EUROMOT

The European Association of Internal Combustion Engine and Alternative Powertrain Manufacturers

EUROMOT TECHNICAL REPORT

Initial results from in-service monitoring (ISM) of gaseous pollutant emissions from Stage V, 56 – 560 kW variable speed NRE internal combustion engines installed in non-road mobile machinery (NRMM)

September 2024

Summary

This technical report contains anonymised ISM test results from EUROMOT member companies collected in the period May 2021 to August 2024 for engine (sub-)categories NRE-v-5 and NRE-v-6, i.e., variable speed engines of category NRE with a range of reference power from 56 to 560 kW (ISM Group A). At the time of publication this is the largest known cohort of non-road in-use emission test results ever compiled into a single analysis.

In general, the results show that in the absence of any mandated pass-fail criteria the in-use gaseous emissions of NOx, THC and CO are nevertheless well-controlled when evaluated on the basis of the current EU ISM Regulation (EU) 2017/654. It recognized that there are still some cases of higher than average in-use NOx emissions under certain operating conditions due to naturally occurring phenomena or to the limitations of the emission control system.

Due to the universal use of selective catalytic reduction (SCR) systems on the engines tested the NOx conformity factor will be influenced by the conditions under which the NRMM was operating and the resultant exhaust gas temperature. Consequently, the same engine, when used in different NRMM, or even in the same NRMM performing different tasks, may give different results.

Introduction

Commission Delegated Regulation (EU) 2017/655 on monitoring of gaseous pollutant emissions from in-service combustion engines installed in non-road mobile machinery (NRMM), amended by both Commission Delegated Regulation (EU) 2018/987 and Commission Delegated Regulation (EU) 2022/2387 as corrected by the Corrigendum published in the Official Journal of the European Union L 321 of 15 December 2022 (hereafter “the Regulation”), sets out the methodology to comply with the requirements of Art. 19 of Stage V Regulation (EU) 2016/1628 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for NRMM. EUROMOT has produced a frequently asked questions (FAQ) guidance document to assist stakeholders involved in this In-Service Monitoring (ISM) which can be found at the following link: https://www.euromot.eu/publication-and-events/publications/

Art. 19 of Regulation (EU) 2016/1628 requires that the gaseous pollutant emissions from engines belonging to engine types or engine families of emission Stage V that have been type-approved in accordance with that Regulation are monitored by testing in-service engines installed in NRMM and operated over their normal operating duty cycles. Such ISM testing is to be conducted under the responsibility of the engine manufacturer (hereafter “manufacturer”) and in compliance with the requirements of the approval authority, on engines that have been correctly maintained, in compliance with the provisions on the selection of engines, test procedures and reporting of results for the in-scope engine categories. Correspondingly, the Regulation establishes the ISM methodology for in-service internal combustion engines installed in NRMM using portable emission measurement systems (PEMS).

It should be noted that whilst the Regulation mandates that manufacturers conduct ISM testing, it does not mandate any pass-fail criteria for the engines that are tested. This is because, as set out by Art. 19 of Regulation (EU) 2016/1628, the ISM programme is intended to gather information on the extent to which the emissions measured from the test cycle correspond to the emissions measured in actual operation. It also enables suitable test methodologies to be evaluated on a large scale, and lessons learned accordingly. i.e., the ISM programme is a project to inform future rulemaking.

This technical report contains anonymised test results from EUROMOT member companies collected in the period May 2021 to August 2024. The reported results are a summary from tests independently conducted by the manufacturers concerned and submitted to EU approval authorities according to the requirements of the Regulation. Before 26 December 2022 the Regulation applied only to engine (sub-)categories NRE-v-5 and NRE-v-6, i.e., variable speed engines of category NRE with a range of reference power from 56 to 560 kW, now known as ISM Group A; This technical report solely covers that ISM Group.

The amending Delegated Regulation (EU) 2022/2387 has now extended the scope to all the other stage V engine categories. Those other categories may be the subject of future reports, but these are not included in this report.

EUROMOT was not directly involved in conducting the testing or calculating the results but has merely provided a platform for collating, assessing and publishing those results in the absence of any other centralised mechanism to provide this up to now.

