Portable Emissions Measurement Systems (PEMS) as tools for identifying real-world emissions factors, quantifying AQ contributions & informing fleet-planning strategies

Real-world Emissions Measurements

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Straddle carrier

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Introduction

- In any location there are many local and trans-boundary contributions to the pollutants important to site-specific air quality
- For mobile and stationary internal combustion engine sources, contributions are usually estimated according to emissions factors (EF)
- These EF:
  - Are technology level specific (related to certification emissions standard)
  - Assume an ideal duty-cycle that cannot be representative of all real-use profiles
  - Can't recognise that multiple emissions control approaches (engine measures / aftertreatment) can be applied within the same technology level, potentially leading to large inaccuracies
  - Often predict pollutant emissions from CO_2 emitted, and rely on the calculation of CO_2 from volumetric fuel consumed
  - Are the best estimates we have!
- Measurement of pollutant emissions using PEMS can provide the opportunity to measure real-time CO_2 and pollutant emissions of actual duty cycles on non-road mobile machinery applications from different technology levels and emissions control system approaches
  - Data gathered can be used to understand emissions between, and within, technology levels of a specific NRMM type, compare actual emissions with EF predictions and help guide fleet renewal strategy

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Objectives

- Inspect NRMM applications (dockyard straddle cranes) and develop approach for installation of PEMS that allows rapid switching between applications
- Conduct appropriate risk assessments for installation and operation, through close collaboration with facility operator
- Install PEMS
- Develop test protocol for daily operation, including validation of PEMS function
- Identify 3 realistic operational duty-cycles and conduct in-use emissions testing on a variety of applications
  - Including repeat tests
- Assess and compare g/h emissions from applications:
  - Of different technology classes: Stage II, IIIA (= US Tier 3), IIIB, IV
  - From different manufacturers (and emissions control approaches) within the same Stage IIIA technology class
- Compare measured emissions with calculated EF
- Propose approaches for reduction of emissions via retrofit and fleet renewal

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- Introduction
- Objectives
- **Technical Approach**
- Results
- Conclusions

6 Straddle Cranes, of 4 Emissions Standards, were Tested

Abbreviation

NOEL II
- 3 container height
- 317kW; Noell Stage II specification; no catalytic aftertreatment

SCA_IIIA
- 3 container height
- 370kW; Scania Stage IIIA; no catalytic aftertreatment

QSM_IIIA
- 3 container height
- 300kW; Cummins "QSM" Tier 3 (=Stage IIIA); no catalytic aftertreatment

QSA_IIIA
- 4 container height
- 300kW; Cummins "QSA" Tier 3 (=Stage IIIA); no catalytic aftertreatment

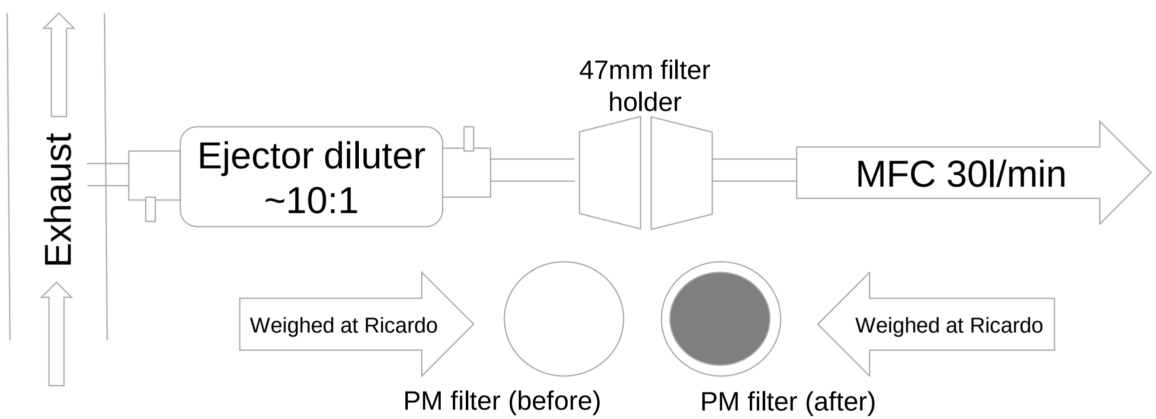
AGS_IIIB
- 3 container height
- 317kW; Agco Sisu Stage IIIB; DOC and SCR

