Non-road Mobile Machinery in Service Monitoring Based on PEMS

JRC Experiences in the Development of the Regulatory Proposal

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NRMM emission regulations: Background

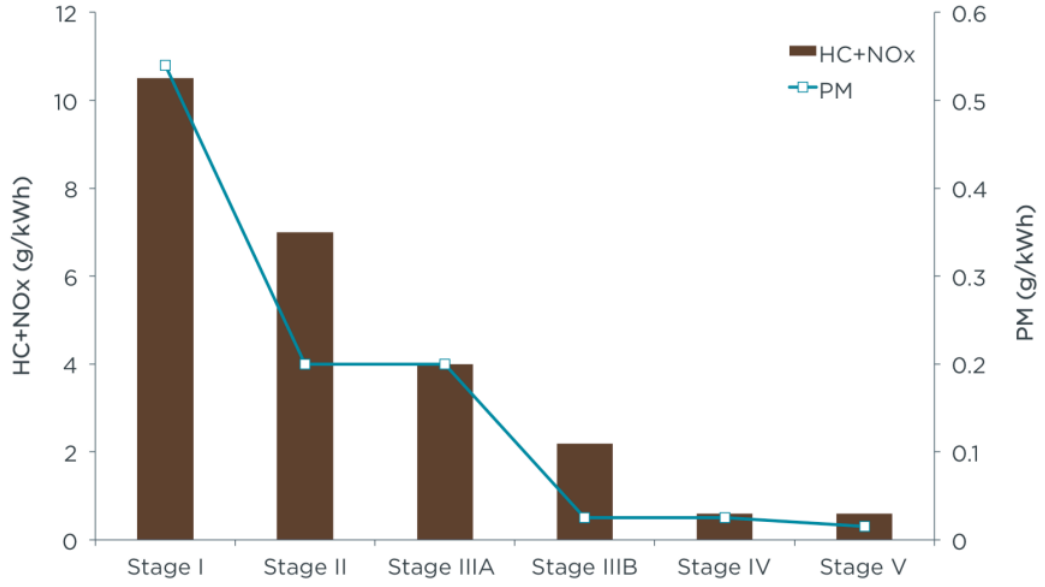

Figure 1. Emission limits from Stage I to Stage V for HC + NOx and PM

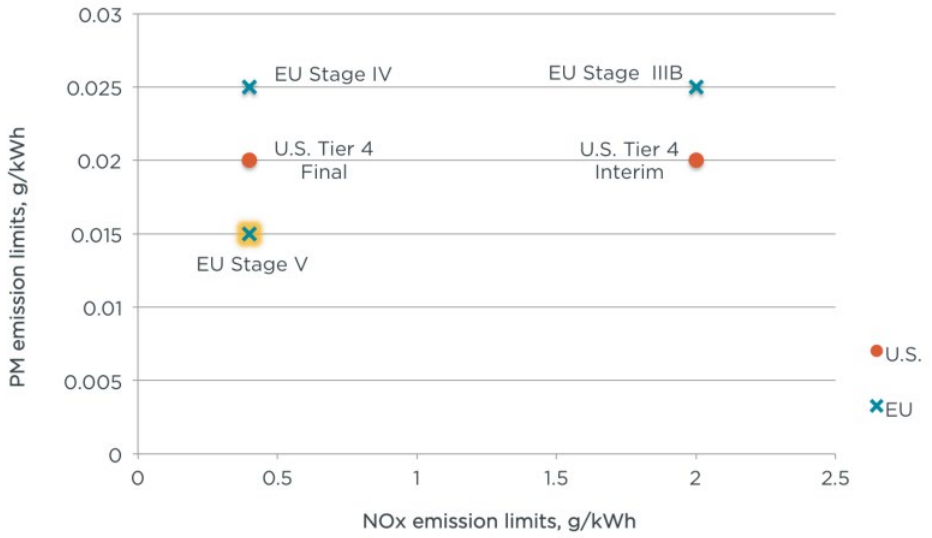

Figure 2. Comparison of PM and NOx emission limits between the U.S. and EU

- EU has adopted seven directives (six different emission stages)
- The current STAGE V is laid down in Regulation (EU) 2016/1628
- Stricter limits on emissions of NOx and PM
- PN emission limit introduced for certain engine groups.

