processed as NOx_Accel 1, 2 and 3 respectively, with section 5 being further analysed as the main dynamic acceleration drive.

Dynamic Acceleration Tests – How Consistent?

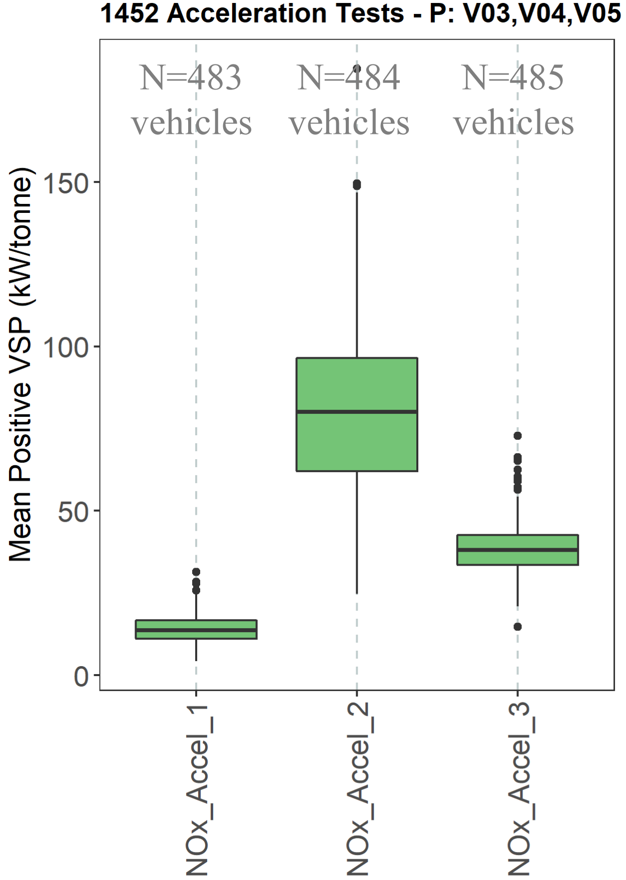
Distance



Maximum Vehicle Speed

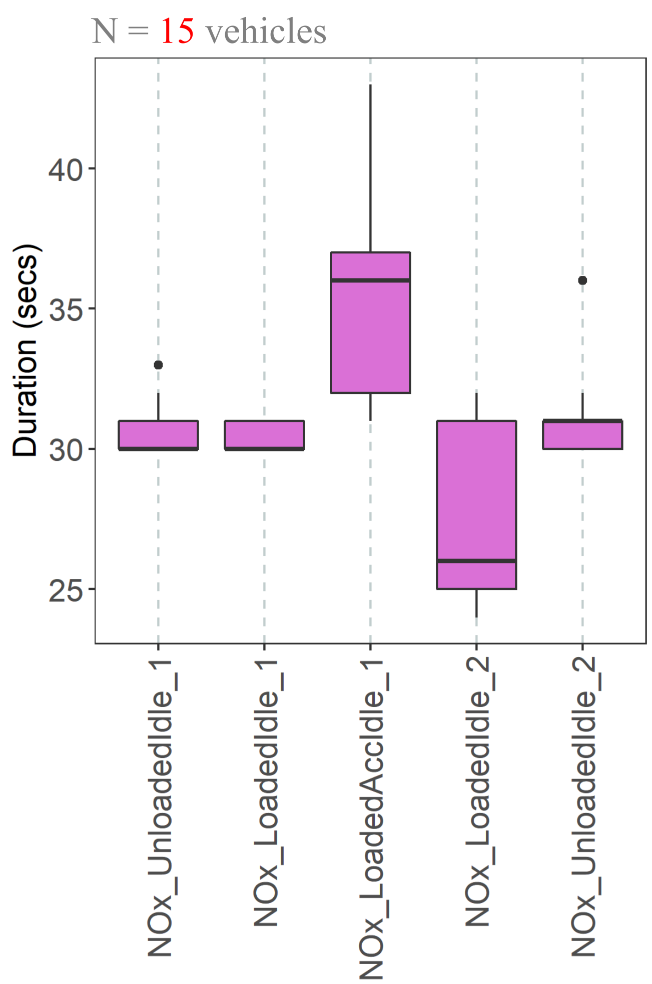


Positive VSP

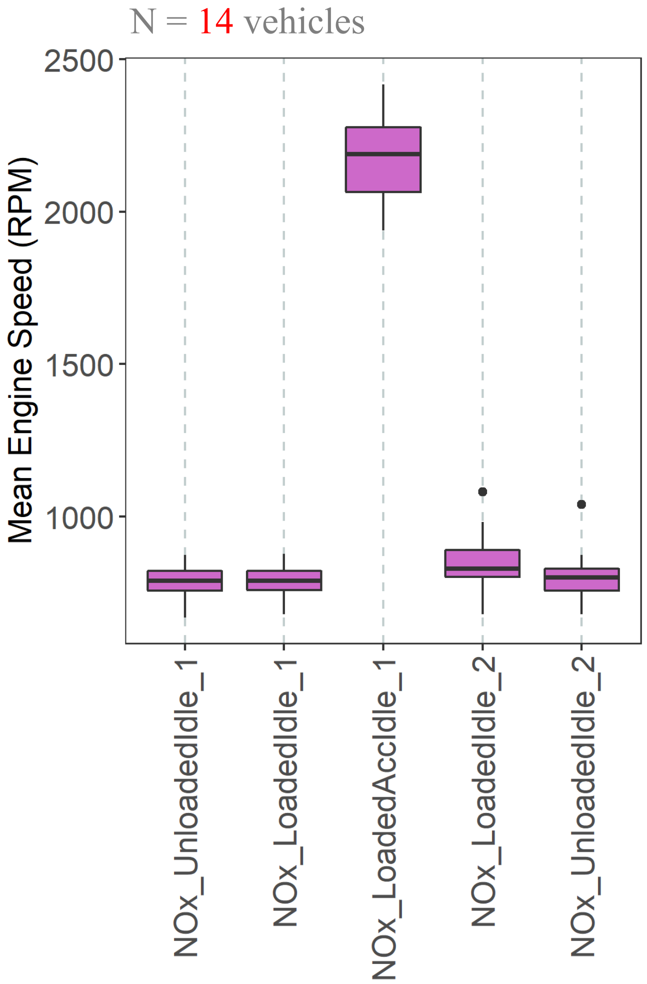


NOx Static Idle Test – Comparison of Stages

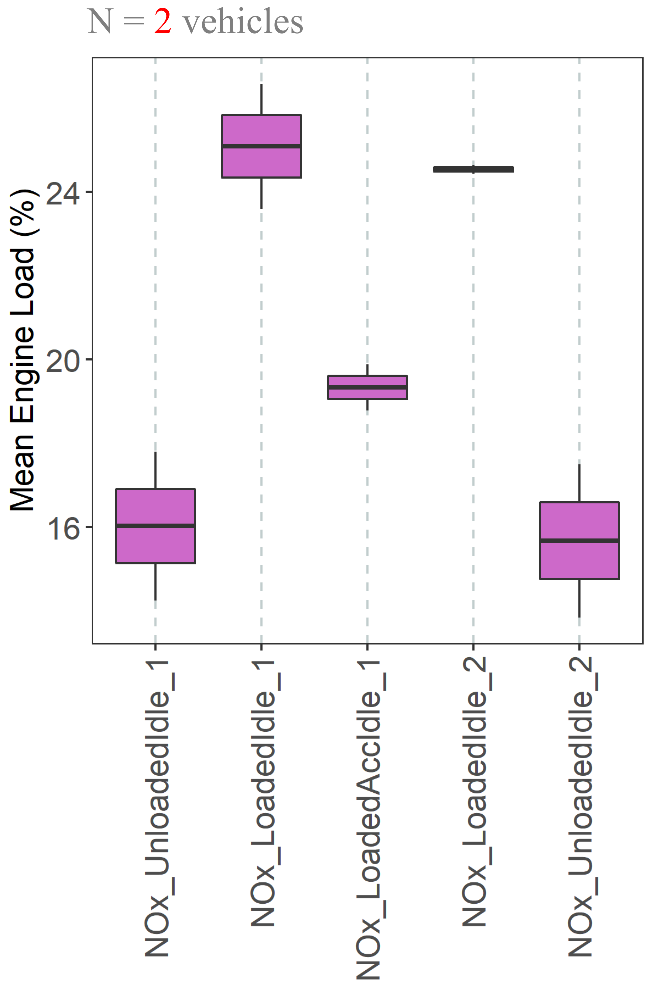
Duration



Engine RPM



Engine Load

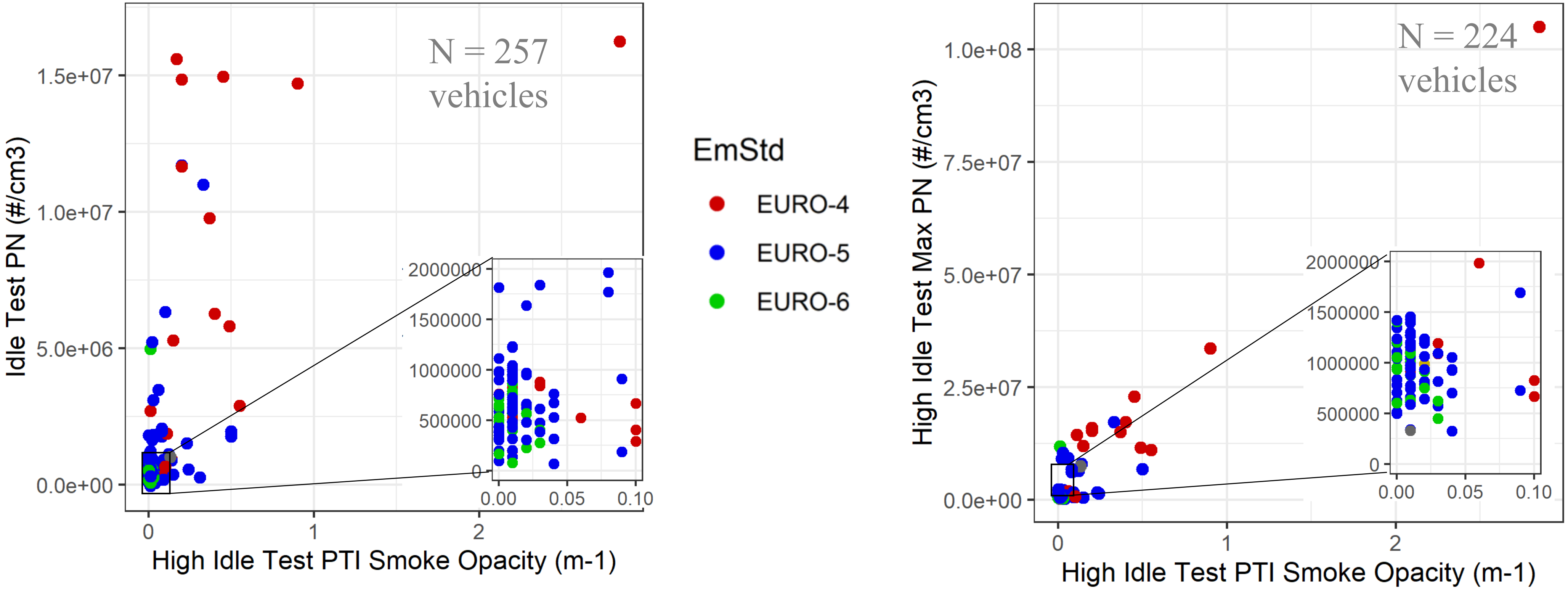


Enhanced PTI (parSYNC) *vs* **Official PTI**

for Particulates and CO

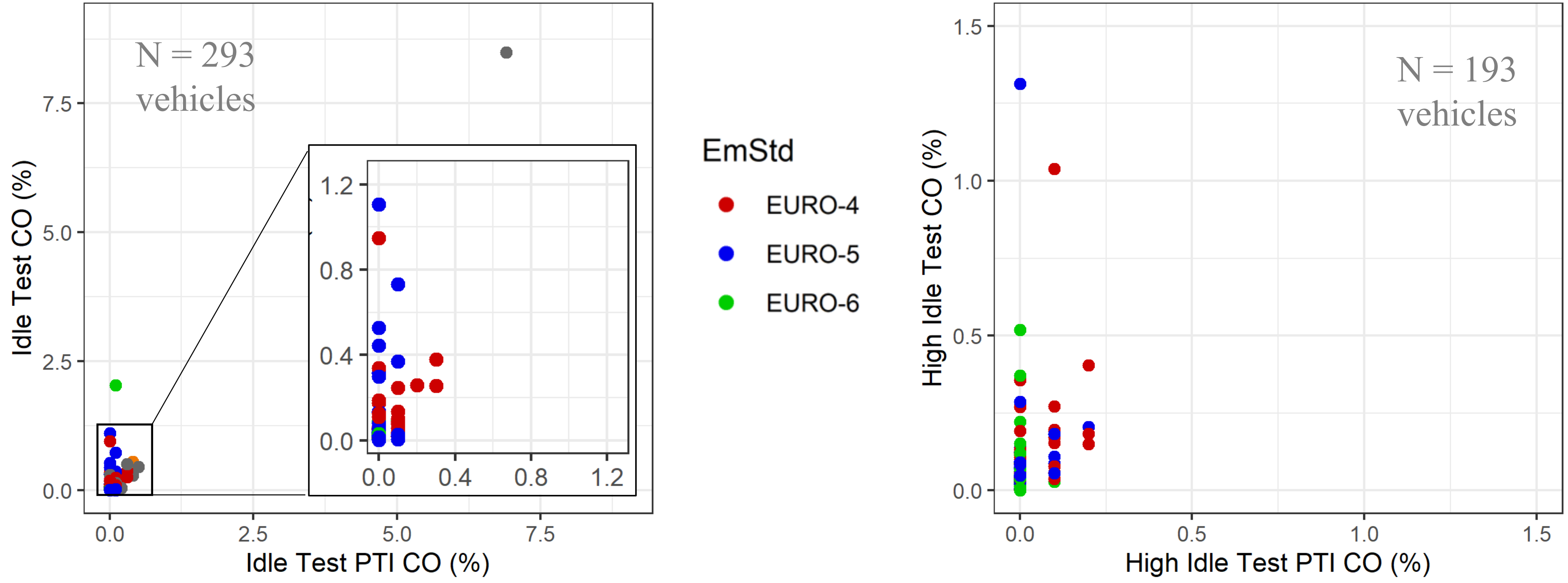
parSYNC PN *vs* PTI Smoke Opacity

Some correlation seen between parSYNC PN (Idle and High Idle) and PTI Opacity (only High Idle).