VOLV_IV
- 3 container height
- 265kW; Volvo Penta Stage IV; EGR, DOC and SCR

It is not clear whether other engines than the Stage IV Volvo have EGR

Portable Emissions Measurement Systems – PEMS Horiba OBS-ONE and PM Sampling

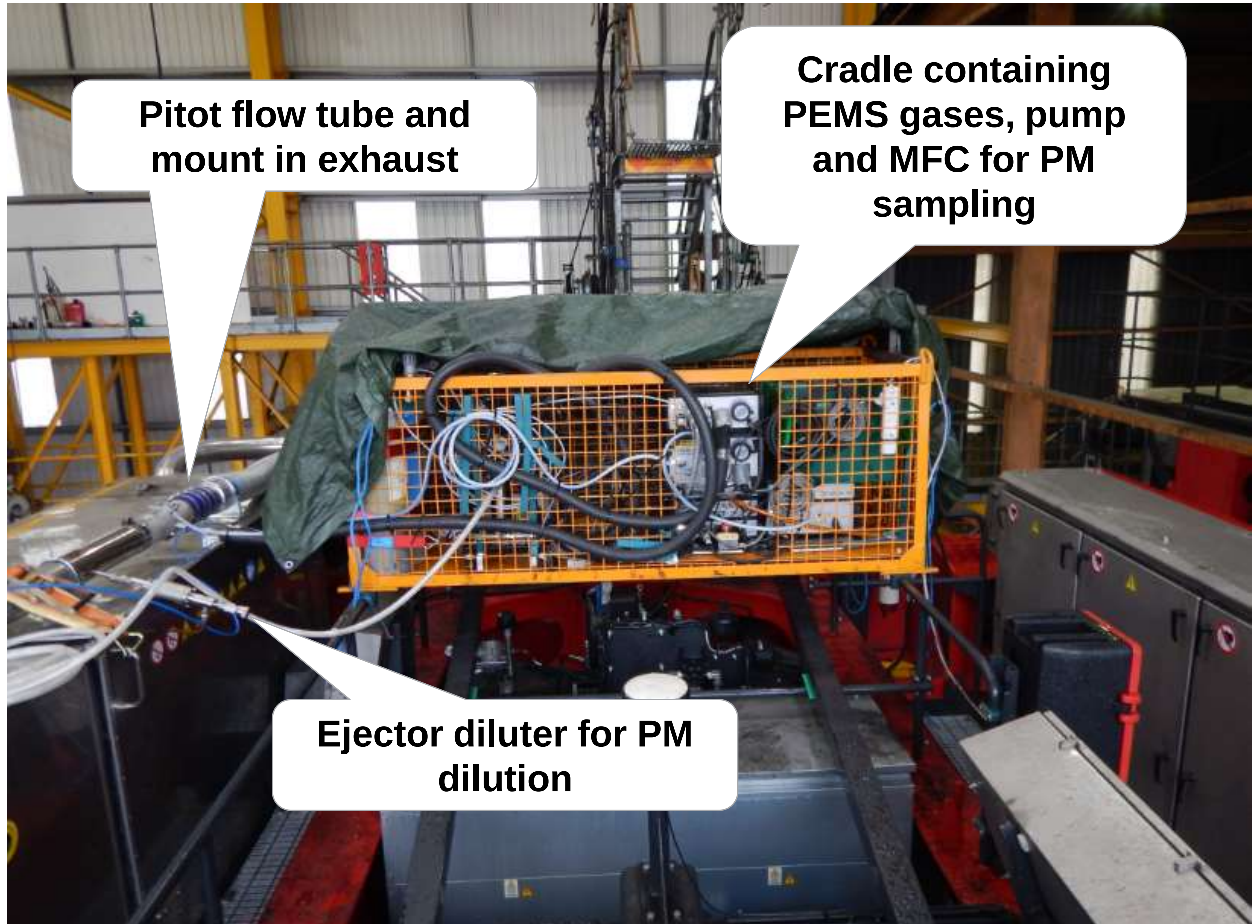
Analyte	Method	Range
CO	Heated NDIR	0-0.5 to 0-10 vol%
CO_2	Heated NDIR	0-5 to 0-20 vol%
NO, NOx, NO_2	Heated-dual CLD	0-100 to 0-3000 ppm
THC	Heated FID	0-100 to 0-10000 ppmC
Sampling Method	Wet measurement	-
Exhaust Flow Rate	Pitot flow meter “F”	0-30 m^3/min @ 20°C
Standard Signal Measurements	Exhaust temperature, Exhaust pressure, Atmospheric pressure, Atmospheric temperature, Atmospheric humidity, GPS signal, Road speed	



- PEMS enables the measurement of selected exhaust emissions under real-world operation
- Exhaust gas concentrations are measured directly from the exhaust along with volumetric flow, pressure and temperature
- Analytical approaches are matched to lab-based certification equipment
- Mass emissions are calculated from concentration (ppm) and exhaust mass flow data
- Vehicle parameters and geographic / topographic features are recorded
- PM could only be measured using fixed dilution ratio and fixed filter flow, so steady state sampling was recommended
- Selected PM approach provides comparable data between applications, but only at a semi-quantitative level

Installation of PEMS gases and PM Sampling

Straddle carrier



Cradle mounted on the top of straddle carrier: enabled rapid transfer between applications

Duty cycles

- Three cycles were developed
  - **"Warm-up & Drive" cycle [WUDC]; one-off tests on each application**
    - Representative operation (< 2.5km)
    - Cold start and initial driving from cold to location of normal usage
      - Includes catalyst light-off effects
      - Gaseous emissions only all applications
  - **"Normal operation" cycle [NOPC]; at least 3 repeats per application**
    - Representative operation (5 -11km)
    - Lower load driving and carrying, idling, plus high load container lifting
    - Predominant operating mode
    - Gaseous emissions only all applications
  - **"PM lifts" cycle [PMLC]; ≥ 10 lifts per repeat, 1 - 3 repeats**
    - Artificially created static condition (no driving) to evaluate PM emissions
    - Aggressive operation with multiple lifting of a container
    - Identify average emissions during a single lift event
    - Gaseous emissions and PM all (except no PM on Euro II)