- Source: ICCT, 2016

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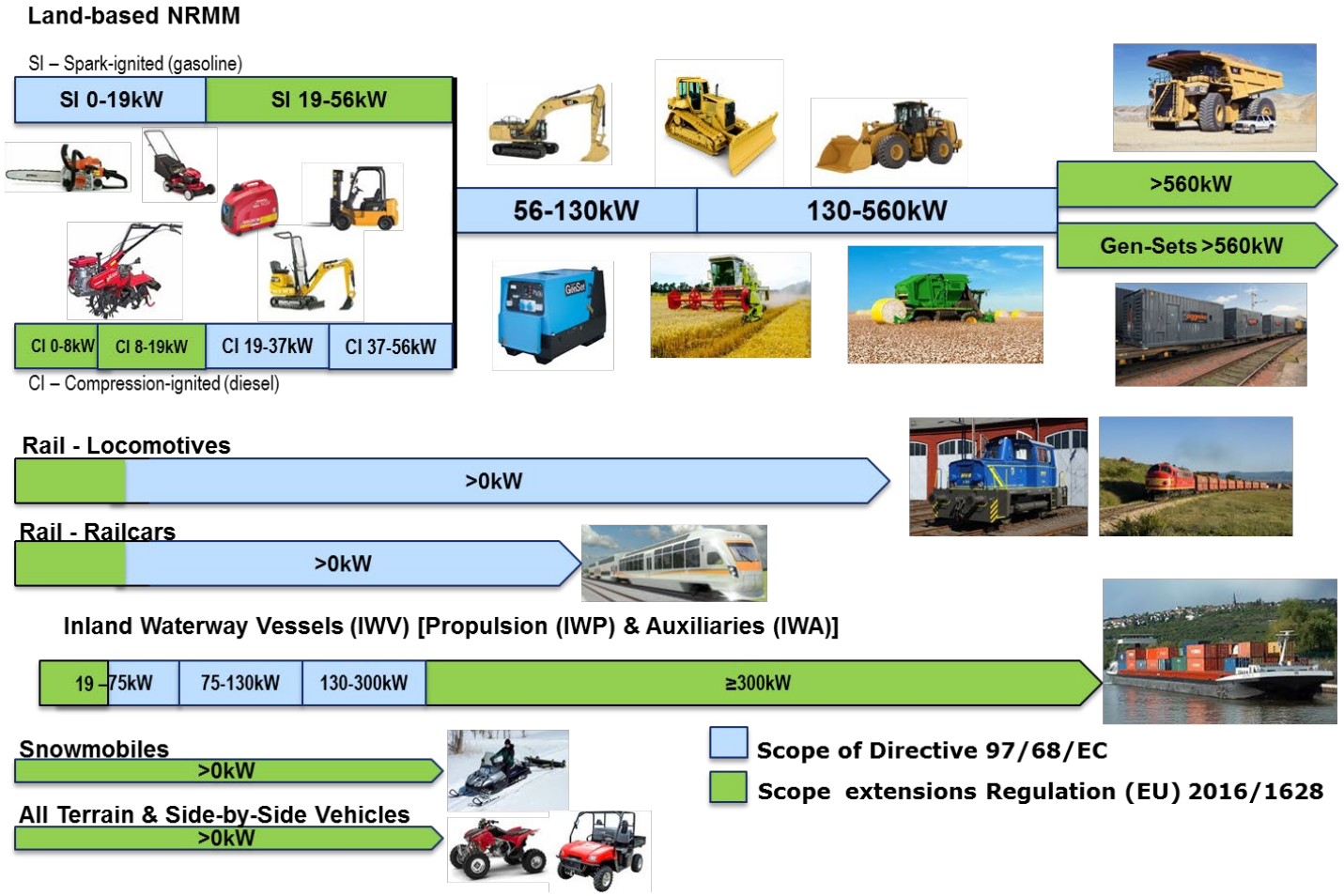
NRMM Stage V: Scope of application

- The regulation places all the engines in STAGE V. Each engine category must comply with a given set of emission limits.
- Strive alignment with (higher) US EPA standards, where appropriate
- Align the emission limits, where possible, to those in the on-road sector.



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NRMM Stage V: New elements

- Introduced PN emission limit of $1 \cdot 10^{12}$ #/kWh for:
  - NRE (19 kW ≤ P ≤560 KW), IWP (P≥300 kW), IWA (P≥300 kW), RLR (all)




- Monitoring of emissions of in-service engines (all engines)*
  - Exploratory programme on measurement of gaseous emissions of variable speed engines of categories NRE-v-5 and NRE-v-6 (56 to 560 kW)**
  - Pilot Programmes for definition of procedures for all other categories

* *Art. 19 of Regulation (EU) 2016/1628*
** *Regulation (EU) 2017/655*

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Monitoring of emissions of in-service NRMM engines (ISM)*

Goals

- To define the compliance limits for pollutant emissions of engine types or engine families during in-service operations: the so-called in-service conformity (ISC); and
- to ensure that the designed procedure, which is based on a reduced set of data, is appropriate to guarantee the limitation of the emissions of engines installed in NRMM over their normal operation.

Status

- Pilot programs were carried out on the categories that could have represented the major issues and uncertainties (applicability and suitability)

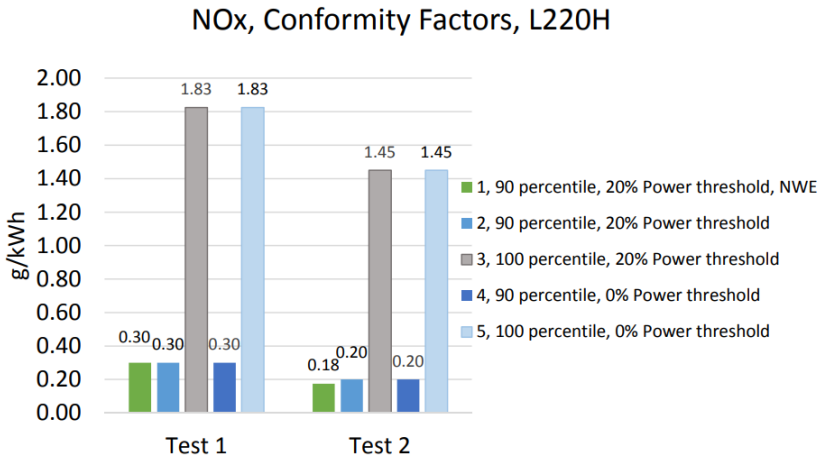
** Regulation (EU) 2017/655*

ISM procedure (Engines 56 kW≤P≤560 kW)

- The procedure has already been explored with success to monitor the gaseous pollutant emissions from variable speed engines in the 56 kW to 560 kW power range (engines of categories NRE-v-5 and NRE-v-6).
- In literature, it is possible to find different reports* that evidenced that approach is feasible (the procedure and the relative prescriptions work very well for these engine categories) .

In particular, TNO concluded that:

"A Stage V engine equipped with SCR, as used on a drilling rig, is very clean as well. This indicates that the Stage V limit for stationary engines and the emissions abatement technology SCR can be very effective."



* Literature examples:

a) Test Report OMT 4005 (2015), On-board Emission Measurement on Wheel Loaders with Different Emission Standards, Sweden, AVL MTC.
b) Test Report OMT 5005 (2016), On-board Emission Measurement on Wheel Loaders in Different Test Cycles, Sweden, AVL MTC.
c) Test Report R10221 (2021), Real-world emissions of non-road mobile machinery, TNO.