The data used in the calculations presented in this report is not selective, i.e. every Group A ISM result provided to the EUROMOT secretariat up to August 2024 has been used in the analysis. At the time of publication this is the largest known cohort of non-road in-use emission test results ever compiled into a single analysis.

Engine and NRMM selection

Manufacturers were independently responsible for selecting engines and NRMM to test in consultation with their respective approval authority. The Regulation requires that selected engines are:

- Installed in one of the most representative categories of NRMM for the subject engines[1];
- Properly maintained with no active faults or evidence of misuse[2]; and
- Representing in a balanced manner across the applicable engine families and types the widest variety of engine types and categories of NRMM[3,4].

It is not required to test every engine type and engine family[5], though the data included in this report is from the largest and most comprehensive sample of engines and NRMM known to exist to date, comprising more than one-hundred and fifty ISM tests from a wide range of agricultural, construction and industrial applications including one or more of each of the following:

- Agricultural: Tractors, combine and forage harvesters, forestry machinery
- Construction: Excavators, loaders, bulldozers, dump trucks
- Industrial: Telescopic handlers, all-terrain cranes, other material handling NRMM

Although the ISM groups all variable speed NRE engines 56 – 560 kW together, some sub-division was applied to the tests submitted by EUROMOT members to provide a richer evaluation of the results.

Specifically, for deeper evaluation results were artificially sub-divided into the three applications listed above (Agricultural, Construction, Industrial) and into the power bands 56 – 75 kW, 75 – 130 kW, 130 – 225 kW, 225 – 450 kW and 450 – 560 kW.

Multiple results were available in each of the power bands except 56 – 75 kW which is not represented in this data set.

[1] Regulation (EU) 2017/655, Annex, Point 1.3
[2] Regulation (EU) 2017/655, Annex, Point 1.3
[3] Regulation (EU) 2017/655, Annex, Point 2.4
[4] Regulation (EU) 2017/655, Annex, Point 2.6
[5] Regulation (EU) 2017/655, Annex, Point 2.6

NRMM operation

The Regulation requires that selected NRMM are operated:

- To perform representative work of the NRMM[6];
- To not include disproportionate amount of idle[7]; and
- To comprise sufficient load activity to achieve the minimum test duration[8].

For the engines in this technical report, the ISM test was required to accumulate between five and seven times the amount of work the parent engine previously delivered on the hot NRTC type-approval test cycle[9].

The ISM test may comprise operation at the usual worksite of the NRMM with its usual operator fulfilling whatever task is required, or alternatively where that is not possible the NRMM may be operated on a test duty cycle intended to represent normal operation. To meet the minimum test duration, it is generally permitted to combine up to three separate operating sequences obtained within a 72-hour period to create a single ISM test[10], but NRMM which operate with consistently low load and cannot normally meet these criteria are necessarily discounted from ISM unless no alternative NRMM is available for selection.

The following is a summary of the types of NRMM operation that are represented in the ISM tests presented in this report, separated into the three generic categories:

Agricultural
Ploughing, harrowing, cultivating, tillage, fertilising, mulching, manure spreading, seeding, general field activity, grubbing, chopping, harvesting, threshing, silage and transport.
Construction
Driving/tracking to/from site, loading, transport, unloading, spreading, excavating, grading, slot dozing, trench backfill, ripping, moving stockpiles, load and carry, and low load stop-start roadside maintenance.
Industrial
Driving to/from site, lift and place at height & distance, loading/unloading, load transportation, light and heavy material handling and attachment changes.

It is notable that, whilst targeting *'normal'* activities for the NRMM concerned, the operator will inevitably be aware of the installation of the PEMS equipment and the need to achieve sufficient loaded non-idle operation, so there may be an unconscious bias towards good operating practices, avoiding poor practices such as unnecessary idle periods.