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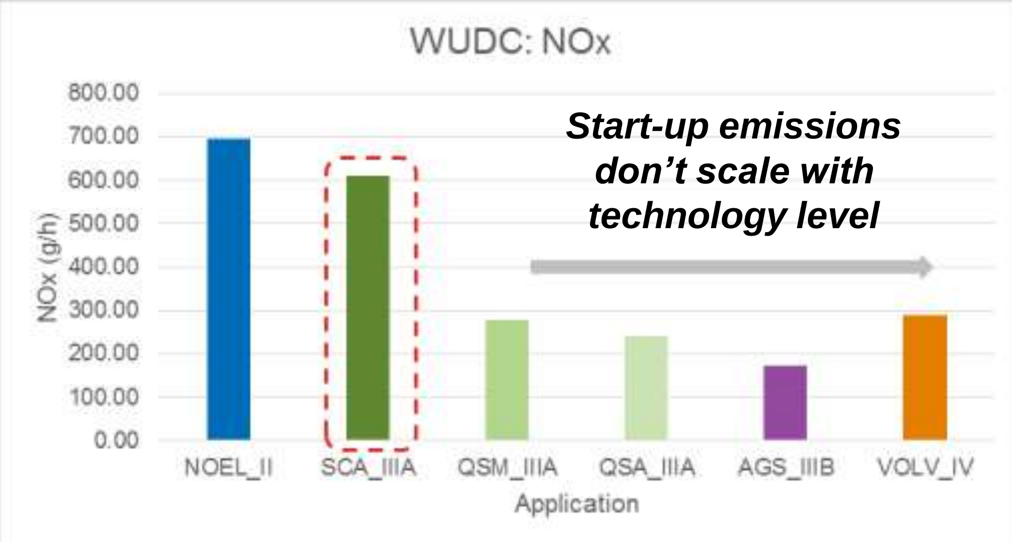
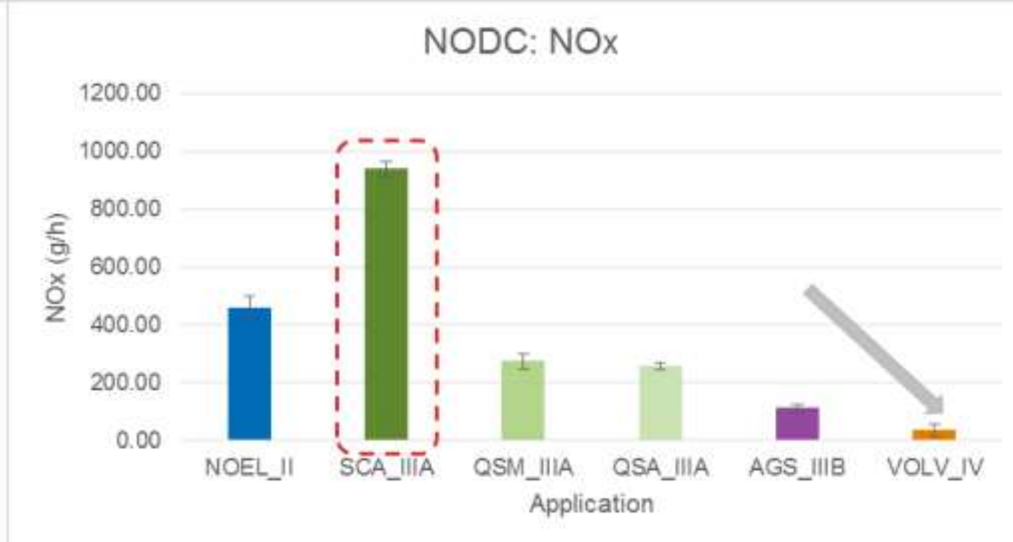
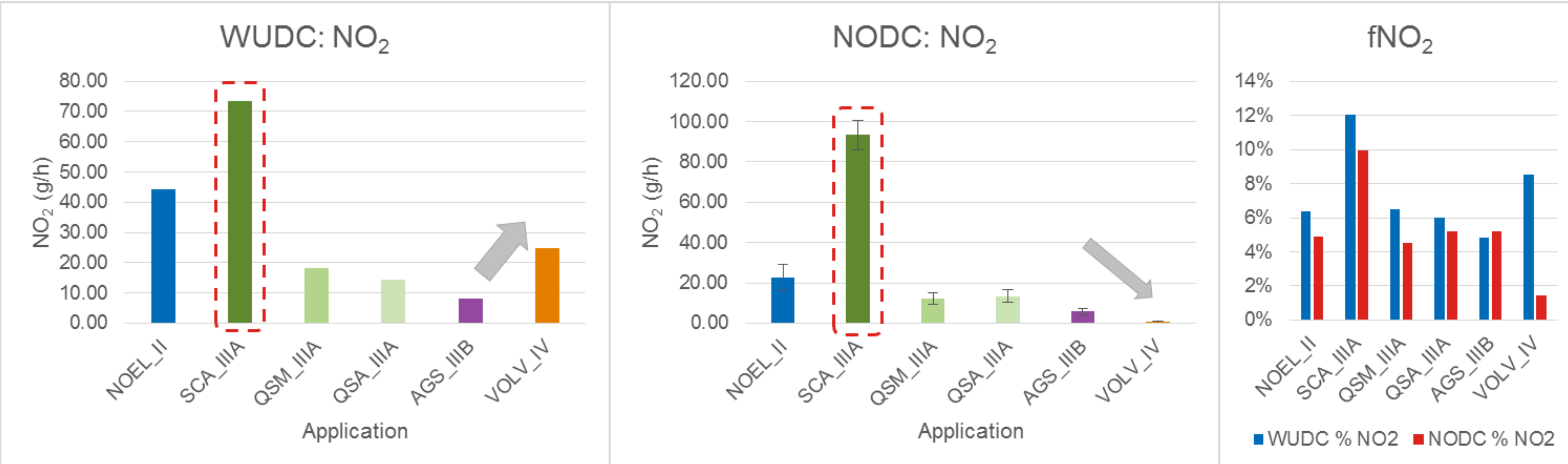
NOx emissions in g/h: WUDC and NODC
g/h is direct indicator of NOx release to environment