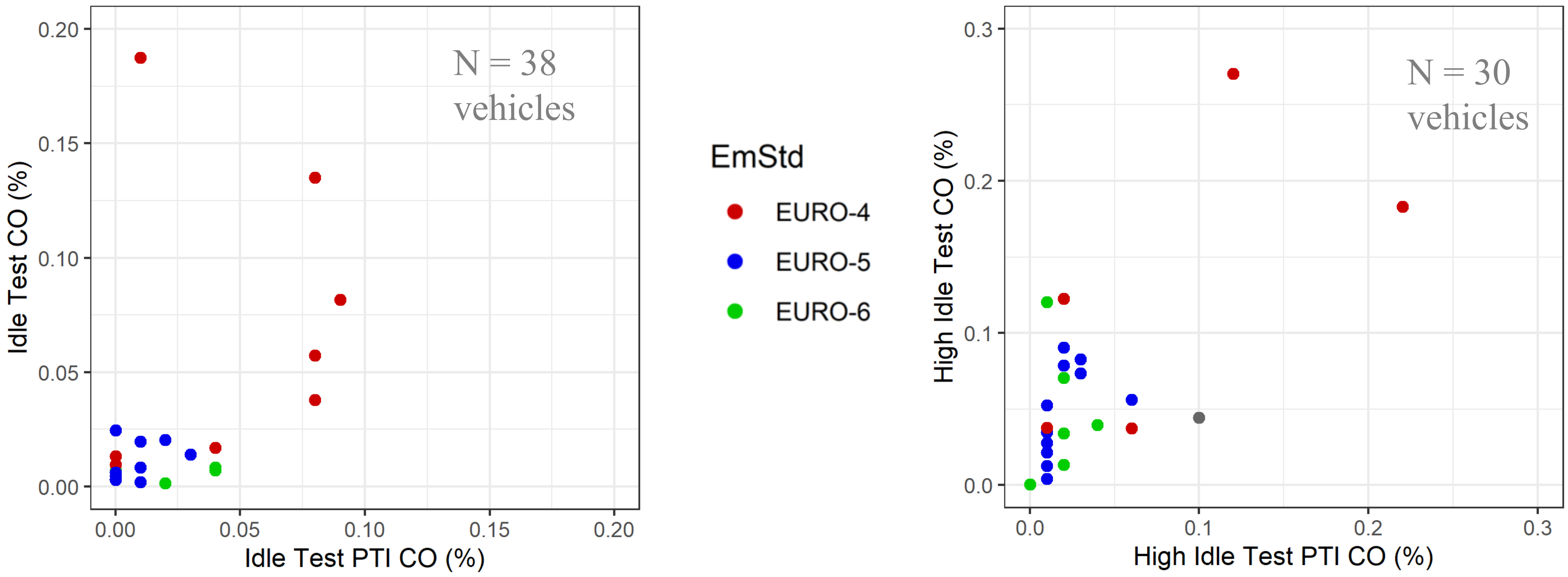
parSYNC CO *vs* PTI CO

Poor correlation between parSYNC CO and PTI CO. PTI CO sensor simply reports “0.0” for most readings.



parSYNC CO *vs* PTI CO (higher resolution)

Even looking at the results reported to 2 decimal places, the correlation is weak. Differences in methods will affect the correlation



Summary of Fleet Emissions
by Fuel and Euro Standard

Fleet-average Emissions

Fuel	Emission Std.	Metric	NOx (ppm)			CO (%)			PN (#/cm3)		
			Idle	High Idle	Accel	Idle	High Idle	Accel	Idle	High Idle	Accel
Petrol	Euro 4	Mean	27	75	52	0.05	0.13	0.11	2.0E+06	3.7E+06	3.3E+06
		1σ	74	199	156	0.17	0.36	0.30	5.2E+06	7.7E+06	6.2E+06
		2σ	121	324	260	0.29	0.59	0.50	8.3E+06	1.2E+07	9.1E+06
	Euro 5	Mean	27	49	93	0.06	0.09	0.05	2.5E+06	4.4E+06	4.7E+06
		1σ	103	141	405	0.23	0.29	0.14	4.6E+06	7.9E+06	8.5E+06
		2σ	180	232	718	0.40	0.48	0.24	6.7E+06	1.1E+07	1.2E+07
	Euro 6	Mean	17	24	24	0.04	0.05	0.03	2.4E+06	3.1E+06	3.0E+06
		1σ	56	69	67	0.28	0.14	0.09	4.3E+06	5.6E+06	4.9E+06
		2σ	95	115	109	0.52	0.23	0.16	6.2E+06	8.0E+06	6.8E+06
Diesel	Euro 4	Mean	142	139	181	0.02	0.05	0.03	5.0E+06	8.6E+06	7.4E+06
		1σ	228	201	296	0.05	0.14	0.08	8.2E+06	1.7E+07	1.4E+07
		2σ	315	263	410	0.09	0.22	0.13	1.1E+07	2.4E+07	2.1E+07
	Euro 5	Mean	154	137	207	0.01	0.02	0.03	1.2E+06	1.7E+06	2.0E+06
		1σ	257	203	314	0.02	0.06	0.13	3.3E+06	4.9E+06	5.1E+06
		2σ	360	269	420	0.03	0.10	0.22	5.4E+06	8.0E+06	8.3E+06
	Euro 6	Mean	71	93	116	0.01	0.02	0.01	9.9E+05	1.2E+06	1.5E+06
		1σ	146	155	219	0.02	0.06	0.03	2.9E+06	3.8E+06	4.4E+06
		2σ	221	216	322	0.03	0.10	0.05	4.7E+06	6.4E+06	7.3E+06

Applied Enhanced PTI - Examples

Fuel	Emission Std.	Metric	NOx (ppm)			CO (%)			PN (#/cm3)		
			Idle	High Idle	Accel	Idle	High Idle	Accel	Idle	High Idle	Accel
Petrol	Euro 4	Mean									
		1σ									
		2σ									
	Euro 5	Mean									
		1σ									
		2σ									
	Euro 6	Mean									
		1σ									
		2σ									
Diesel	Euro 4	Mean									
		1σ									
		[illegible]									
	Eu[illegible]	[illegible]									
		[illegible]									
		[illegible]									
	Euro 6	Mean									
		1σ									
		2σ									

Still only 5 extra minutes

<u>Progressive testing path (less time)</u>

1. Perform idle test and compare emissions level of each pollutant against its limit (e.g. 1σ). *If* any pollutant exceeds limit, *then*:
2. Perform high idle test and compare pollutants against limit (e.g. 1σ). *If* any pollutant exceeds limit, *then*:
3. Perform acceleration test and compare pollutants against limit (e.g. 1σ). *If* any pollutant exceeds limit, *then*:
4. Vehicle fails the PTI

<u>Cumulative testing path (more comprehensive)</u>

Conduct idle, high idle, and acceleration tests. *If* vehicle exceeds the limit (e.g. 2σ) for any two tests, *then*, it fails the PTI.

Identification of High Emitters using the Enhanced PTI protocol

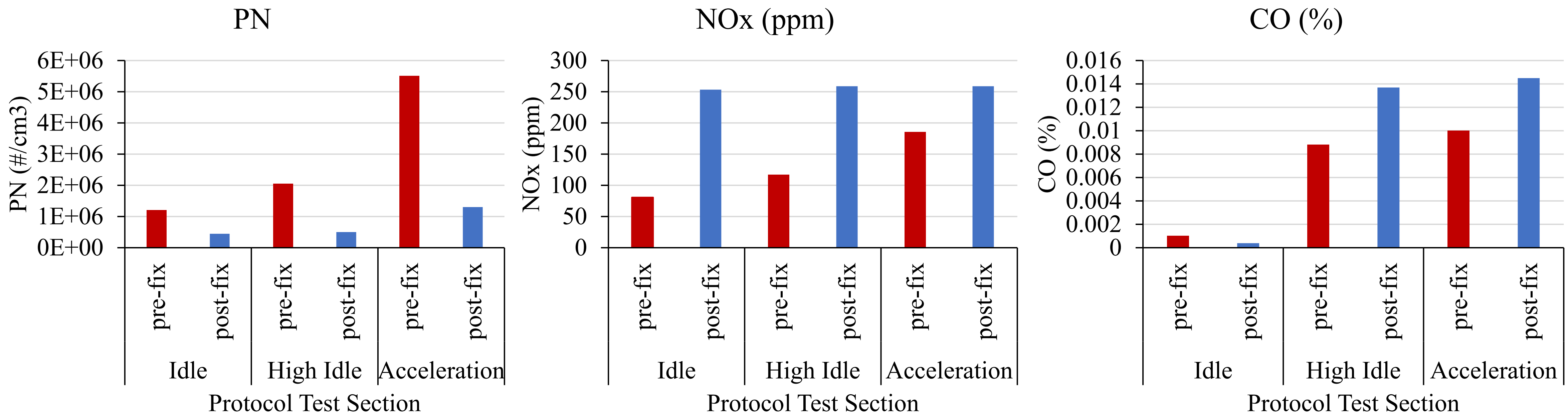
(1) Fuel Injector Fault

Fault: fuel injector, tested before and after fix

After fix: PN ↓ NOx ↑ CO ↑

Official PTI test results were not reported

Make	Model	Model Year	Odometer (km)	EngineSize (L)	Fuel Type	Engine Power (kW)	Euro#
VOLVO	V70	2006	304,000	2.4	Diesel	136	EURO-4



(2) DPF warning light – potentially faulty

Fault: blinking DPF malfunction indicator light, no fix performed, MIL cause unknown

- Passed PTI smoke opacity test but PN values between 85-90th percentiles of all Euro 5 diesel vehicles for all enhanced PTI test types (CO idle and high idle results ranged from the 23-37th percentiles).

Make	Model	Model Year	Odometer (km)	Engine Size (L)	Fuel Type	Engine Power (kW)	Euro#
SUBARU	LEGACY	2010	263K	2.0	Diesel	110	EURO-5

	Mean PN conc	Maximum PN conc
Idle Test	88th Percentile	NA
High Idle Test	89th Percentile	88th Percentile
Acceleration Test	87th Percentile	86th Percentile