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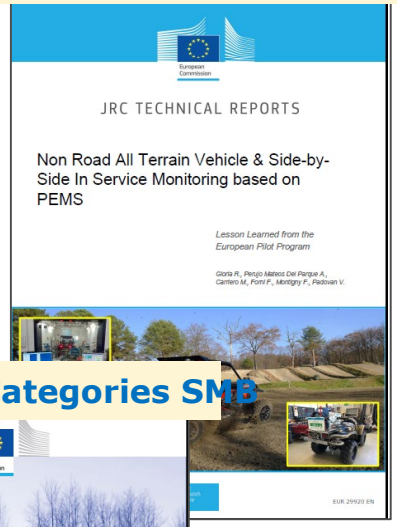
Monitoring of emissions of in-service NRMM engines (ISM) - Methodology

Engines of Categories NRE-v-1, NRE-v-2, NRE-c-1, NRE-c-2 (CI engines P<19kW)

Engines of Categories ATS



Engines of Categories SMB

- Test procedure is applicable to gaseous emissions of variable and constant speed engines;
- Compulsory use of PEMS (Portable Emission Measurement System) measuring NOx, HC, CO and CO_2 (testing in engine-dyno is allowed in some circumstances/categories);
- Data Evaluation: Calculating process based on sub-sets (or 'windows') using the so called "Averaging window approach" WBW and CO_2-BW

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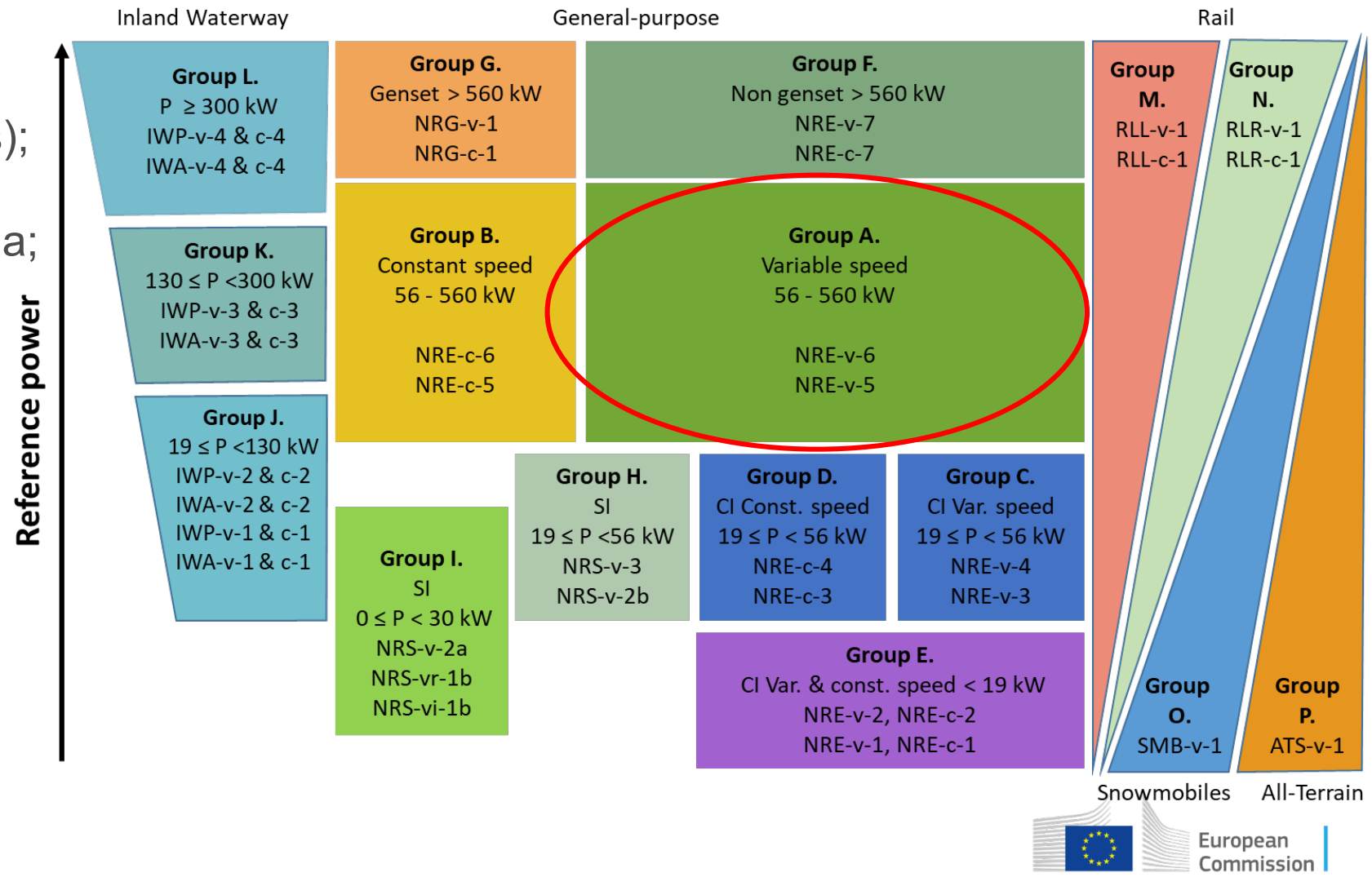
Monitoring of emissions of in-service NRMM engines (ISM)

- NRE & NRG (all sub-categories);
- NRS-vr-1b, NRS-vi-1b NRS-v-2a; NRS-v-2b & NRS-v-3;
- IWP & IWA (all sub-categories),
- RLL & RLR (all sub-categories)
- Snowmobiles (SMB-v-1)
- All-Terrain Vehicles (ATS-v-1)