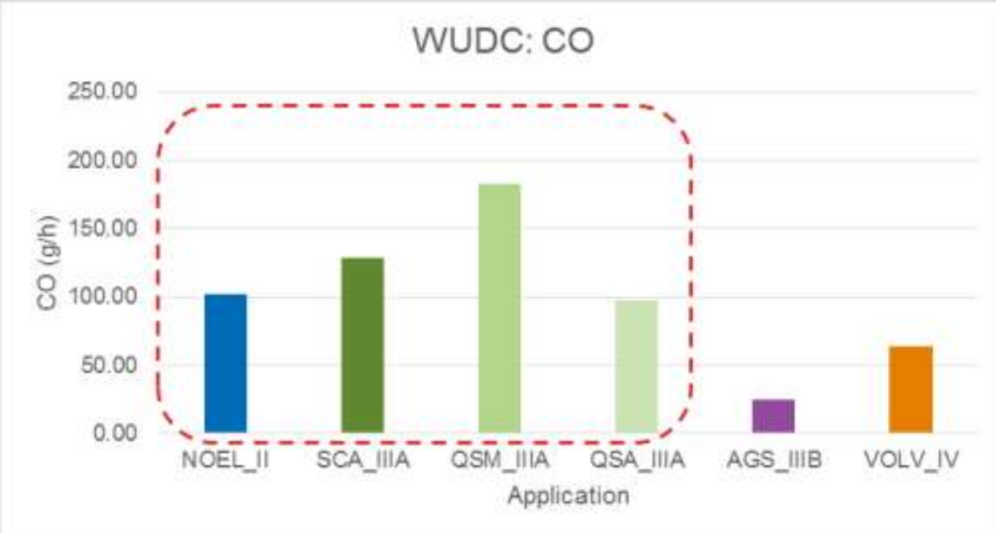
- **WUDC (limited time / distance of operation)**
  - Similar emissions from both Cummins IIIA engines; Scania IIIA higher (engine calibration effect)
  - AGS_IIIB and VOLV_IV NOx emissions appear high relative to IIIA Cummins due to limited SCR impact at cold start
  - SCR light-off impact in short duration test (VOLV test shorter than AGS) may explain IIIB v IV effect
  - Duty cycle not expected to be a major contributor to total NOx emissions from the daily operation of straddle cranes
- **NODC (dominant operating mode)**
  - NOx emissions from different technologies generally reduce with emissions standard
    - Scania IIIA has higher NOx, than Stage II engine: likely calibration effect and offset by lower PM
  - Lowest emissions from VOLV_IV reflects demands of lower certification emissions and increased effectiveness of SCR system combined with EGR
    - Clear benefit also with Stage IIIB over earlier technologies
  - Cummins engines again similar on NOx

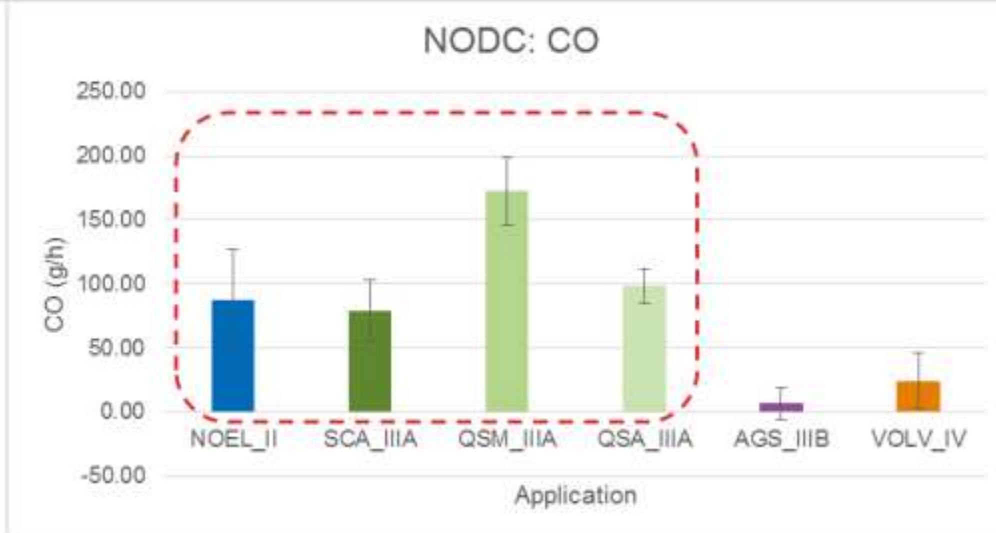
NO_2 emissions in g/h: WUDC and NODC
g/h is direct indicator of NOx release to environment