[6] Regulation (EU) 2017/655, Annex, Section 3.2
[7] Regulation (EU) 2017/655, Annex, Point 3.2.3(b)
[8] Regulation (EU) 2017/655, Annex, Point 3.2.3(c)
[9] Regulation (EU) 2017/655, Annex, Appendix 2, Section 2
[10] Regulation (EU) 2017/655, Annex, Section 4.2

Ambient Conditions

The applicable range of ambient conditions for ISM set out in the Regulation is ambient pressure equal or greater than 82.5 kPa and ambient temperature of – 7 to + 38°C at sea level, reducing to + 30°C at 1700 m altitude[11]. The results contained in this technical report were obtained from the following range of ambient conditions:

- 86 – 101 kPa
- 1 – 35 °C

Test Validation and Evaluation

The Regulation requires that for a valid test:

- Considerable care is taken to ensure high quality time-aligned second-by-second data[12] with little or no signal loss[13];
- Cold start data is excluded[14];
- Non-working events (>2mins at < 10% power) are identified via prescribed method[15]; and
- At least 50% of moving average windows are 'valid'

Valid windows are those with an average power exceeding 20% of maximum engine power (reduced to 10% from 26 December 2022 onwards)[16].

The moving average window (MAW) method established by the European Commission Joint Research Centre (JRC) is widely used in European automotive legislation for evaluating in-use emission test data. The general principle is to collect second-by-second data which is then subsequently post-processed into sections, each representing a particular sequential window of time[17]. Both work-based and CO_2-based moving average window calculations are performed, though this report only focuses on the former.

The work-based emission result for the window is calculated by dividing the cumulative mass of emissions emitted during the window of time by the cumulative work performed during that same period[18]. The start time of the window is then incremented by one second and the calculation repeated, resulting in a series of time-overlapped windows. Each window is arranged to contain the same amount of work, therefore eliminating the amount of work used in the calculation as a confounding factor in the result.

For the same mass rate of emissions to the atmosphere the brake specific emissions will increase exponentially as power tends to zero (brake specific emissions are infinite when the engine is not delivering any power).

[11] Regulation (EU) 2017/655, Annex, Section 3.3
[12] Regulation (EU) 2017/655, Annex, Appendices 1 – 3
[13] Regulation (EU) 2017/655, Annex, Point 4.3
[14] Regulation (EU) 2017/655, Annex, Appendix 3, Point 2.4
[15] Regulation (EU) 2017/655, Annex, Appendix 4
[16] Regulation (EU) 2017/655, Annex, Appendix 5, Section 2.2.2
[17] Regulation (EU) 2017/655, Annex, Appendix 5
[18] Regulation (EU) 2017/655, Annex, Appendix 5, section 2.2.1

The bias from that that mathematical fact is minimized by:

- The inclusion within each window of data points with a range of different power
- The exclusion of non-working events
- The minimum average window power threshold of 20% (10% from 26 December 2022)

Nevertheless, to comply with the ISM requirements the minimum (best), maximum (worst) and 90th cumulative percentile window results are calculated and reported twice[19]:

- Using only valid averaging windows comprising working events
- Using all averaging windows and events (i.e. inclusive of invalid windows and non-working (low power) events)

Reporting

Manufacturers are required to report the ISM results to their applicable approval authority(ies) using a standard template[20]. Additionally, a summary report is provided to the approval authority which was intended to be made publicly available[21] alongside manufacturer's type-approval results, however the corresponding module of the European Commission Internal Market Information (IMI) database[22] has never been developed.

Due to the file size and confidential nature of the instantaneous (second-by-second) data this is not included in the test reports submitted to approval authorities but remains available to the applicable approval authority(ies) and European Commission direct from the manufacturer upon request for a 10-year period[23].

This document contains a summary of more than one-hundred and fifty test reports submitted to approval authorities provided by manufacturers to EUROMOT on a voluntary anonymised basis. EUROMOT does not hold manufacturers' second-by-second data.

Results

The results from ISM are given as conformity factors. That is a ratio between the brake-specific emission of the gaseous pollutant divided by the applicable test cycle emission limit[24]. Results are presented in this report for the conformity factors of oxides of nitrogen (NOx), total hydrocarbons (THC) and carbon monoxide (CO).