ISM engine groups



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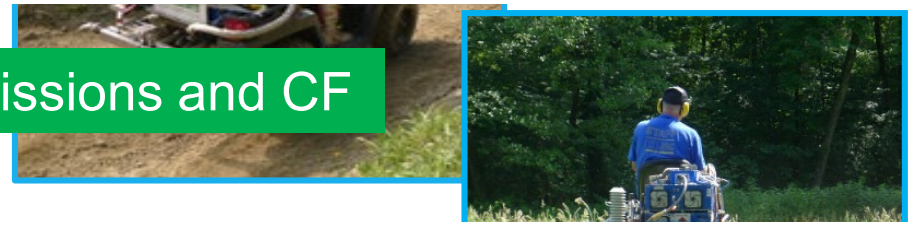
ISM procedure main adaptations (for no ECU engines)

- NRE v 5/6 (56≤P≤560 kW) **(ECU)**
- ATS, SMB, NRE v/c 1,2 **(NO ECU)**

Reference magnitudes

- Reference magnitude (WORK & CO_2) is obtained at the applicable test cycles (Hot-start NRTC)

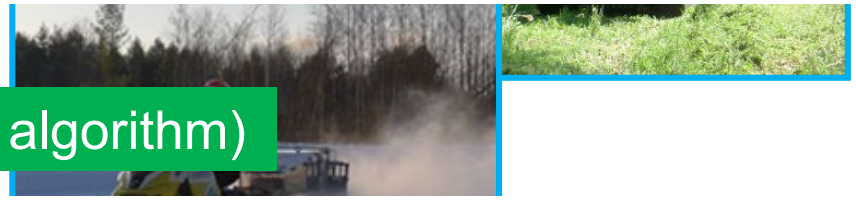
- Reference magnitude (CO_2) is obtained at the applicable STEADY test cycles (NRSC only)



Determination of gaseous pollutant emissions and CF

- ISM engine data evaluation: WMAW & CO2MAW

- ISM engine data evaluation: only CO_2MAW

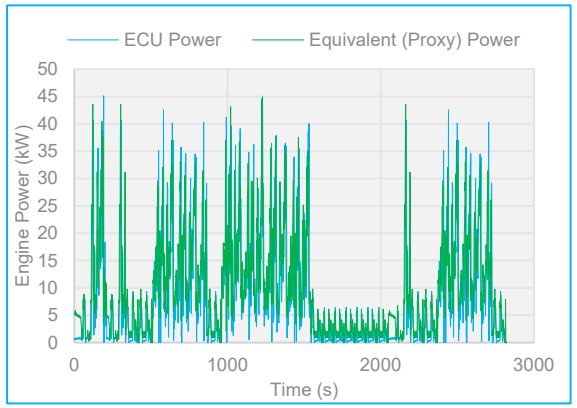


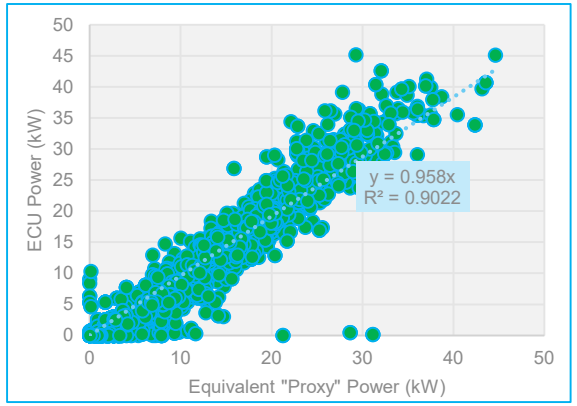
Working not working events (Marking algorithm)

- Based on POWER calculated from ECU signals
- Based on POWER EQUIVALENT calculated from PEMS CO_2 signal (VELINE method)

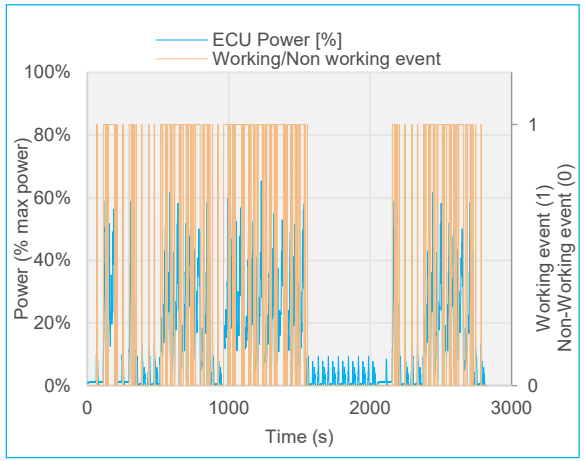
ISM: VELINE method validation (SMB example)

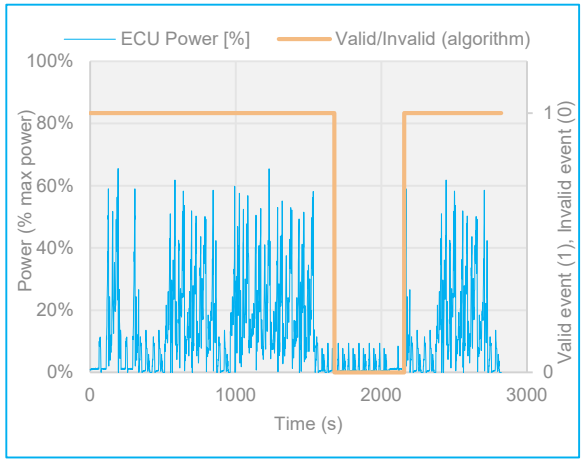
- SMB data
- Engine:
  - 3 cylinders (4-stroke)
  - Gasoline
  - 900 cc - 68,9 kW