- Similar differences between applications and technologies for NO_2 emissions, as seen with NOx emissions
- Fraction of NOx present as NO_2 is low (compared to on-road applications) at 12%, or less
  - Only Stage IIIB and IV applications have diesel oxidation catalysts (DOC), so NO_2 measured is produced **by the engine** from earlier technologies
  - NO_2 needed by SCR systems for optimum “fast reaction” of NOx reduction, is increased across the DOC but then consumed in the SCR
  - Despite DOC, lowest absolute and proportion of NO_2 seen from Stage IV application

CO emissions in g/h

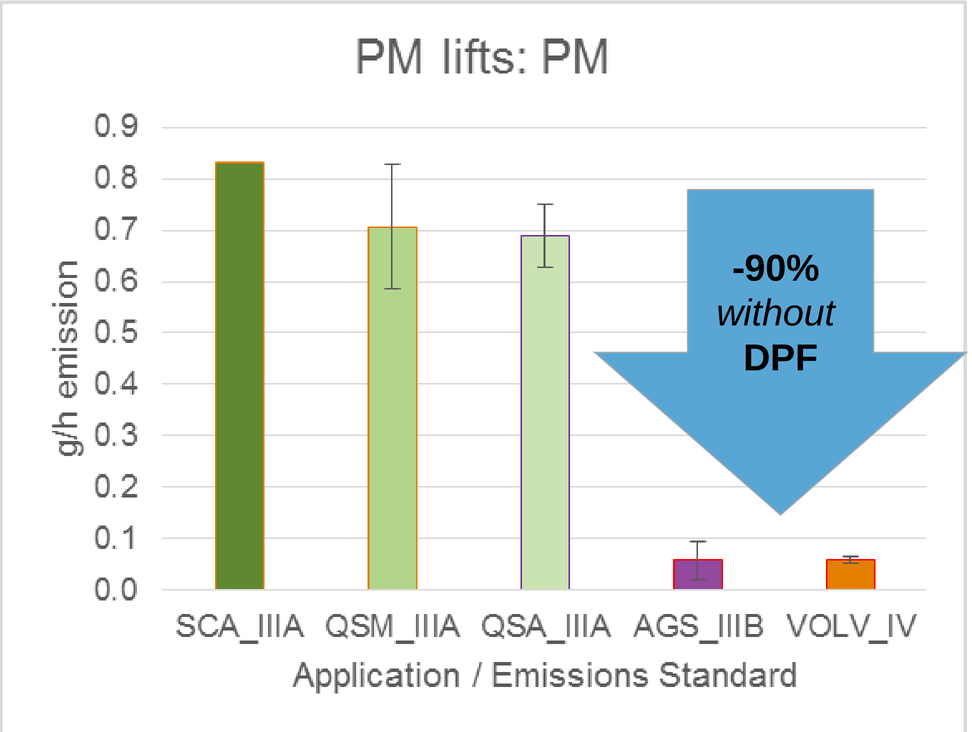




- CO emissions clearly lower from IIIB and IV than from earlier technologies
  - No engine calibration influence on CO at Stage IIIA
- Higher exhaust temps in NODC than WUDC leads to higher catalyst efficiency and lower CO emissions
- Lower CO from Stage IIIB than Stage IV may reflect more active DOC with earlier technology engine
  - Or, potentially, higher engine-out CO from the stage IV application

PM Emissions g/h

These data are only semi-quantitative, as the sampling approach is only accurate when used for steady state measurements, but data are comparable between applications



- PM emissions were measured from 5/6 of the applications (not Stage II)
- Stage IIIA NOx and soot (EC) trade-off likely
- PM also contains organic materials and these may be invisible (smokeless) but contribute significantly to PM

- The Scania Stage IIIA application results suggest a different calibration strategy than the Cummins Stage IIIA engines
  - The Scania engine sees similar PM, as well as higher NOx (as seen earlier), conversely the Cummins engine has a strategy targeting lower engine-out NOx, at the cost of high PM
  - Scania engine likely has lower soot/smoke even though PM is similar, as NOx is higher
- Stage IIIB & Stage IV PM levels are similar at ~50mg/h, at least 90% below observed Stage IIIA levels

Visual inspection of PM filters reveals low engine-out soot/PM strategies for Scania, Agco and Volvo but a high PM / Low NOx approach for Cummins