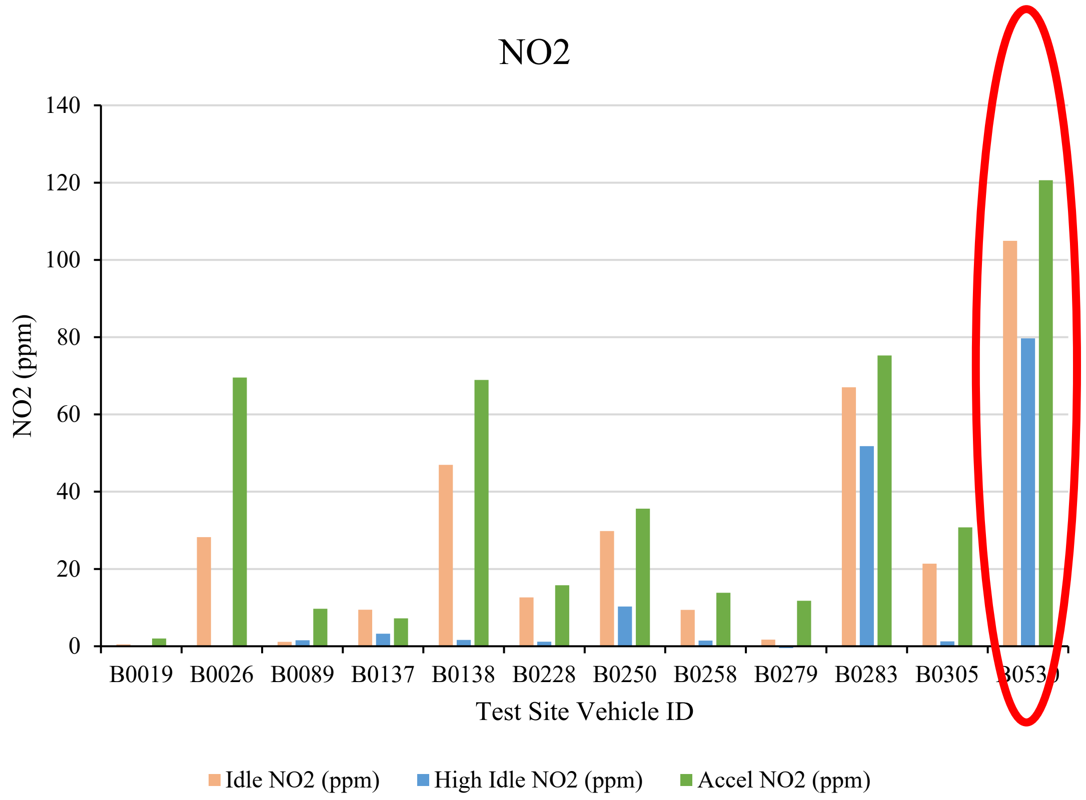
(3) Illegal Modification

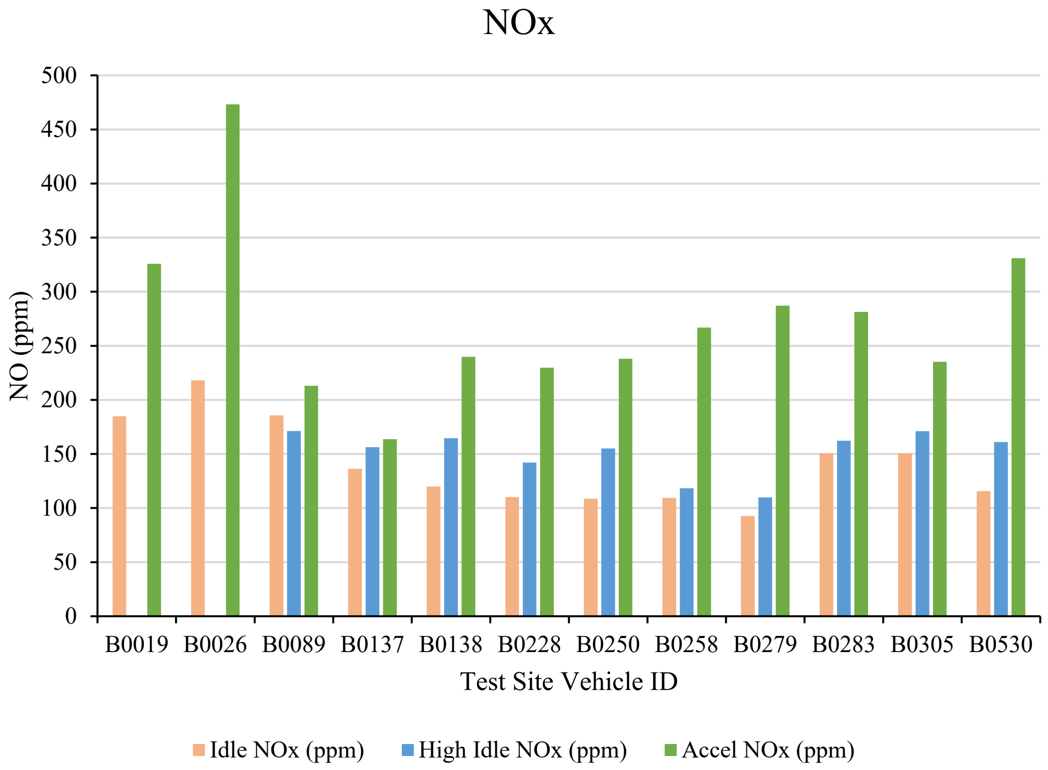
A vehicle was brought to the garage with an illegal KCR box identified.

Make	Model	Model Year	Odometer (km)	Engine Size (L)	Fuel Type	Engine Power (kW)	Euro#
VOLVO	XC70	2013	86K	2.4	Diesel	133	EURO-5

(3) Illegal Modification

This vehicle had the highest NO_2 (all tests) compared to other 2.4L Diesel Euro 5 Volvos tested in 2021, though overall NOx was not (and CO was insignificant).



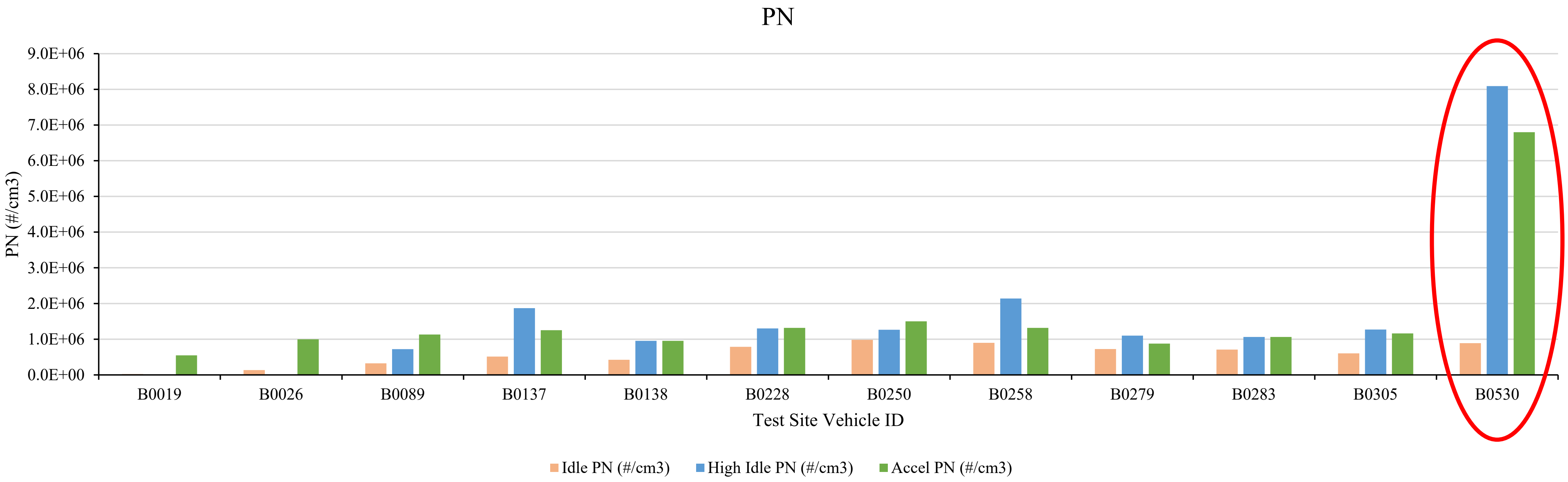


(3) Illegal Modification

This vehicle then had the greatest PN – on high idle and acceleration tests only – compared to other 2.4L Diesel Euro 5 Volvos tested in 2021

Does this indicate an idle PN test is insufficient to catch some high emitters?

The vehicle passed its official PTI smoke opacity test (0.14 result vs 1.5 limit)

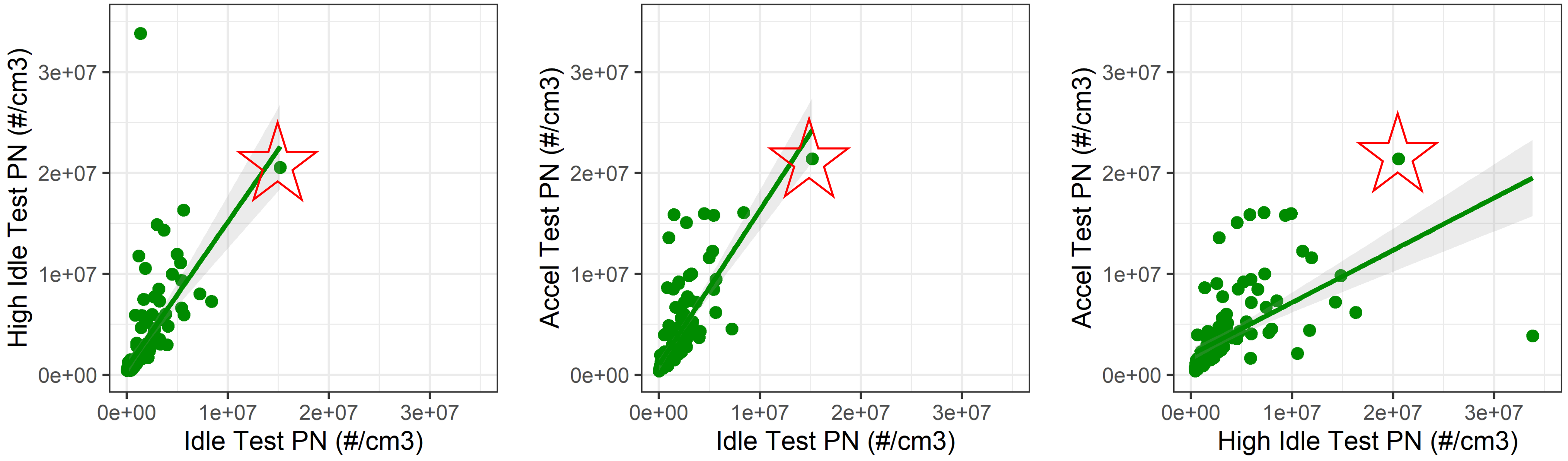


(4) high PN emitter

Vehicle with high PN emissions on all three tests, but passed the PTI smoke opacity test due to a rev limiter requiring alternative testing.

CO was 0.012% idle, 0.15% mean high idle, and 0.015% mean acceleration tests (83rd, 89th and 97th percentiles of Euro 6 diesels, respectively)

Make	Model	Model Year	Odometer (km)	EngineSize (L)	Fuel Type	Engine Power (kW)	Euro#
VOLVO	V70	2014	322K	1.6	Diesel	133	EURO-6

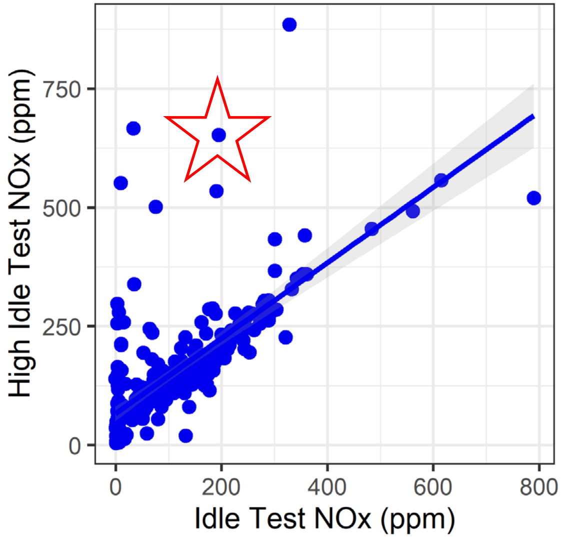


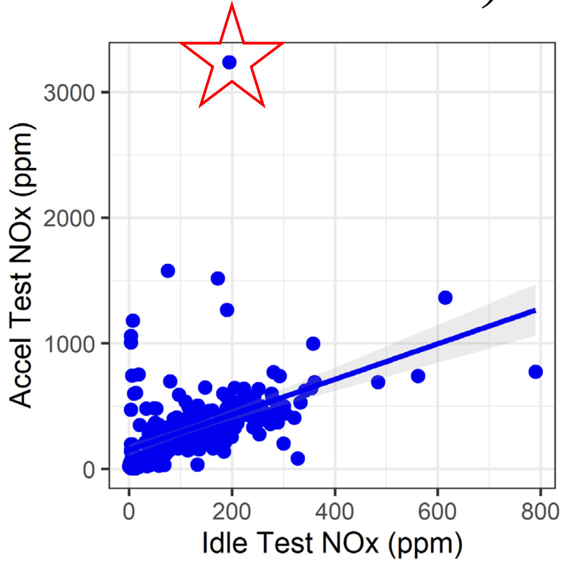
(5) high NOx emitter

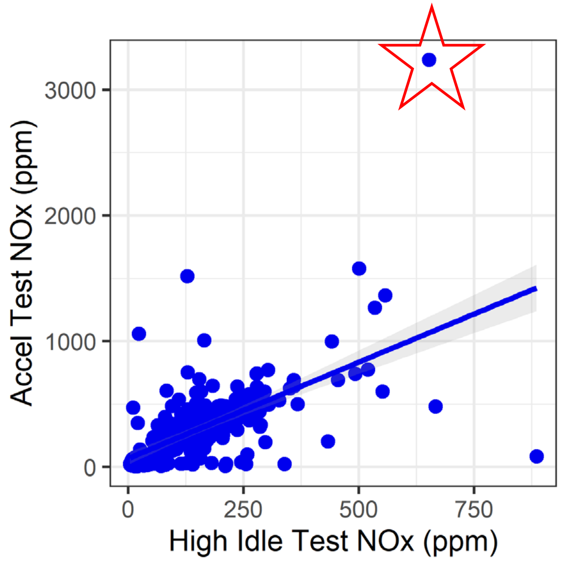
Vehicle with high NO emissions on High Idle and Acceleration tests.
The vehicle passed its official PTI test, with low CO concs on all tests.

Make	Model	Model Year	Odometer (km)	Engine Size (L)	Fuel Type	Engine Power (kW)	Euro#
SKODA	SUPERB	2011	179	1.4	Petrol	92	EURO-6

Fact vehicle is not high-emitting on the Idle test indicates a loaded test required for NOx (Acceleration test best).







(6-8) Failed CO PTI Test

Three vehicles failed the official PTI CO test. All were older vehicles, with high NOx pollutant concentrations (PN was high for B0367 only).

SiteVehID	Make	Model	Model Year	Odometer (km)	Fuel Type	Engine Power (kW)	Euro#	High Idle Result	High Idle Limit	Idle Result	Idle Limit
B0367	VOLVO	244-410-2111	1979	137K	Petrol	74	NA	NA	NA	6.9	4.5
B0301	AUDI	A6	1996	350K	Petrol	92	EURO-2	0.7	0.3	0.4	0.5
B0543	BMW	316I	1997	219K	Petrol	75	NA	0.5	0.3	0.3	0.5

	Mean Idle PN	Mean Idle CO	Mean High Idle CO	Mean Idle NOx	Mean High Idle NOx	Max Accel NOx
B0367	100th Percentile	100th Percentile	100th Percentile	100th Percentile	98th Percentile	100th Percentile
B0301	60th Percentile	98th Percentile	NA	98th Percentile	NA	99th Percentile
B0543	18th Percentile	97th Percentile	99th Percentile	97th Percentile	100th Percentile	96th Percentile

No vehicle failed PTI Opacity.