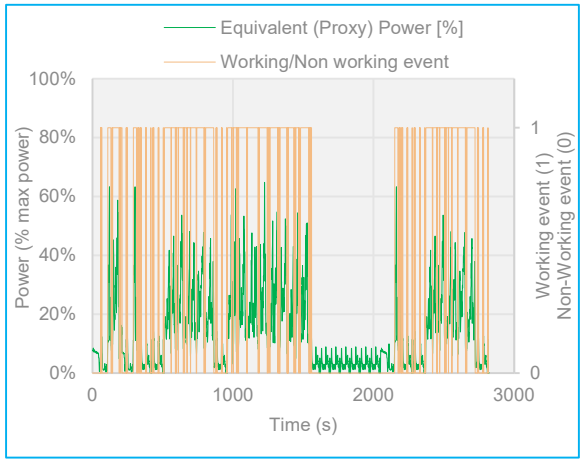


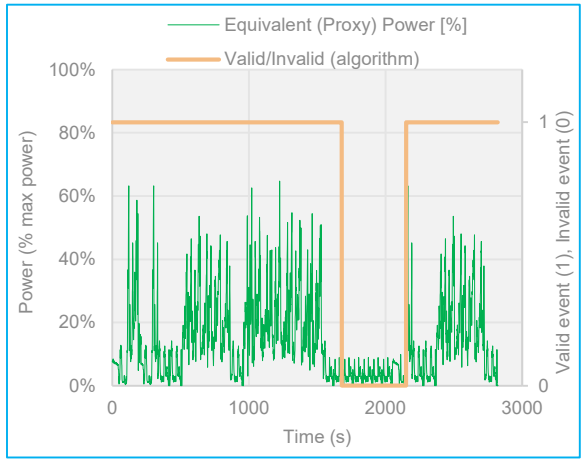
ECU





Proxy Power





Working/Non Working event

ESCLUSION: BASELINE (P <10% P_{max})	ECU MEASURED	CALCULATED
Total Number of events	2821	2821
Number of events with P<10% Pmax	1657	1375
% of non-working events	58.74%	48.74%

Valid/Invalid (marking algorithm)

EXCLUSION: BASELINE (P<10% Pmax) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	ECU MEASURED	CALCULATED
Total Number of events	2821	2821
Number of invalid events	477	471
% of invalid events	16.91%	16.70%

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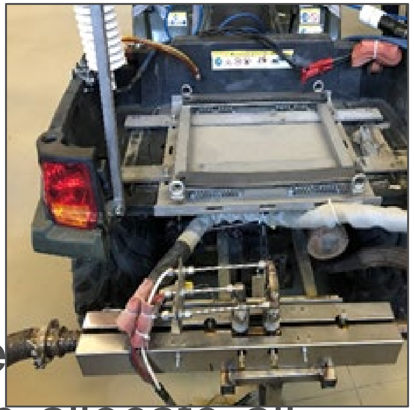
Main technical challenges & difficulties in NRMM ISM program

- PEMS mounting and operations
- Measurement of emissions: uncertainty in concentration.
- Measurement of emissions: uncertainty in mass emission (EFM measurement for single, 2/3 cylinders engines).
- ISM testing below 0°C – Ambient Temperature has a strong impact on battery duration (SMB).

PEMS mounting and operations – General provisions (no ECU engines)

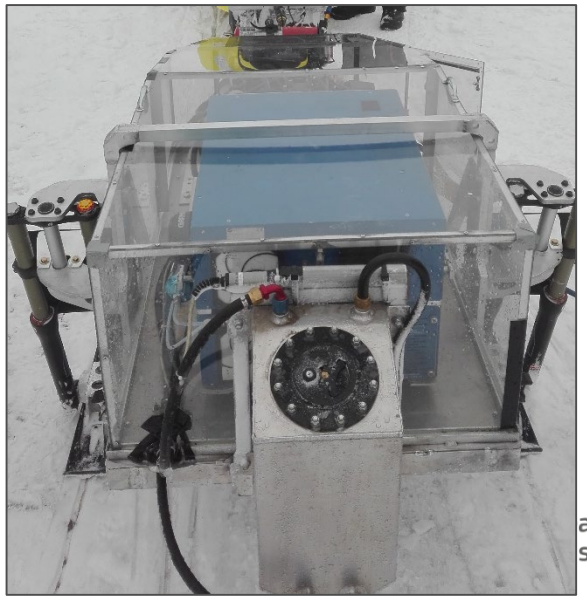
- The installation and operation of the PEMS equipment have been more complicated than expected;
- Mechanical works necessary to safely installing the gas analyzer and the EFM;
- It is necessary to use a suitable coverage to protect the equipment from dust, water, shocks, etc.;



- trolley or an additional supporting vehicle in which allocate all the instrumentation.

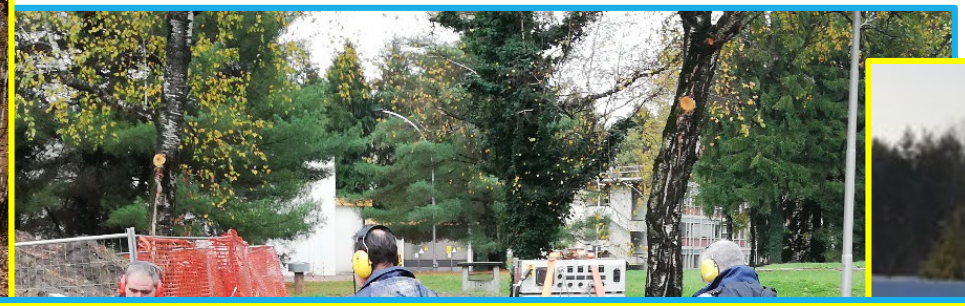
PEMS mounting and operations – Special provisions (SMB)

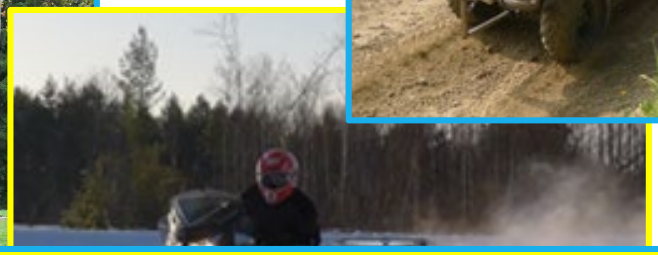
- In the snowmobiles the exhaust exits is downward, close to snow surface. Indirect measurement of the exhaust mass flow is highly recommended (e.g. fuel flow rate and the carbon balance method).
- Installation of instruments on a sleigh able to adsorb the shocks (cushioned forks/dampers).
- The fuel must be conditioned to avoid condensation and freezing problem in the fuel flow measurement system.