Different engine calibration solutions for Stage IIIA target low tailpipe NOx and result in higher soot (Cummins) and target soot at the cost of higher NOx (Scania)

IIIB and IV applications also target engine-out soot and use SCR to limit NOx. The DOC employed with SCR will also have some benefit for PM reduction

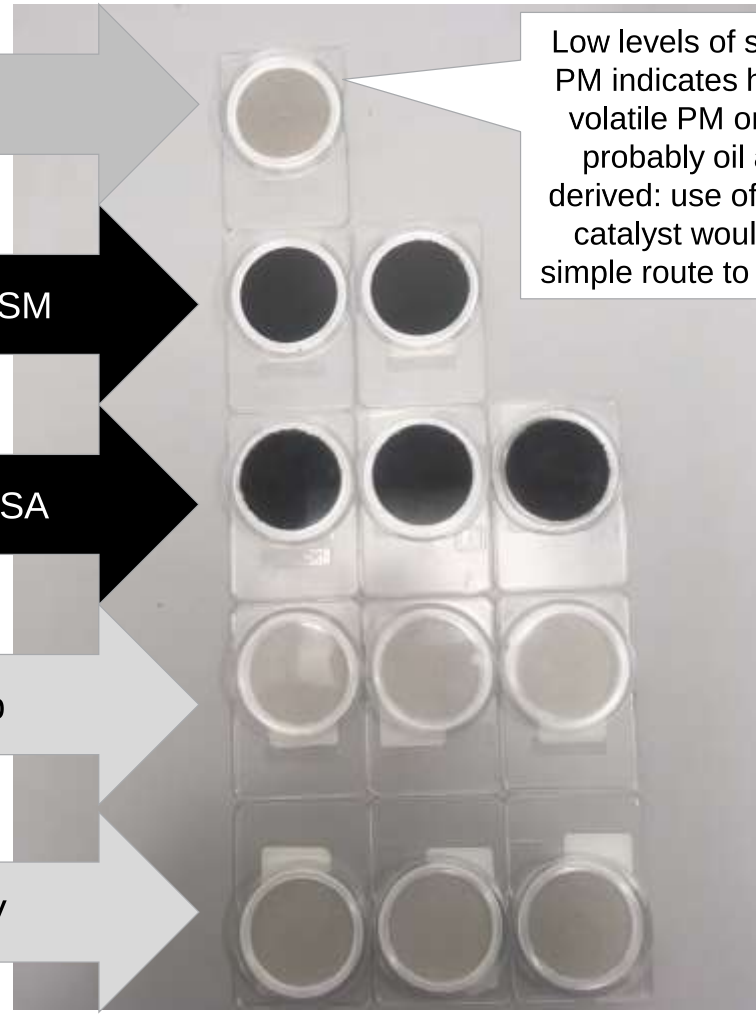
Scania Stage IIIa

Cummins Stage IIIa, QSM

Cummins Stage IIIa, QSA

Agco Sisu Stage IIIb

Volvo Penta Stage IV



Low levels of soot, but high PM indicates high levels of volatile PM on the filter – probably oil and/or fuel derived: use of an oxidation catalyst would provide a simple route to PM reduction

PM filters from "PM Lifts"

Technology comparisons summary

- Emissions from nominally identical technology levels may not necessarily show the same levels of emissions
  - E.g. Stage IIIA NOx (Scania ≠ Cummins)
- A trend in one emission (e.g. NOx) will not necessarily be reflected in other emissions
  - E.g. Measured NOx reductions between technologies do not guarantee PM reductions
- Reductions in emissions between technology levels cannot be guaranteed
  - E.g. Stage IIIA < Stage II
  - These depend on engine measures, aftertreatment function and specific operation
- **To understand these with confidence, measurements must be made!**

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“True EF” NOx [g NOx / g CO_2]