Fleet-Average Trends by Euro Standards

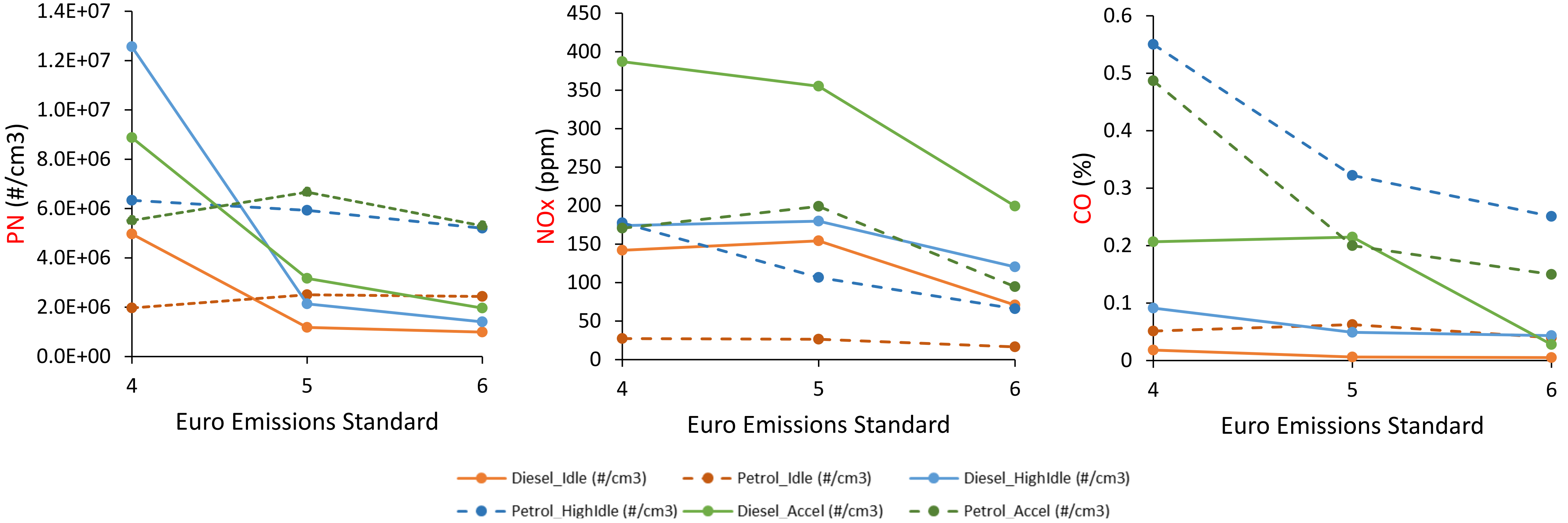
for PN, NOx, CO_2, and CO

Evolution of fleet emissions by EURO stds - Absolute

PN: Diesel cleaner than Petrol for Euro 5 and 6. DPFs provide significant reduction from Euro 4 levels. Petrol vehicles need more controls.

NOx: The real-world PTI emissions for vehicles increased compared to the type approval limits from EURO4 to EURO5, but then decreased to EURO6.

CO: Generally decreasing through the EURO standards for both fuel types.

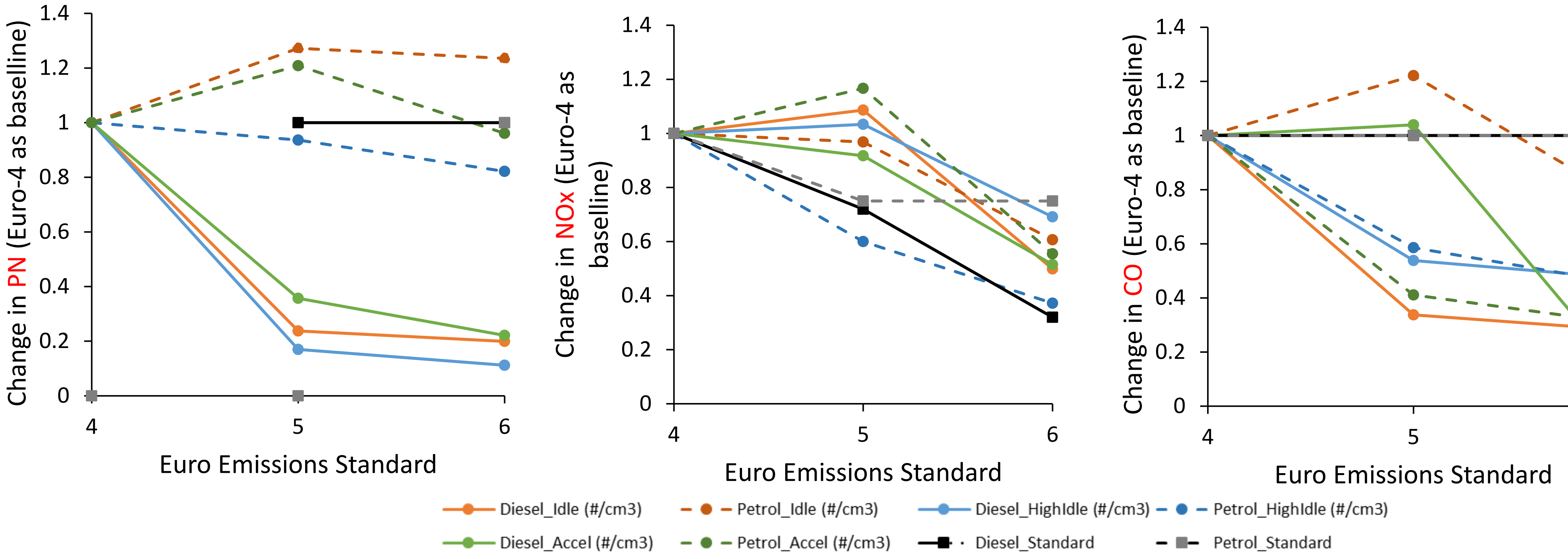


Evolution of fleet emissions by EURO stds - Relative

PN: Petrol vehicles needs more controls. Diesel vehicles are well-controlled by the standards.

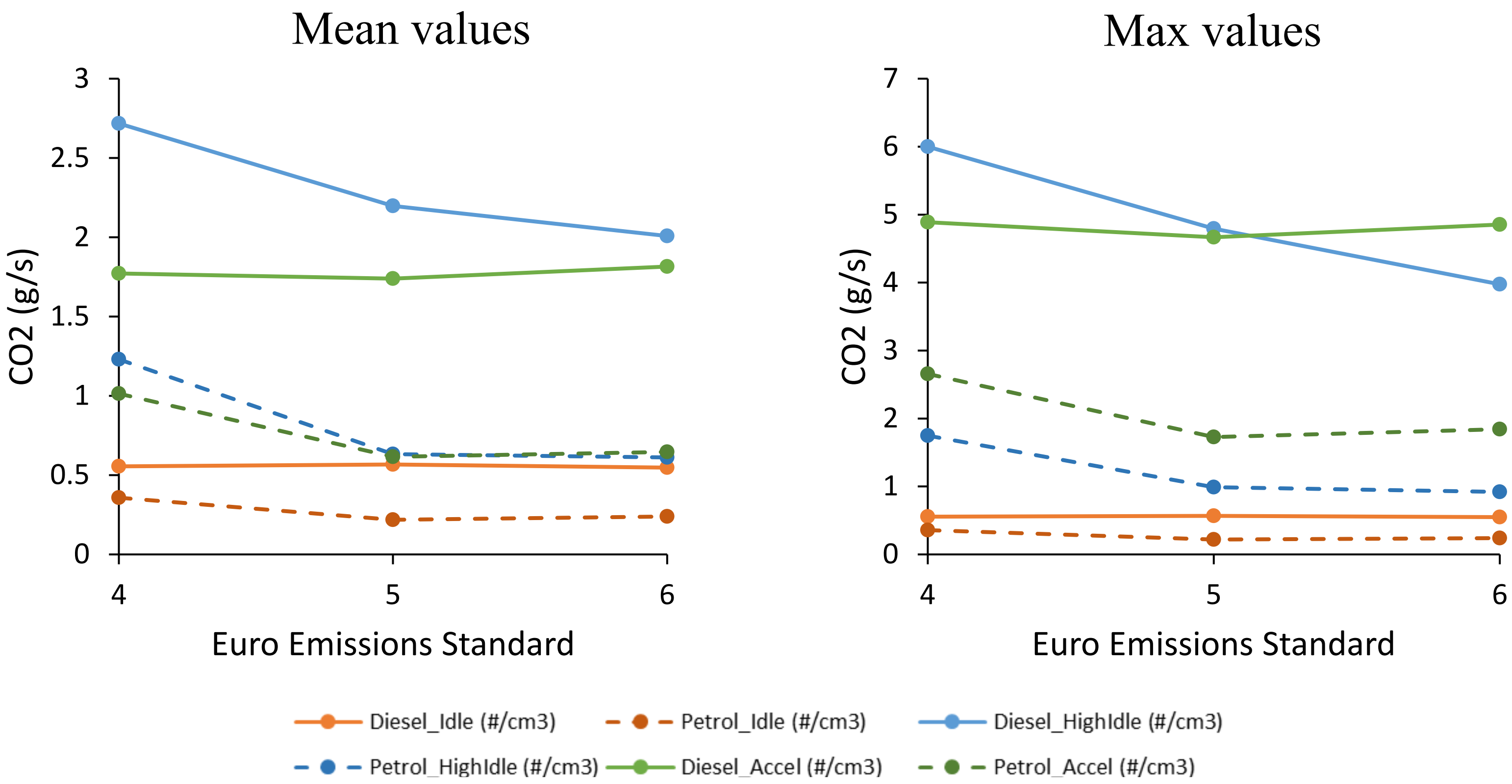
NOx: EURO-6 vehicles reverse the increase seen in EURO-5 but diesel vehicles still fail to deliver the level of reductions in real-world emissions as per diesel emission standards.

CO: CO from EURO-6 petrol and diesel vehicles is lower compared to EURO-4 levels and standards.



CO_2 emissions by EURO stds - Absolute

CO_2 from vehicles has decreased from Euro 4 to Euro 5 but no big change seen going from Euro 5 to Euro 6 emission standard vehicles.

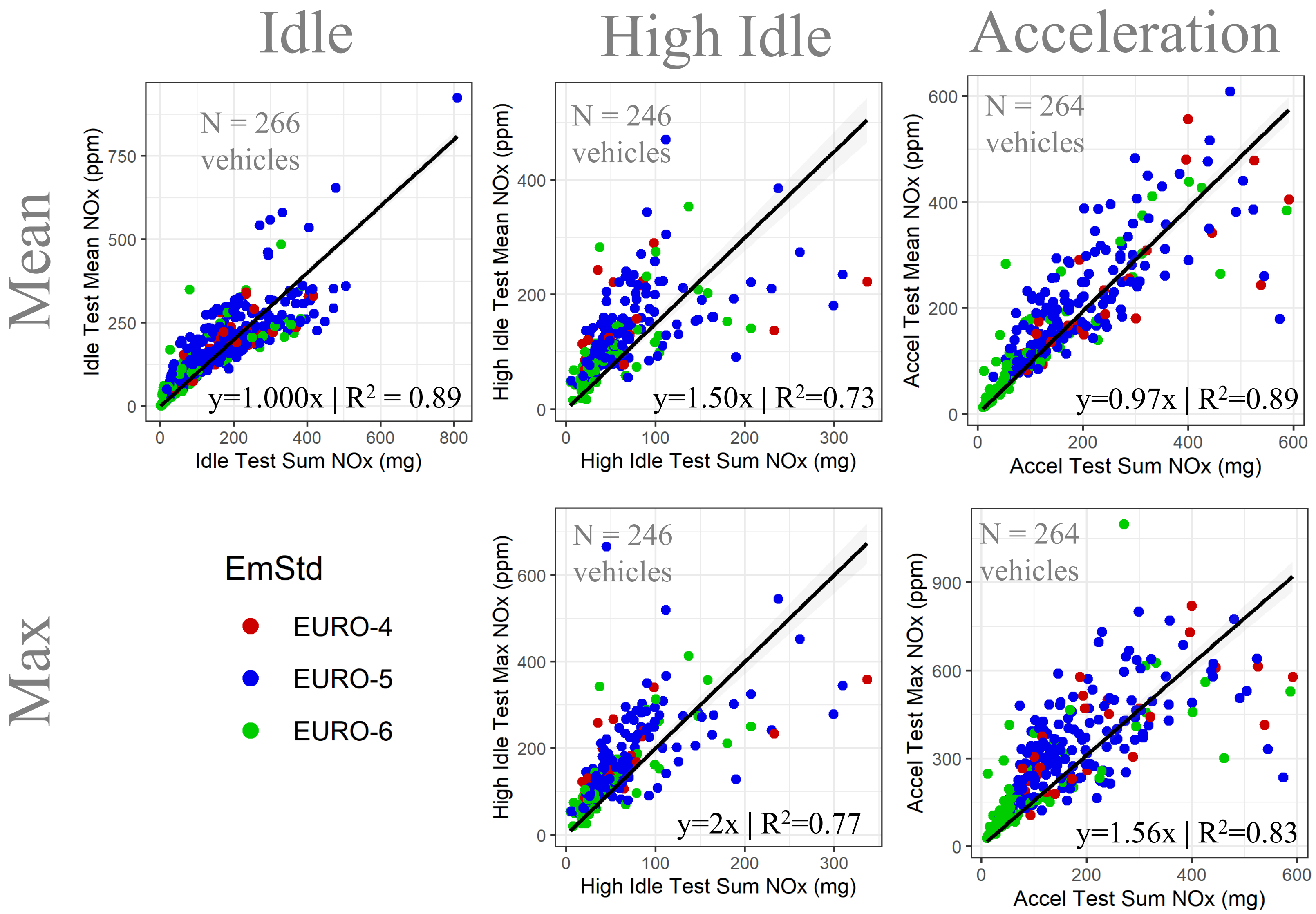


NOx emissions - Concentration *vs* Mass

Smaller sample sizes for petrol vehicles in this section because many vehicles reported zero for OBD-based intake air flow rate (which was used to estimate exhaust flow rate).