- Photo courtesy of MTU

PEMS mounting and operations




Yes, it is possible!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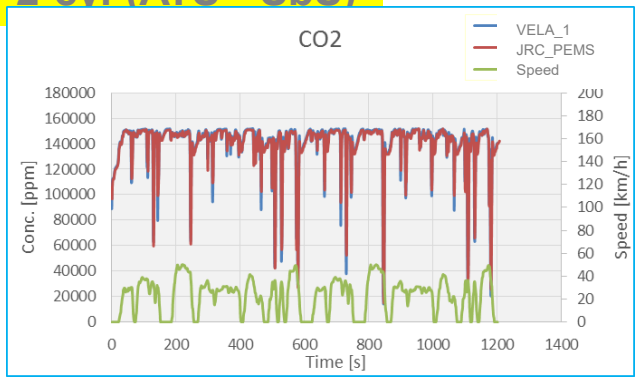
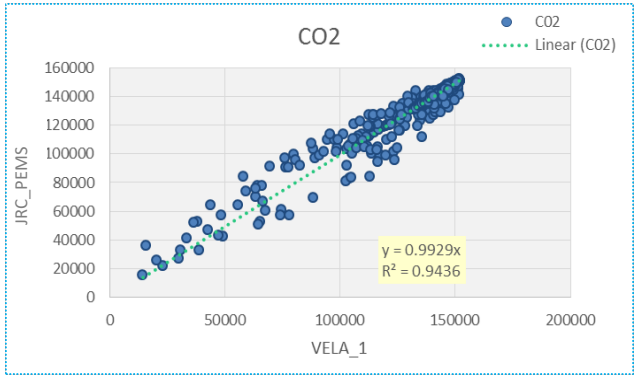
ISM challenges: Uncertainty in measurements

- Concentration

- Mass emissions

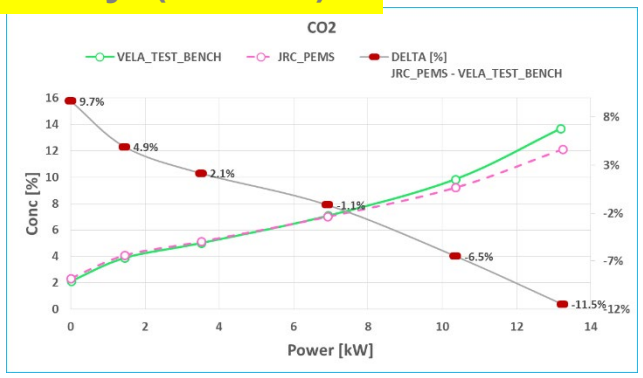
2-cyl (ATS - SbS)

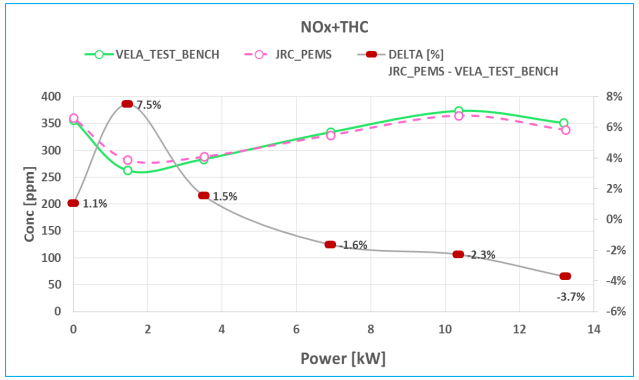




- Very good correlation between the laboratory-base analytical instrumets and PEMS measurements.

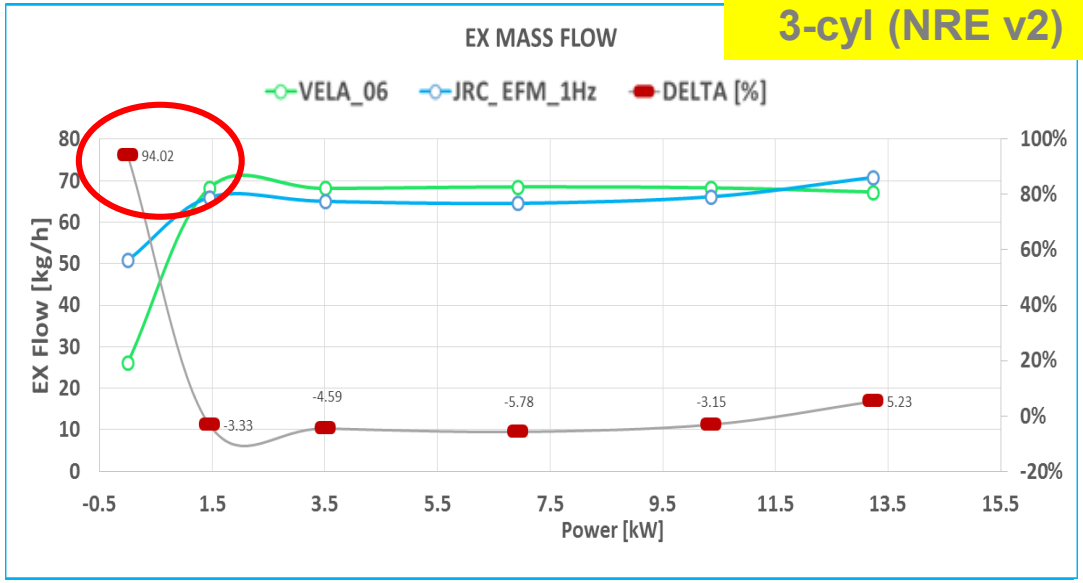
3-cyl (NRE v2)