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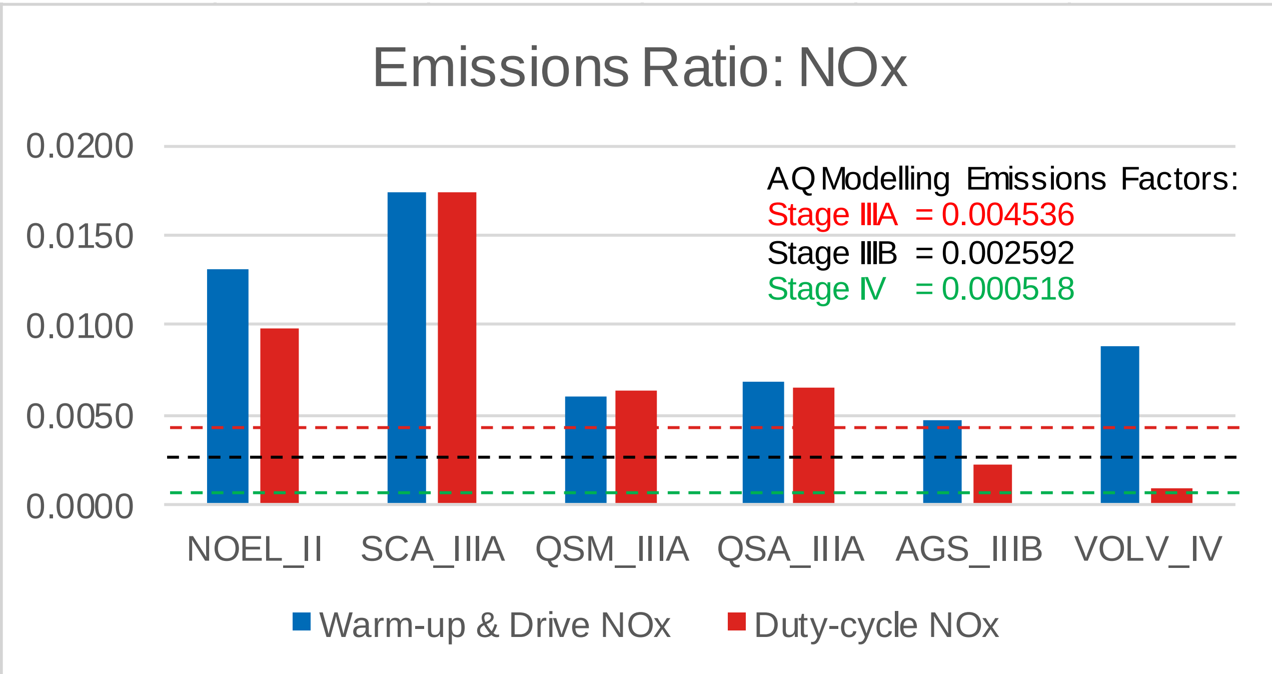
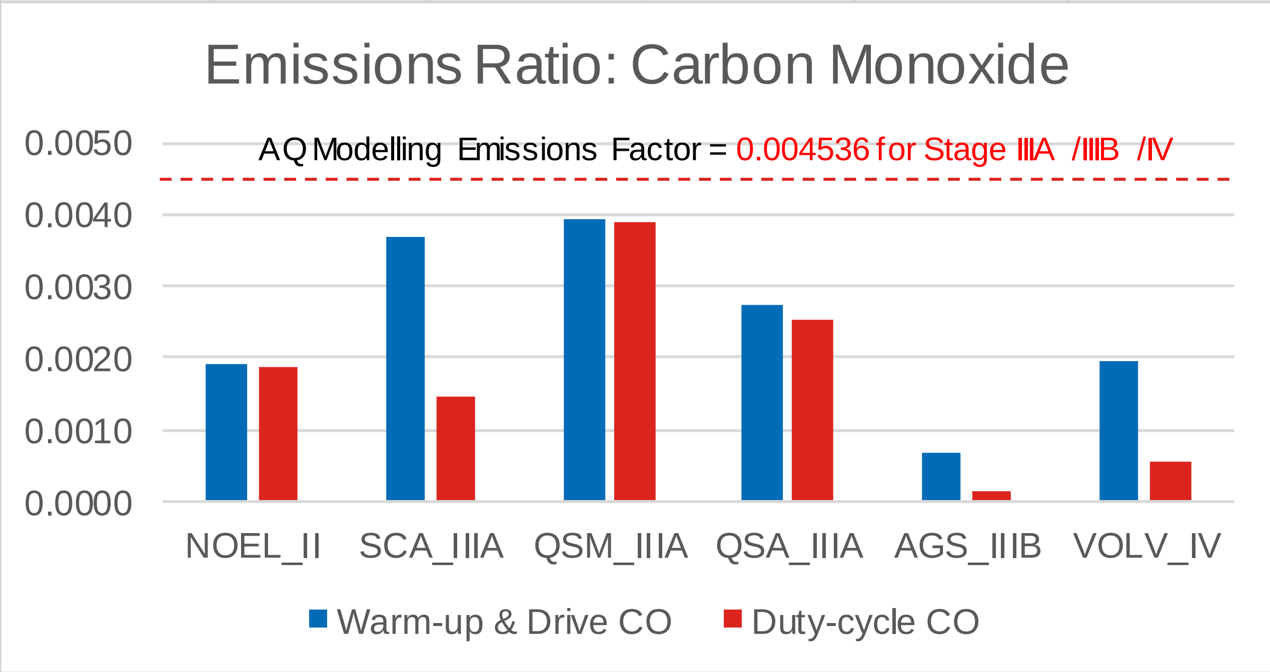


Ratio of True EF to AQ EF

Normalised NOx	Warm-up & Drive	Duty-cycle
NOEL_II	2.9	2.1
SCA_IIIA	3.8	3.8
QSM_IIIA	1.3	1.4
QSA_IIIA	1.5	1.5
AGS_IIIB	1.8	0.9
VOLV_IV	17.1	1.6

- True EF for Stage II and Stage IIIA applications consistently higher than EF used to quantify AQ contributions
  - Scania IIIA application has ~4x the emissions levels of NOx on a g/gCO_2 basis
- However, True EF for Stage IIIB and Stage IV are close to, or below the AQ factors for the “duty cycle”, which is expected to be the main contributor to measured emissions
  - SCR performance at cold start is relatively poor for the Stage IV though
- A recalculation of emissions contributions based on real factors is used to set a benchmark for emissions improvements