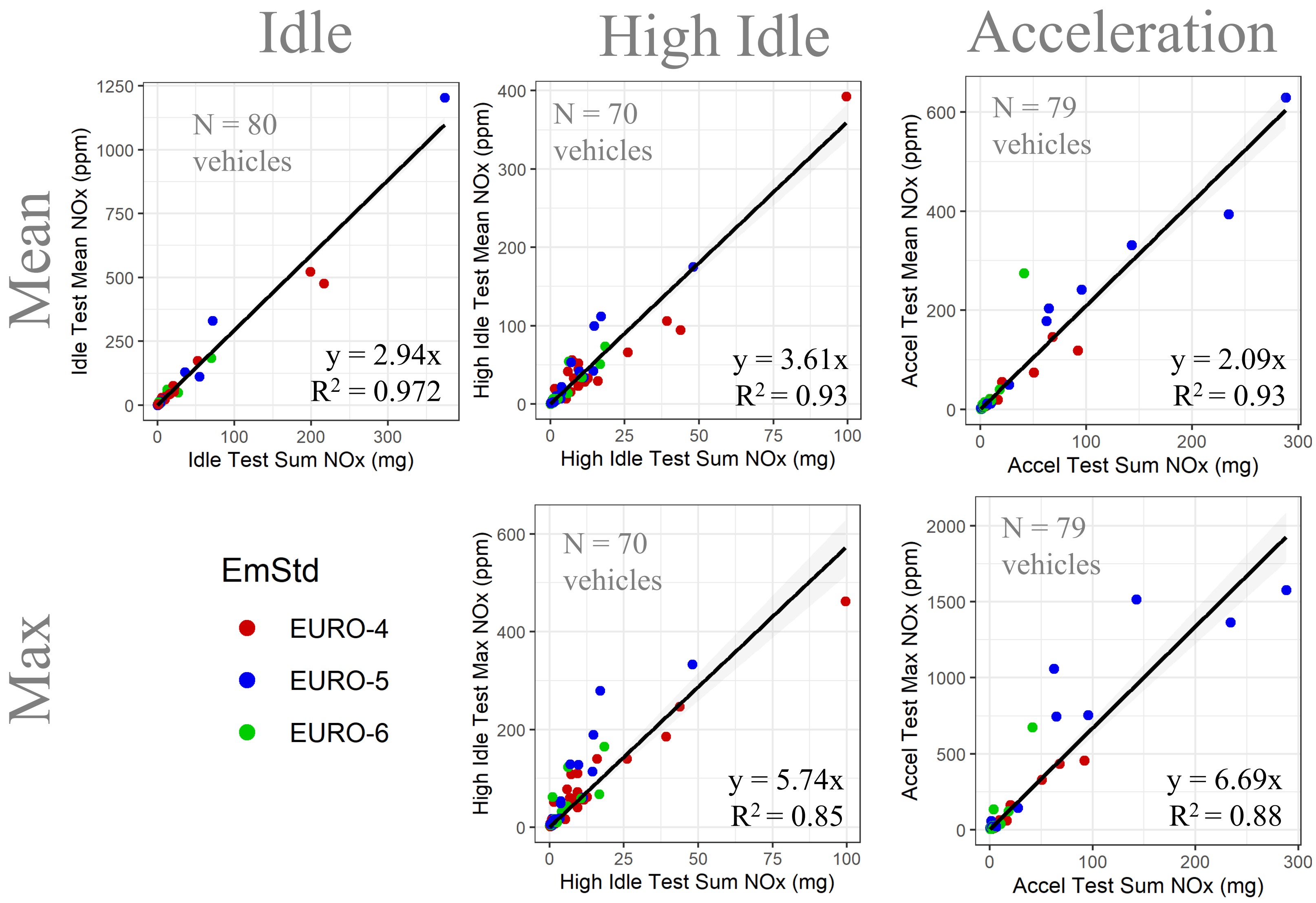
Diesel NOx Emissions – Concentration vs Mass

- NOx (ppm) ∝ NOx (mass)… strong +ve
- Max value stronger on high idle, mean value stronger on acceleration
- **Acceleration and idle tests give higher correlation coefficients than high idle**



Petrol NOx Emissions – Concentration vs Mass

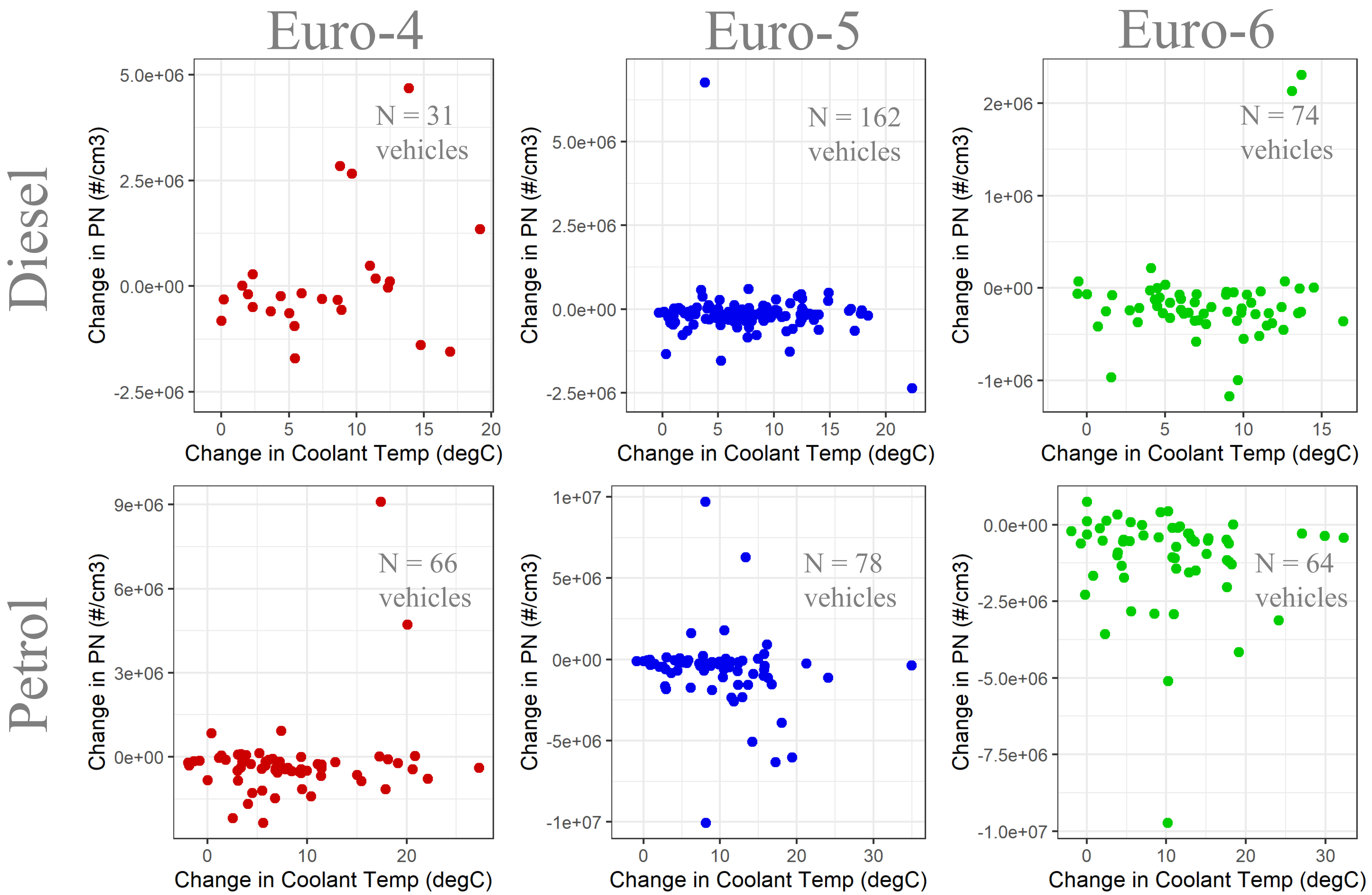
- ➢NOx (ppm) ∝ NOx (mass)… strong +ve
- ➢Mean values give stronger correlation than mass
- ➢**Idle test gives highest correlation** (high idle and acceleration tests are similar)



Investigation of Temperature Conditioning

for PN and NOx

Does PN change with changing Engine Coolant Temperature?

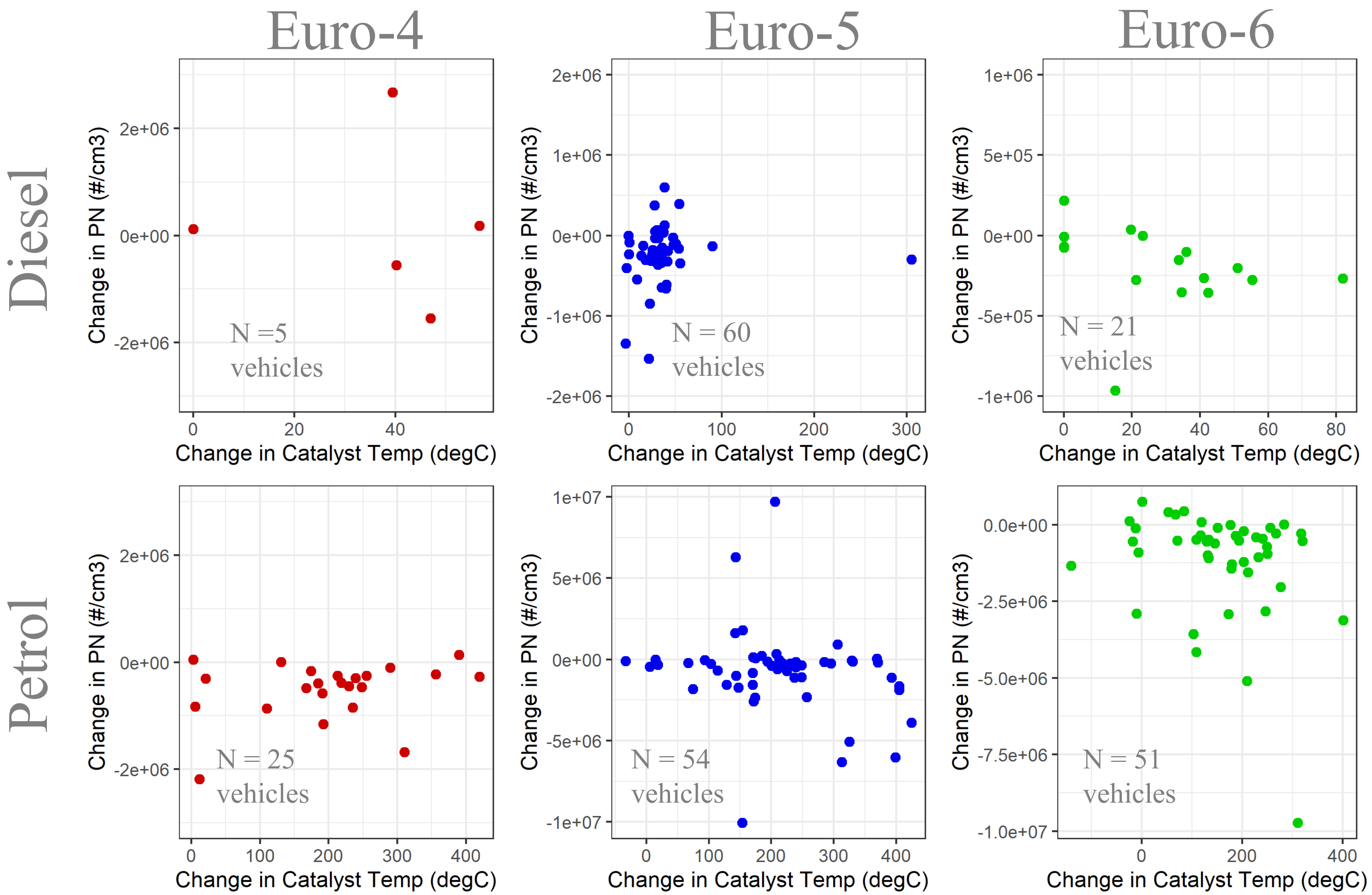


Change in PN concentration *vs* change in engine coolant temperature, between PN Idle 1 and 2 tests (bags 1 and 7 on slide 14 and 15).

PN concentrations on an idle test do not appear to be greatly affected by changes in the engine coolant temperature.

Note: No trend was seen between absolute engine coolant temperature and PN between vehicles either

Does PN change with changing Catalyst Temperature?