- It is governed by the uncertainty EFM.
- Mono and bi-cylinder engines are prone to pulsations.
- **The use of a higher data acquisition velocity EFM is recommended.**

3-cyl (NRE v2)



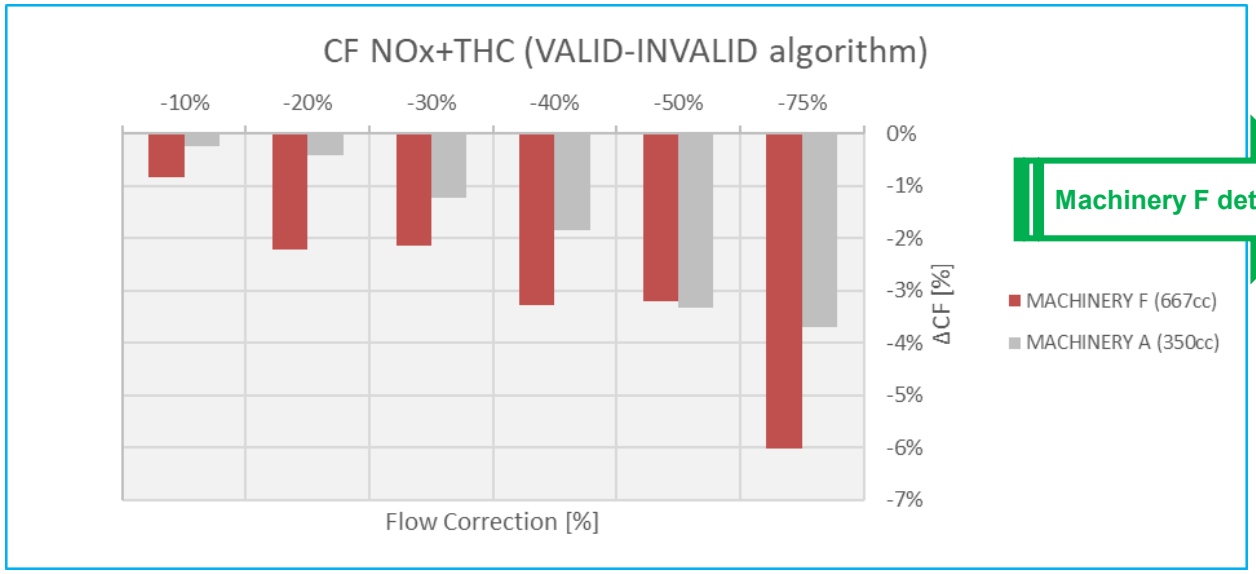
Measurement of emissions – EFM readings

Sensitivity study: A large uncertainty in the EFM translates into a reasonable error in the final CF because the use of the CO_2MAW rather that Work MAW

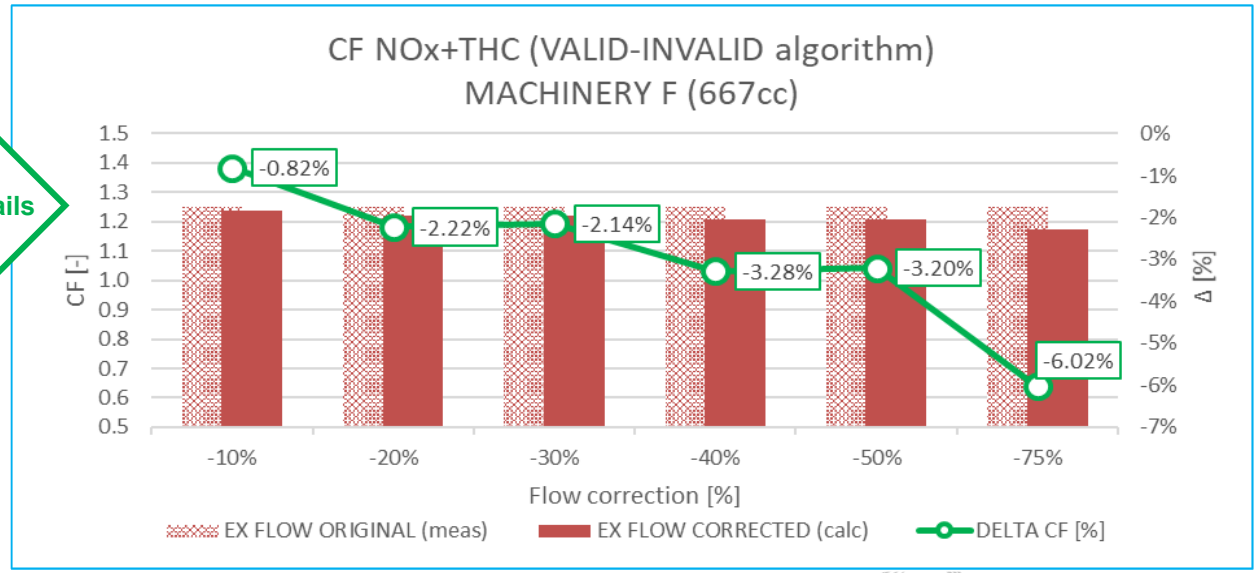
$$CF = \frac{CF_I}{CF_C}$$

$$CF_I = \frac{m}{m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})} \quad \text{(in service ratio)}$$

$$CF_C = \frac{m_L}{m_{CO2,ref}} \quad \text{(certification ratio)}$$



Machinery F details



Using CO2MAW method

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Testing below 0°C (impact in battery duration)