“True EF” CO [g CO / g CO_2]



- True EF for CO are, in all cases lower than the AQ factors
- In particular, AQ factors for Stage IIIB and Stage IV are extremely high compared with the actual ratios observed in this study
- CO primarily an issue for spark ignition engines without TWC

Ratio of True EF to AQ EF

Normalised CO	Warm-up & Drive	Duty-cycle
NOEL_II	0.42	0.41
SCA_IIIA	0.81	0.32
QSM_IIIA	0.86	0.86
QSA_IIIA	0.60	0.55
AGS_IIIB	0.15	0.03
VOLV_IV	0.43	0.12

EF estimates compared with actual measurements - NOx

- The determination of “true emissions factors” for the various technologies, under representative operation, enables the relative contributions of the applications comprising the fleet to be quantified
- These data can then be analysed to determine the technologies that:
  - Contribute the greatest proportion of pollutants
  - Contribute the greatest proportion per unit

- Findings can be used to target fleet renewal and retrofit approaches
- As the fleet evolves, add-on analyses can be used to put new technologies and applications into context

- For example: Straddle Crane NOx Fleet NOx Emissions on an annual basis:

Percentage contribution of each machine type to total emitted NOx/yr

PEMS Measurement Results (NOx)					
	Nox Average kg	Number of applications	Total kg	% contribution	% Contribution/ machine
Stage IV	140	9	1257	1%	0.12%
AG IIIB	587	16	9385	8%	0.51%
QSM IIIA	1763	7	12344	11%	1.55%
QSA IIIA	1693	8	13545	12%	1.49%
SC IIIA	3932	5	19660	17%	3.45%
NOELL IIIA	1267	18	22812	20%	1.11%
NOELL II	1454	24	34892	31%	1.28%

- Stage II & IIIA applications are the obvious candidates for targeted NOx reductions
  - In particular, Scania and Cummins Stage IIIA units
    - 23% of applications produce 40% of NOx
    - Of the 87 applications, 5 Scania units produce 17% of NOx emissions
  - 24 aged Noell Stage II applications contribute 31% of NOx

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Conclusions (1)

- Emissions differ from the various technology engines, but in normal use lower emissions are observed from applications of later emissions standards
- SCR applications demonstrate lowest levels of NOx, though benefits are reduced in short cycles including cold-start. When fully warmed-up, the Stage IV application has by far the lowest emissions of NOx
- The Stage IIIB and Stage IV applications have the lowest NO_2 emissions as well as the lowest NOx emissions
- Highest NOx was observed from the Stage IIIA Scania, considerably higher than the Stage IIIA Cummins engines
- PM levels from the Scania and Cummins Stage IIIA applications were similar but the chemistry appeared different: the Cummins' were high in carbon (soot), while the Scania is believed to have less elemental carbon and a higher volatile fraction
- PM emissions from the Stage IIIB and Stage IV applications were lower than levels from earlier technologies.
- The presence of oxidation catalysts in the SCR applications led to substantially lower CO from the Stage IIIB and Stage IV applications compared to the earlier technologies

Conclusions (2)

- Measured "True EF" of NOx and PM appeared higher than AQ factors would suggest, but establishing this provides a unique route to targeted emissions reduction
  - Assessment of model specific contributions x the number of vehicles enables cost benefit analyses
- The obvious candidate for emissions reduction would appear to be the Scania Stage IIIA applications, but there are relatively few of these in the fleet and the overall benefit would be limited
  - Addition of a retrofit SCR system would potentially provide both PM and NOx reductions (oxidation catalyst would eliminate PM while participating in the SCR reaction, with SCR reducing NOx)
- The largest benefit for NOx emissions will come from targeting all Stage II Noell applications, or cycling these out of the fleet and replacing with Stage IV vehicles
- DPF retrofits would reduce PM substantially from all applications but greatest benefits would be seen from Stage IIIA, and earlier, applications
- These insights can only be acquired by targeted on-application emissions testing

Any questions?

- Ricardo now has experience using PEMS on:
  - Buses in Brighton
    - Euro III, IV, V; Euro III retrofit SCR
  - Euro 6 a, b, c light-duty diesel passenger cars
    - Including some very low emissions diesels ‘ready for Euro 6d’
  - Euro 6 a, b, c light-duty diesel vans
  - Several Euro 6 light-duty gasoline vehicles
    - Including PN, with and without particle filter
  - Gasoline Plug-in hybrid
  - Euro VI heavy duty trucks
  - Stage IIIB and IV NRMM of several different types, and some applications at Stage II and Stage IIIA

http://www.ricardo.com/Documents/RQ%20pdf/RQ%202014/RQ%20Q3%202014/RQ_Q3_2014.pdf

Acknowledgments: Ricardo

- Thanks to

  RICARDO

  - **Eric White (TC)**
  - **Carl Jemma (TC)**
  - **Bex Smith (TC)**
  - **Guy Hitchcock (E&E)**

- Thanks to

  DP WORLD Southampton

  - **Brin Humphreys**
  - **Steve Long**
  - **Steve Yendall**