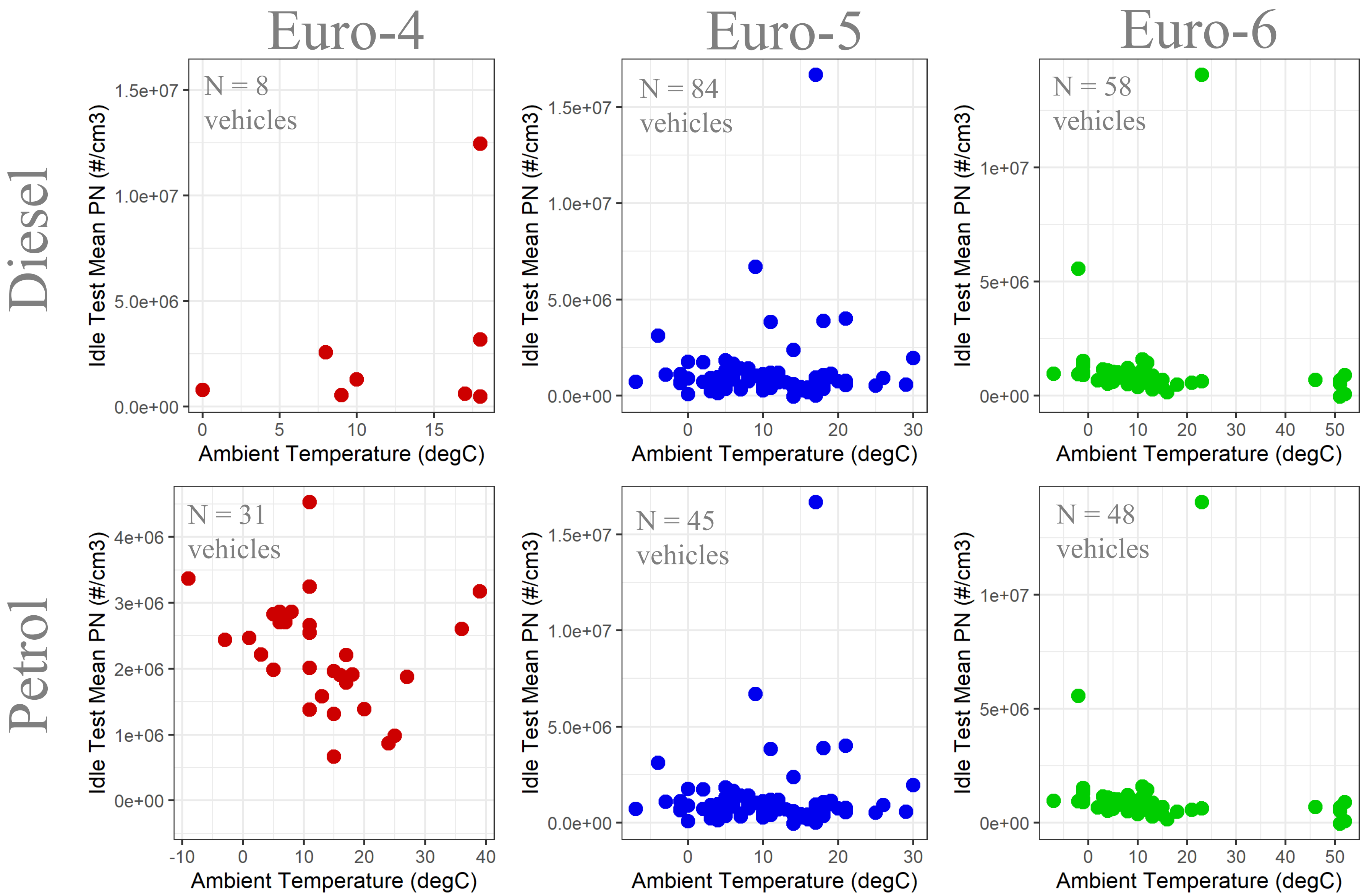


Change in PN concentration *vs* change in catalyst temperature, between PN Idle 1 and 2 tests (bags 1 and 7 on slide 14 and 15).

No correlations seen between PN and catalyst temperature. Particulate filter efficiency is not greatly affected by temperature changes.

Note: The diesel catalyst temperature from ECU does not seem right/meaningful– true aftertreatment temperature should be provided by OEMs.

Does PN trend with Ambient Temperature?

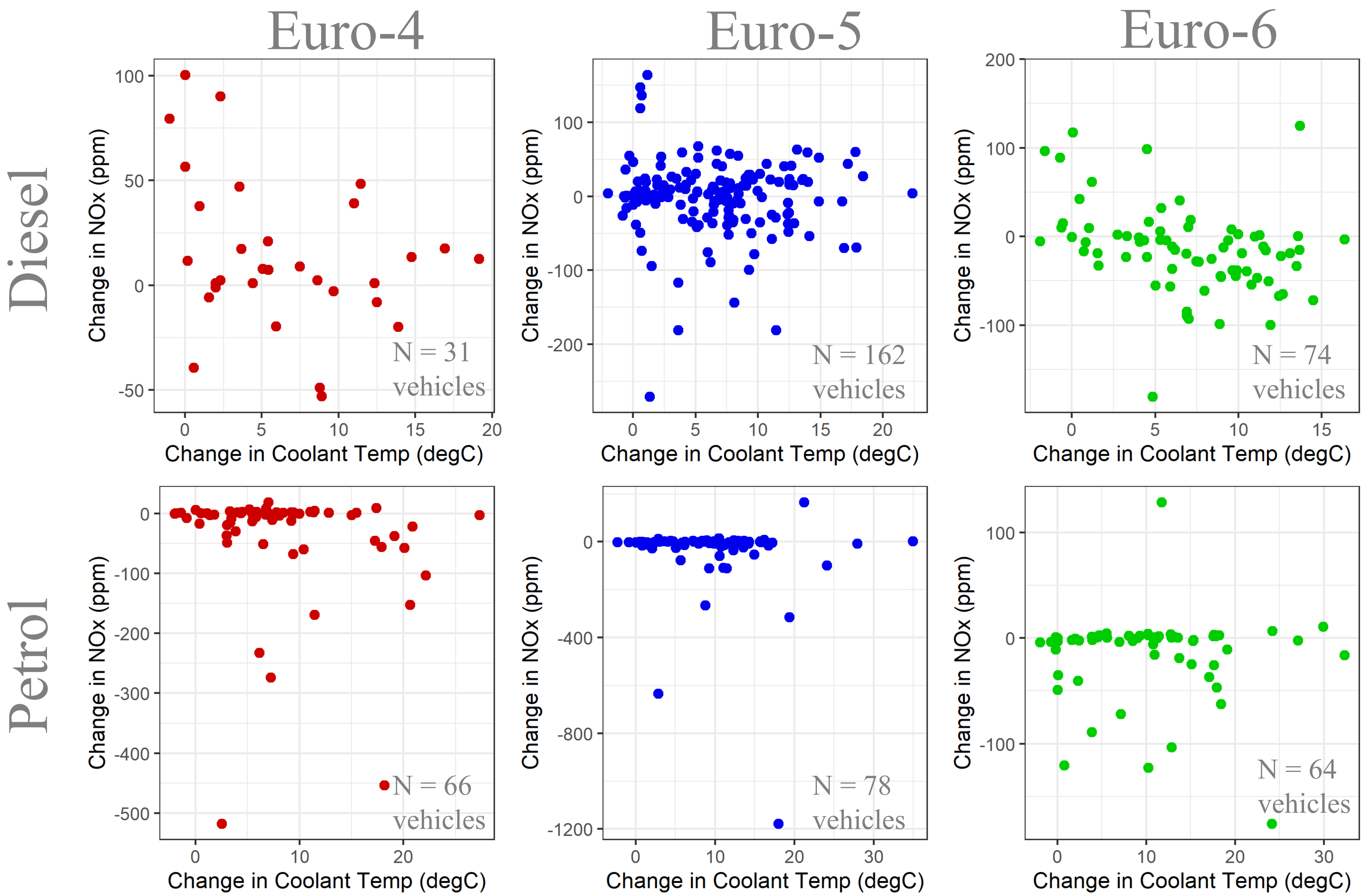


Mean PN concentration *vs* mean ambient temperature (from ECU), from PN Idle 1 tests (bag 1 on slide 14 and 15).

No correlations seen. Particulate filter efficiency is not greatly affected by ambient temperature.

Note: This ambient temperature does not seem correct when considering the Swedish climate – true ambient temperature should be provided by OEMs. We will use weather station data for further analysis

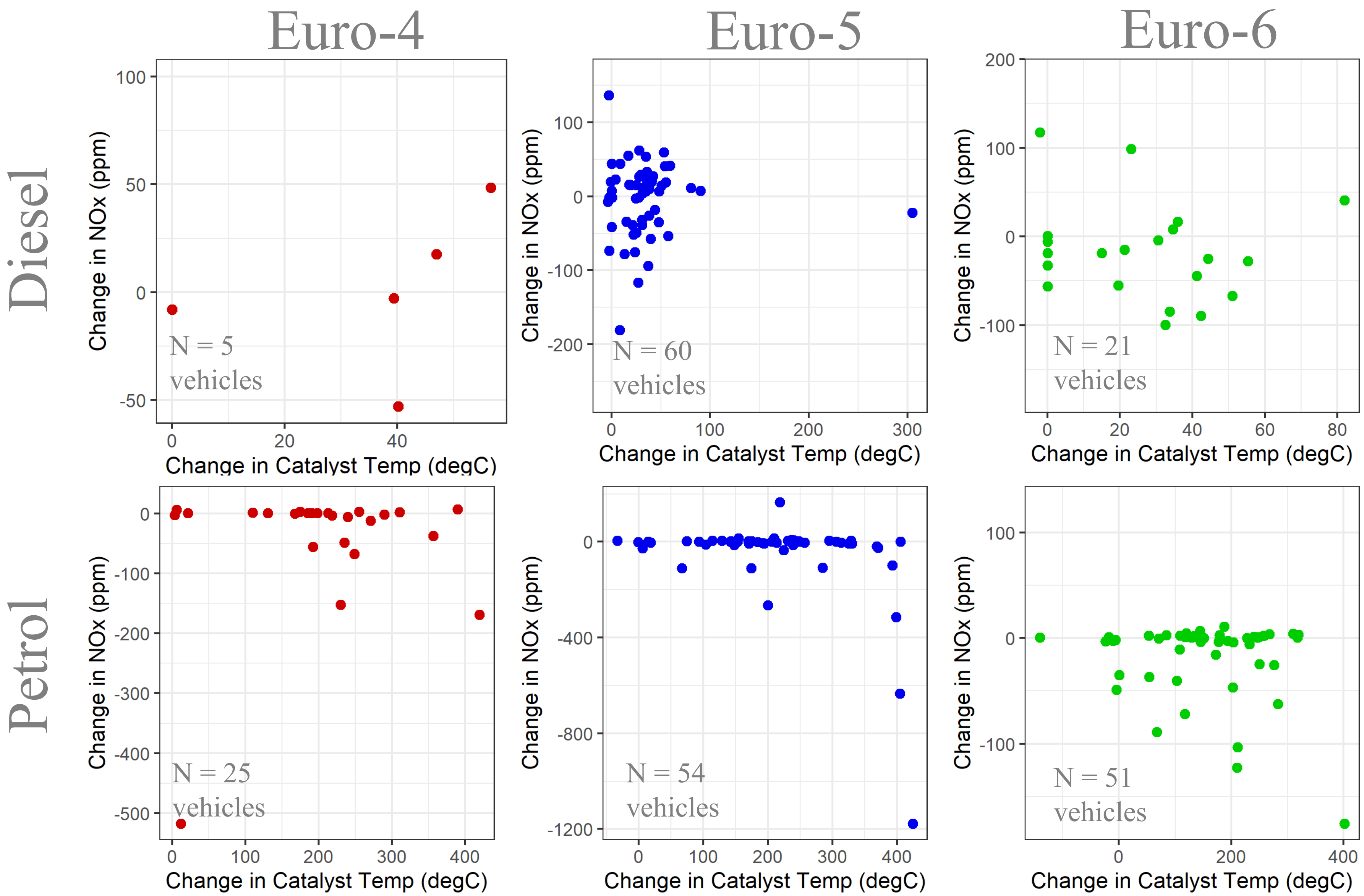
Does NOx change with changing Engine Coolant Temperature?



Change in NOx concentration *vs* change in engine coolant temperature, between PN Idle 1 and 2 tests (bags 1 and 7 on slide 14 and 15).

NOx concentrations on an *idle* test do not appear to be greatly affected by changes in the engine coolant temperature.

Does NOx change with changing Catalyst Temperature?



Change in NOx concentration *vs* change in catalyst temperature, between PN Idle 1 and 2 tests (bags 1 and 7 on slide 14 and 15).

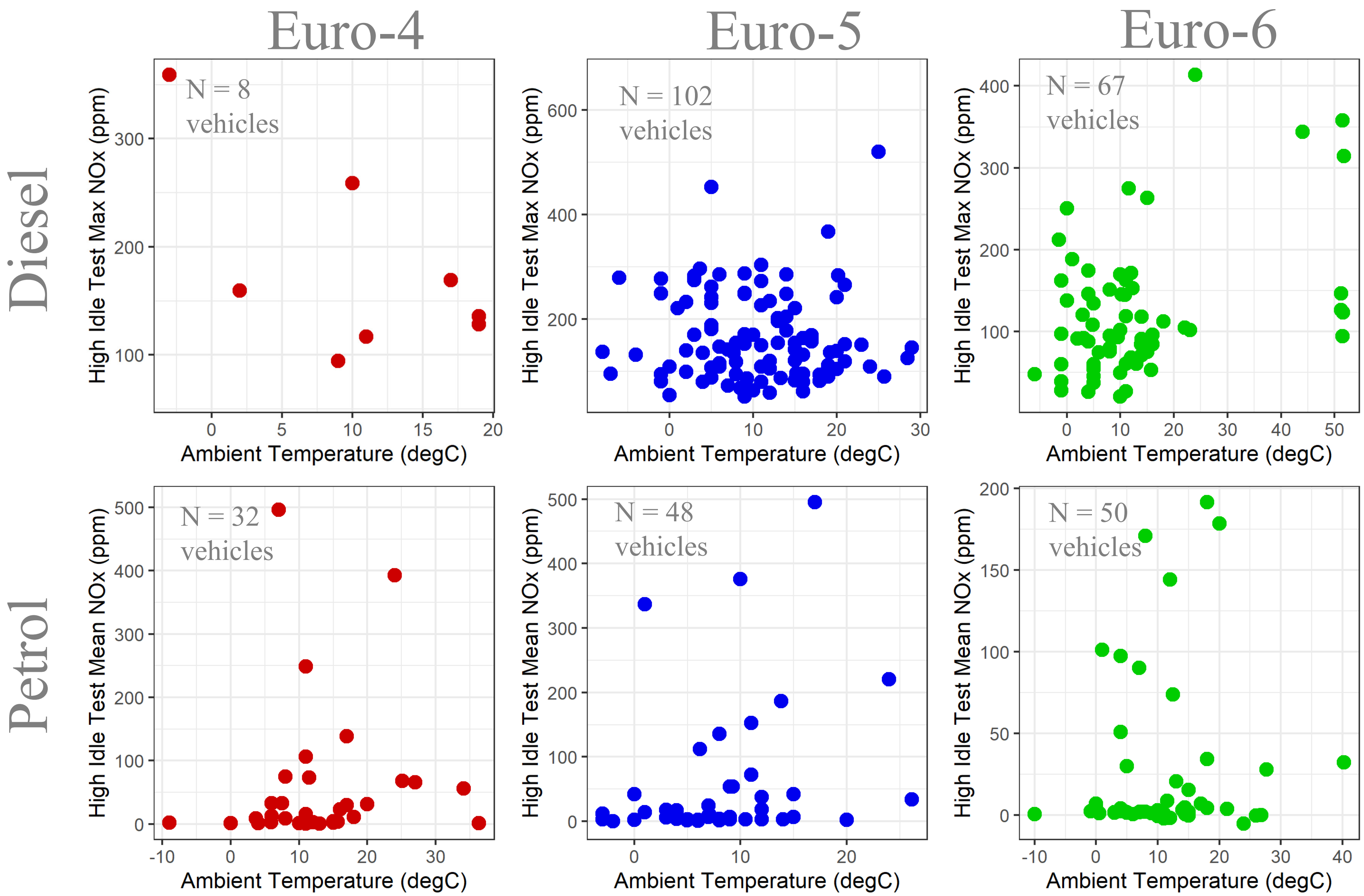
No correlations seen; *Idle* NOx seems unaffected by temperature changes.