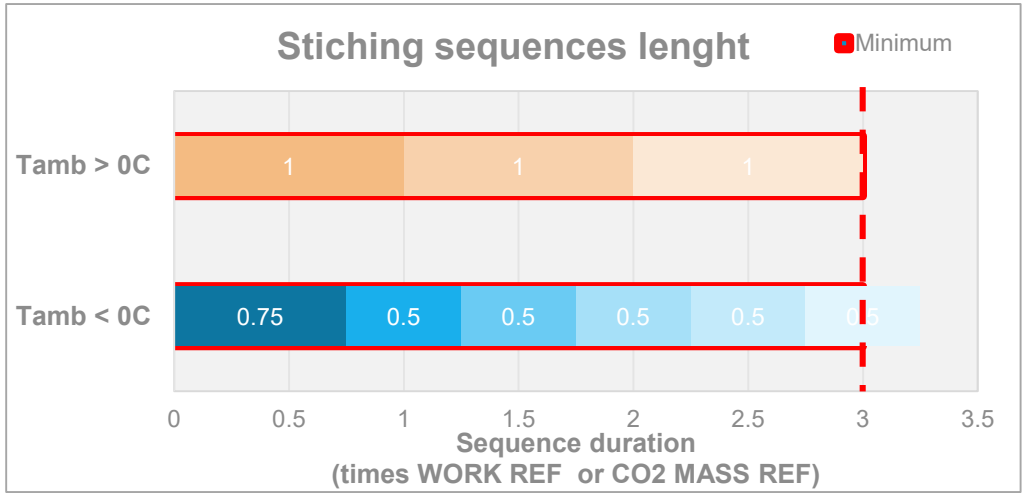
Performing an ISM test at ambient temperature below 0°C, a minimum of one reference work/reference CO2 mass (for cycle NRTC/NRSC) for every sequences is not possible because of battery life. Combined data sampling, using stitching method, is allowed. The combined data sampling shall be considered one ISM test.

Additional requirements:

- The operating sequences shall be joined in a chronological order (including all data not excluded);
- The different operating sequences shall be obtained using the same NRMM and engine;
- Maximum of **three** operating sequences, except in the case of ISM testing performed at 0°C degrees or below (maximum of **six** operating sequences);
- 72 hours is the maximum elapsing period permitted between the first and last operating sequence;

- **Minimum amount of work (kWh) or CO2 mass (g/cycle) for each operating sequence:**

		Tamb >0° C			Tamb <0° C		
GROUP		A, C	H	OTHERS	A, C	H	OTHERS
REF CYCLE		Hot-start NRTC	LSI-NRTC	NRSC	Hot-start NRTC	LSI-NRTC	NRSC
NUMBER OF MAX STITCHING SEQUENCES		3	3	3	6	6	6
MIN DURATION OF EVERY SEQUENCE (times ref work or CO2 ref mass)	1st sequence	1	1	1	0.75	0.75	0.75
	n sequence	1	1	1	0.50	0.50	0.50



ISM: General methodology & principles

- Use the same principles/methodology (technical requirements) for all categories (except NRSh) and for both variable and constant speed engines.
- The ISM test can be carried out by following the normal/usual operations the NRMM undergoes in the field.
- The test duration will be:
  - ISM groups A , C and H: between 5-7 times the reference work or reference CO_2 (NRTC/ LSI-NRTC)
  - ISM groups E, I, O and P: between 3-5 times the reference work or reference CO_2. Due to the power range of these NRMM engines (this still ensures statistical robustness).
  - All other groups: between 5-7 times the reference work or reference CO_2.

The reference work in kWh or CO2 reference mass in g/cycle determined from the type-approval test result using the method set out in Appendix 9 (NRSC rather than NRTC)

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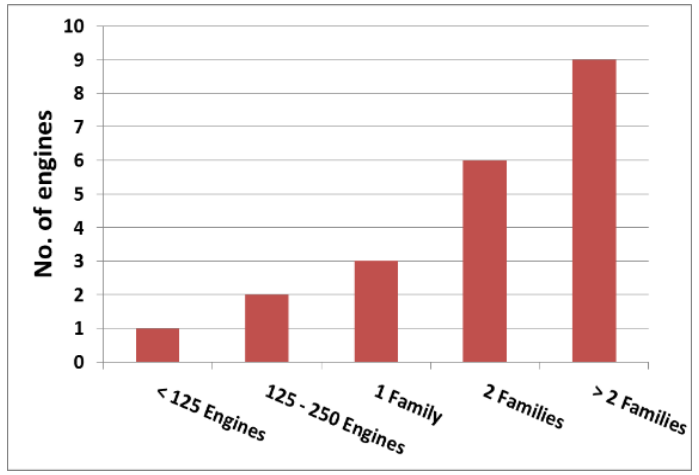
ISM: Testing scheme



- Two testing schemes for ISM (general):
  - Testing scheme based on the Emission Durability Period (EDP)
  - Testing scheme based on a 4 years' period
- For some categories is possible to use:
  - Testing scheme based on the age of non-road mobile machinery (without an operation hour indicator)
  - Testing scheme based on the odometer reading of non-road mobile machinery (machines with an odometer)
- Small volume manufacturers: the number of engines tested are adapted

ISM group A

	% of EDP values	
Reference power of selected engine (kW)	a	b
56 ≤ P < 130	20	55
130 ≤ P ≤ 560	30	70

ISM groups O and P

	% of EDP values	
Group	a	b
O	20	55
P	30	70

Other ISM groups

	% of EDP values	
Reference power of selected engine (kW)	c	d
P < 56	10	40
56 ≤ P < 130	20	55
P ≥ 130	30	70

Closing remarks

- PEMS is suitable for performing ISM measurements in all NRMM engine (sub-) category (except for NRSh & NRS-vr-1a and NRS-vi-1a).
- The experience obtained in the Pilot Programs has been translated into the new text amending the ISM regulation.
- Remains for some mfrs. concerns on the accuracy of PEMS measurements, in particular related EFM reading.
- ISM measurements* made by some manufactures confirms the suitability & robustness of the procedure.

*On diverse engine categories within the 56 ≤ P ≤ 560 kW and outside that range.

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