Note: The diesel catalyst temperature does not always seem right/meaningful– true aftertreatment temperature should be provided by OEMs

Causes of large differences in NOx:

1. *Changes in EGR rate;*
2. *NO_2 constantly increasing from SCR diesels*
3. *Some petrol vehs had very high NO on startup (i.e. PN_1)*

Does NOx trend with Ambient Temperature?



Max NOx concentration *vs* mean ambient temperature (from ECU), for the High Idle test.

No correlations seen. *Idle* NOx is not greatly affected by ambient temperature.

Note: This ambient temperature does not seem correct when considering the Swedish climate – true ambient temperature should be provided by OEMs. We will use weather station data for further analysis.

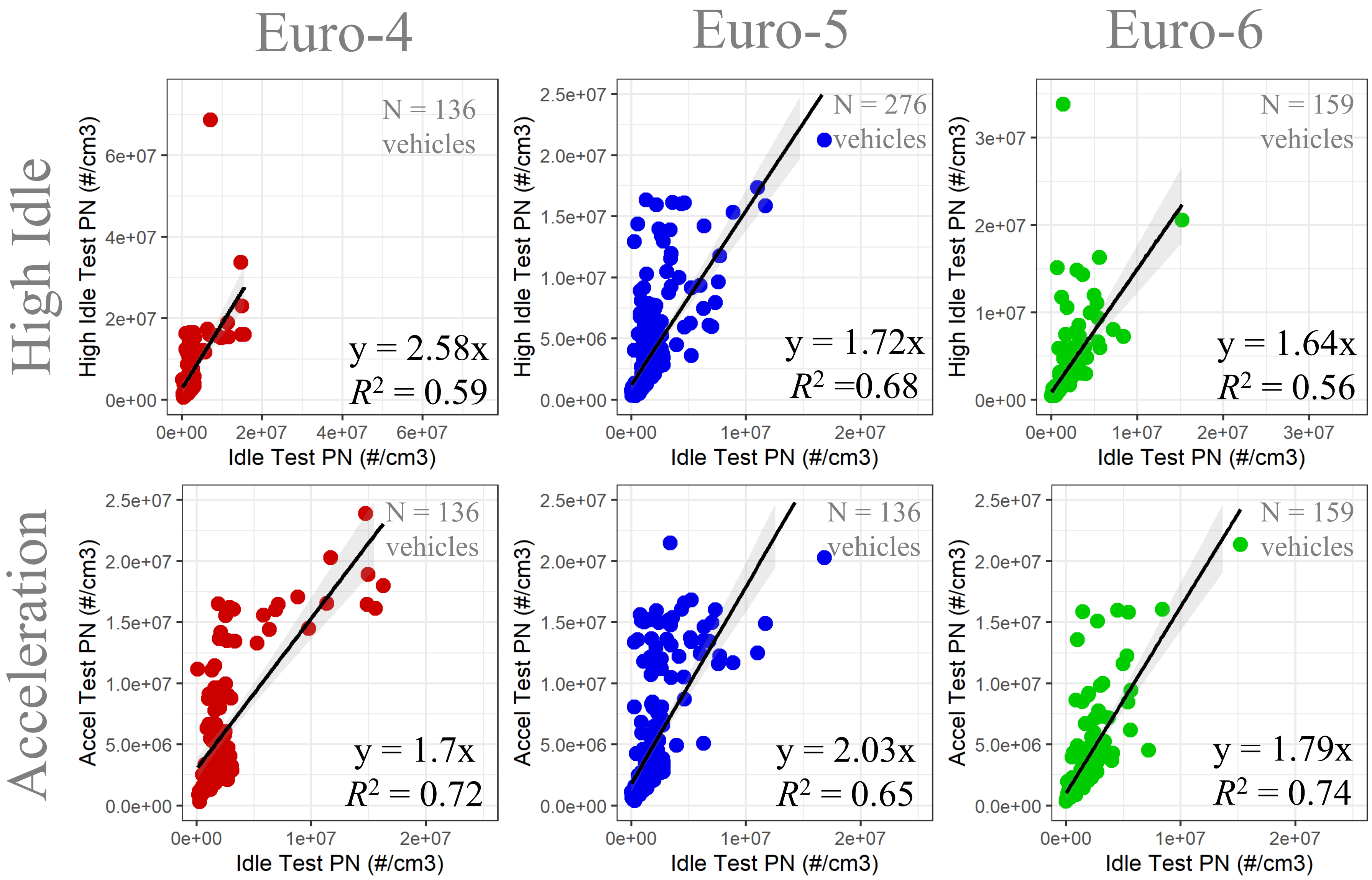
Comparison of Test Type and Metrics

for PN, NOx, and CO

PN – Idle *vs* (High Idle, Acceleration)

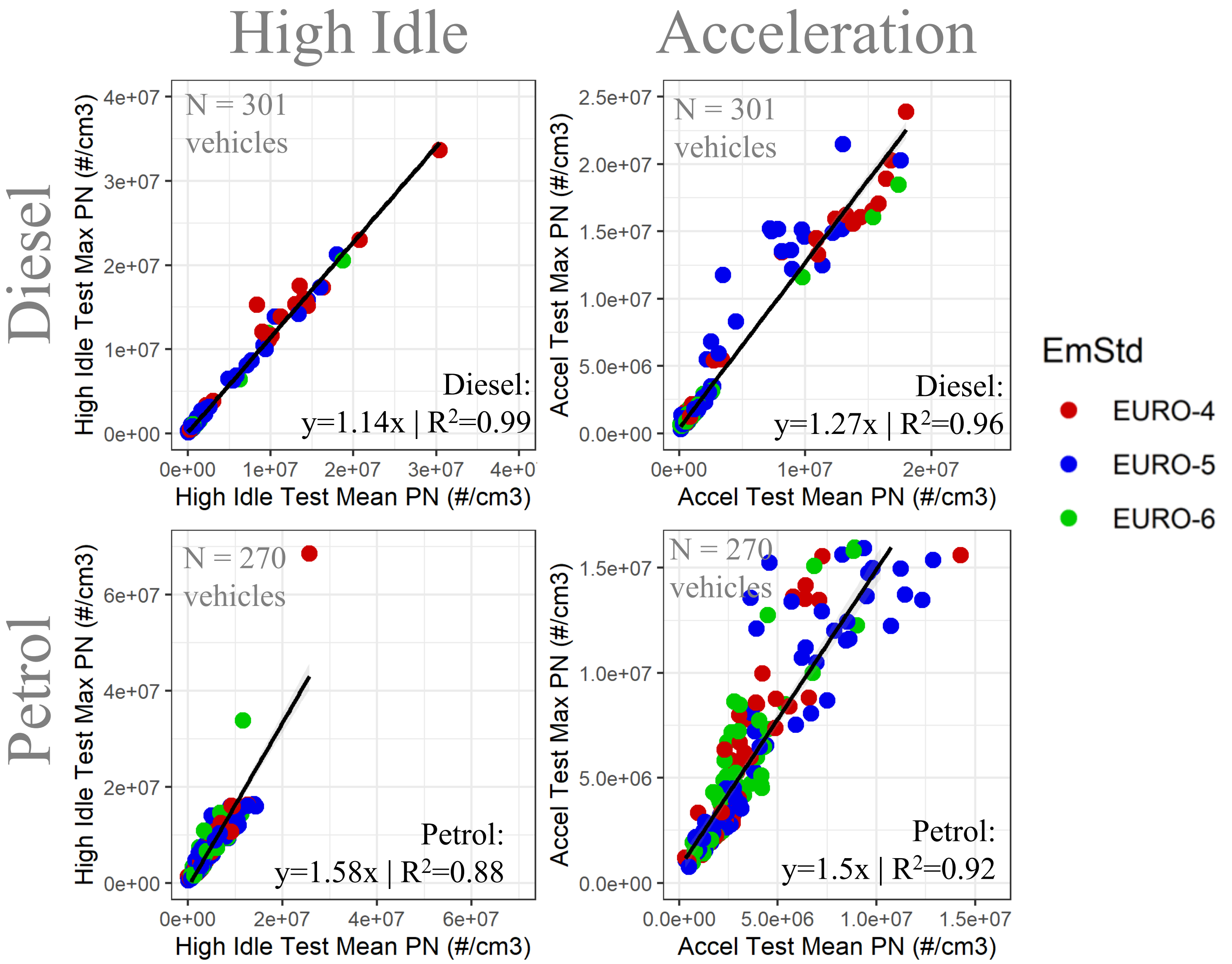
Correlations seen between PN from Idle, High Idle, and Acceleration tests

Indicates **Idle Test may be sufficient to catch high emitters**



PN – Mean *vs* Max

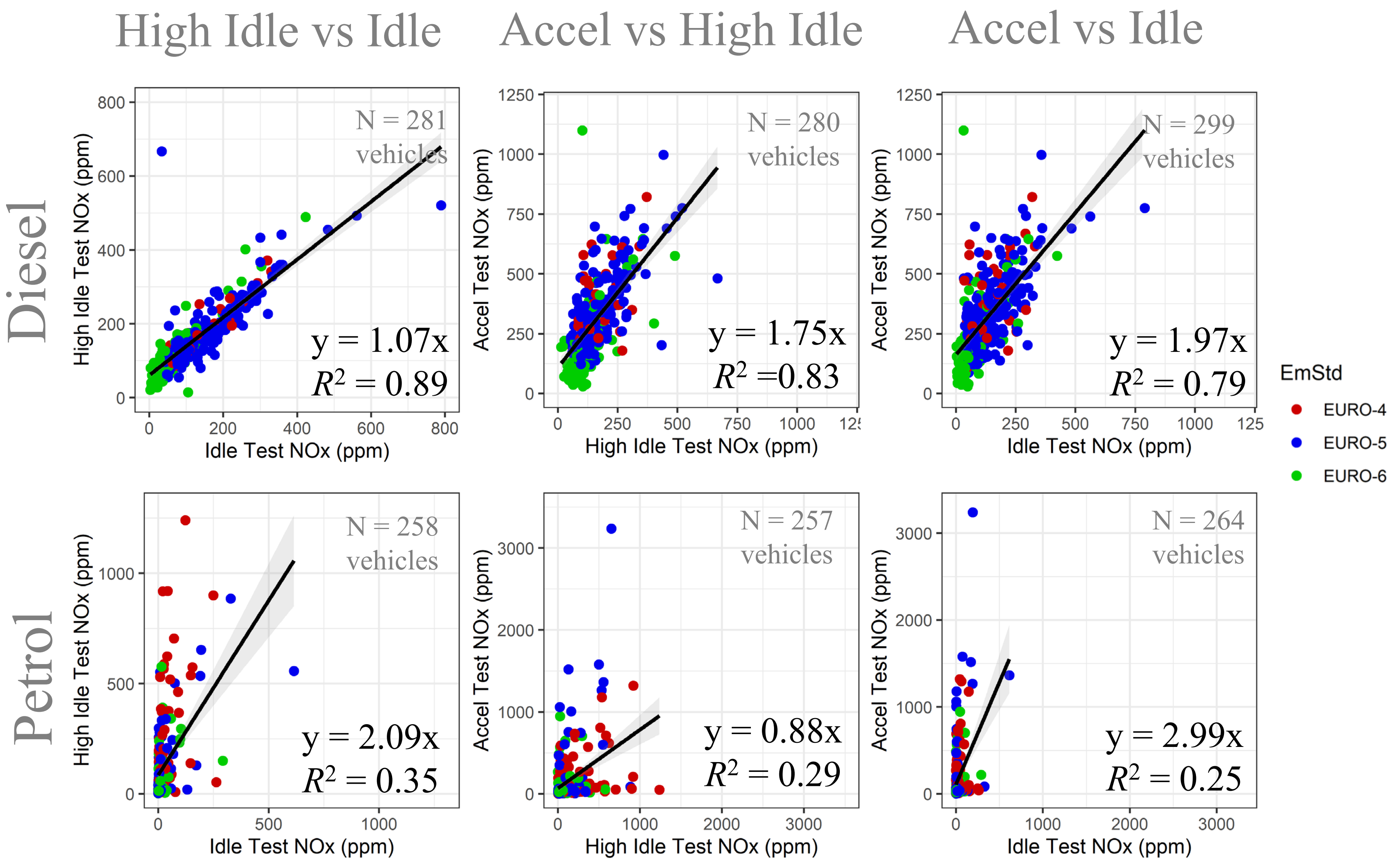
- ➢NOx (ppm) ∝ NOx (mass)… strong +ve
- ➢Suggests Mean value could be used if OBD data is available, but max could be used otherwise (with different pass/fail limits according to the correlation coefficients)



NOx – Idle *vs* (High Idle, Acceleration)

Diesel: Strong correlations between Idle, High Idle, and Acceleration tests

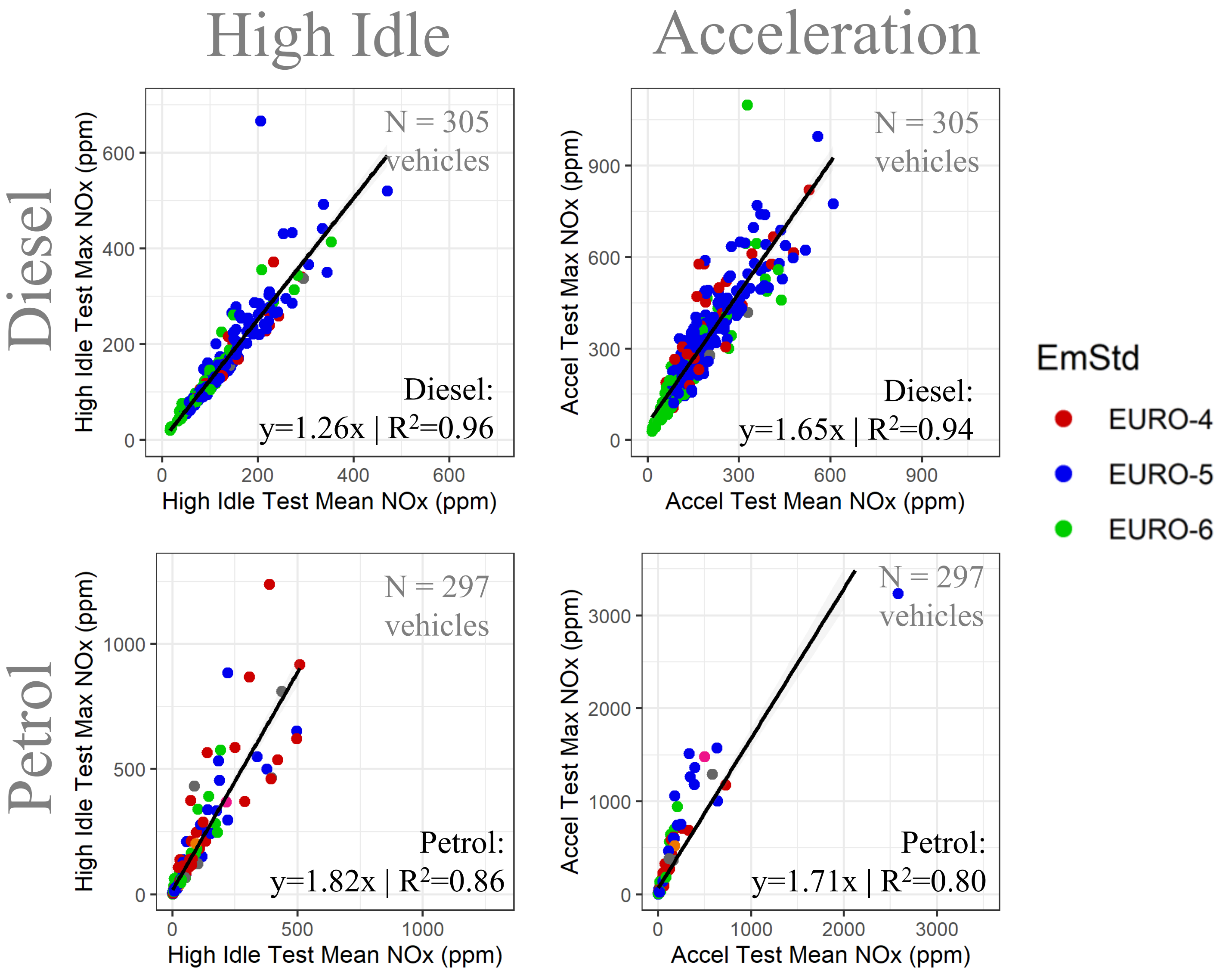
Petrol: Idle test misses some higher emitters – indicates a loaded test is required



NOx – Mean *vs* Max

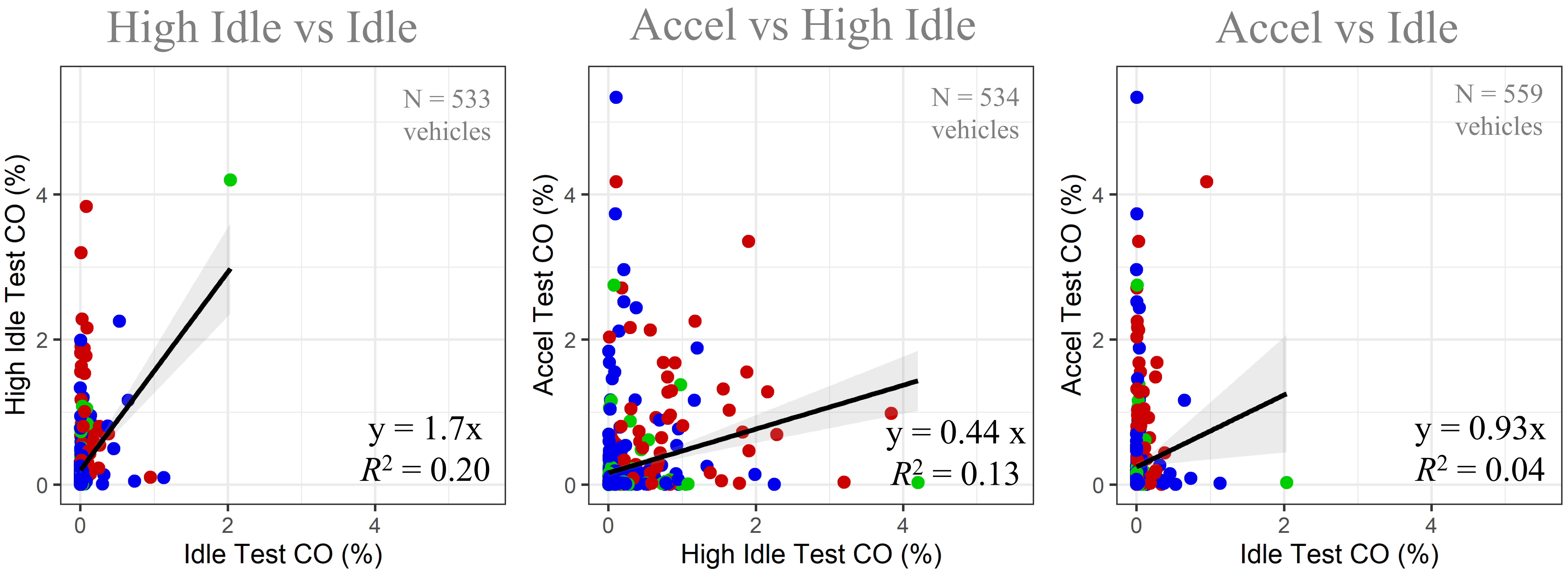
Strong positive correlations seen between the mean NOx value and maximum NOx value for individual vehicles, suggesting these could be interchangeable.

Mean could be used if OBD data is available, but max could be used otherwise (with different pass/fail limits according to the correlation coefficients)



CO – Idle *vs* High Idle *vs* Acceleration

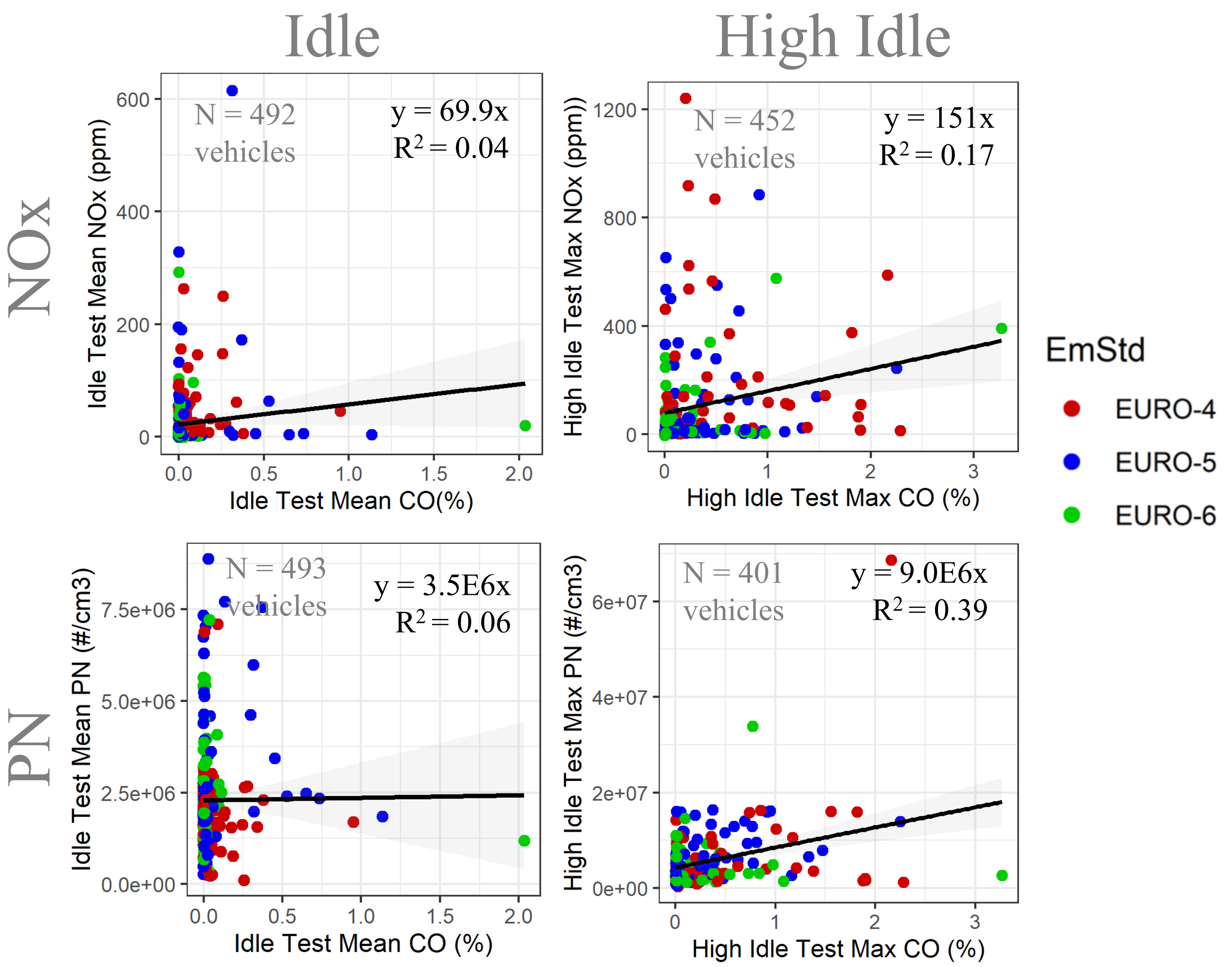
Weak correlations seen between CO from Idle, High Idle, and Acceleration tests – supports the need for multiple CO test types as currently outlined for PTI



Could High CO indicate High NOx or PN for Petrol?

There is not a strong correlation between measured CO concentration and NOx concentration across petrol vehicle tests.

CO should not be used to indicate NOx or PN levels.



Conclusions

Regarding the Enhanced PTI Protocol

- Enhanced PTI requires only 5 additional minutes. Driving tests conducted by human operator have good repeatability
- Enhanced PTI successful in identifying some higher emitting vehicles that were missed by official PTI test
- NOx concentration has good correlations to mass emission for the acceleration test, followed by high idle test
- Engine coolant, catalyst and ambient temperature investigation requires further analysis. Temperatures are not reliably reported by vehicles
- PN has good agreement between all 3 test types – supports that idle testing may be sufficient to identify of high emitters
- NOx has good agreement between the 2 loaded test types (high idle and acceleration) – supports need for loaded test and indicates interchangeability dependent on location. NOx acceleration test is preferred where possible.
- CO has bad agreement between the 3 test types – supports need for multiple test types in order to identify the high emitters

Comparison to current PTI and EURO standards

- Some positive correlation seen between smoke opacity and PN results for vehicles tested.
- Poor correlation was seen between CO results. This is mainly due to the reduced sensitivity of current PTI CO measurement equipment
- CO is not well correlated to NOx or PN for petrol vehicles – CO on petrol vehicles are not a good marker to find high emitters of PN or NOx.
- Comparing Enhanced PTI emission values across EURO standards:
  - PN for petrol vehicles still needs more controls as the concentrations are not decreasing through the EURO standards. Diesel PN is well controlled.
  - For NOx, EURO-6 diesel vehicles reverse the increase seen in EURO-5 but still fail to deliver the level of reductions in real-world emissions as per emission standards.
  - CO is generally decreasing through the EURO standards for both fuel types

Future Work

- Existing dataset
  - Further investigation of limits
  - Analysis of 'static idling load test' in Protocol V05
  - Characterise the different dynamic acceleration drive sections, including VSP characterisation
- Need more test sites and data – preferably 10 sites across Sweden
  - Evaluate effects of selection bias and weather conditions
  - Larger sample size for the static idling methodology
  - Expand testing to cover other NOx characterisation methods outlined in the CITA NOx Position Paper

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Thank you for listening

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Further Info

For full 1Hz traces of the tested vehicles:

PTI Pilot Parts 1 and 2: https://3datx.com/ptipilot/

Part 3 is available at https://3datx.com/request-reports/