Stage V engines within ISM Group A are required not to exceed the applicable emission limits by more than a factor of 2.0 under defined laboratory conditions, above a certain engine speed, when both the torque and power produced are 30% of the maximum or higher[25]. There are also detailed requirements for the base emission control strategy (BECS) and auxiliary emission control strategy (AECS)[26].

[19] Regulation (EU) 2017/655, Annex, Point 8.2
[20] Regulation (EU) 2017/655, Annex, Point 10.1
[21] Regulation (EU) 2017/655, Annex, Point 10.3
[22] Regulation (EU) 2016/1628, Art. 44(3)(b)
[23] Regulation (EU) 2017/655, Annex, Points 7 and 10.2
[24] Regulation (EU) 2017/655, Annex, Appendix 5, Point 2.2.3
[25] Regulation (EU) 2017/654, Annex V
[26] Regulation (EU) 2017/654, Annex IV

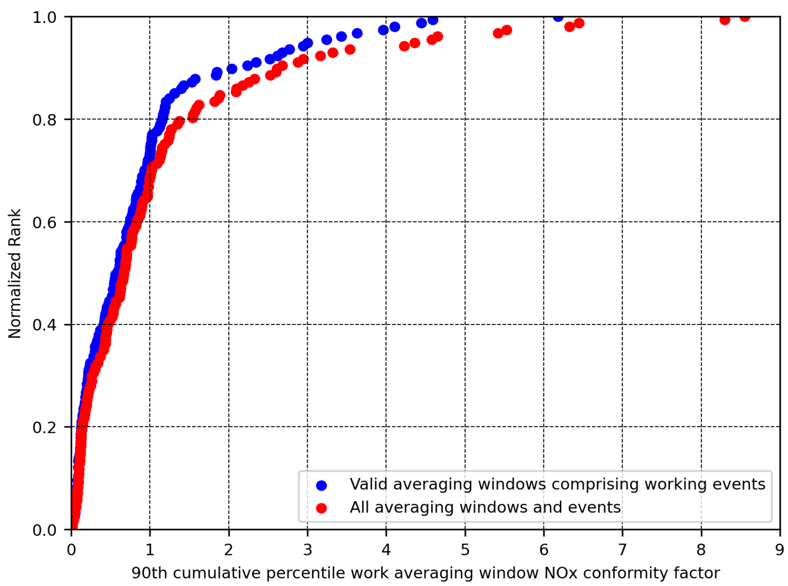
This provides much greater control over in-use emissions than was the case in early emission stages, however, in-use emissions will still vary according to operating conditions due to naturally occurring phenomena or due to the limitations of the emission control system. Consequently, emissions could exceed the factor of 2.0 under certain in-use operating conditions.

NOx

Figure 1 shows the 90th percentile NOx conformity factors for the entire test cohort, reported both for valid averaging windows comprising working events (blue), and all averaging windows and events (red). These results have been arranged in normalised rank order with the best result ranked zero and the worst ranked one. The shape of the line is important as it shows a large proportion of the results are at a very low conformity factor, despite the absence of a mandated in-use pass-fail criteria, with a diminishing tail of higher results.

The statistical evaluation shows that the minimum conformity factor was 0.00, with 25% of the results having a conformity factor of less than 0.18 (blue line) or 0.20 (red line). The average result for the blue and red lines was 0.85 and 1.11 respectively, with 75% of the tests returning a conformity factor no higher than 1.01 and 1.18 respectively.

Figure 1. Normalised Ranks – All Group A categories, applications and power classes: NOx



90th cumulative percentile work averaging window NOx conformity factor	Count	Min	25th Percentile	Avg	50th Percentile	75th Percentile	Max
Valid averaging windows comprising working events	158	0,00	0,18	0,85	0,58	1,01	6,18
All averaging windows and events	158	0,00	0,20	1,11	0,67	1,18	8,55

Figure 2 shows the same data re-plotted as histograms. This clearly shows the distribution skewed towards low conformity factors, with the peak of the distribution in the range 0.00-0.25. The five highest bars are all in the range 0.00-1.25.

Figure 2. Histogram – All Group A categories, applications and power classes: NOx

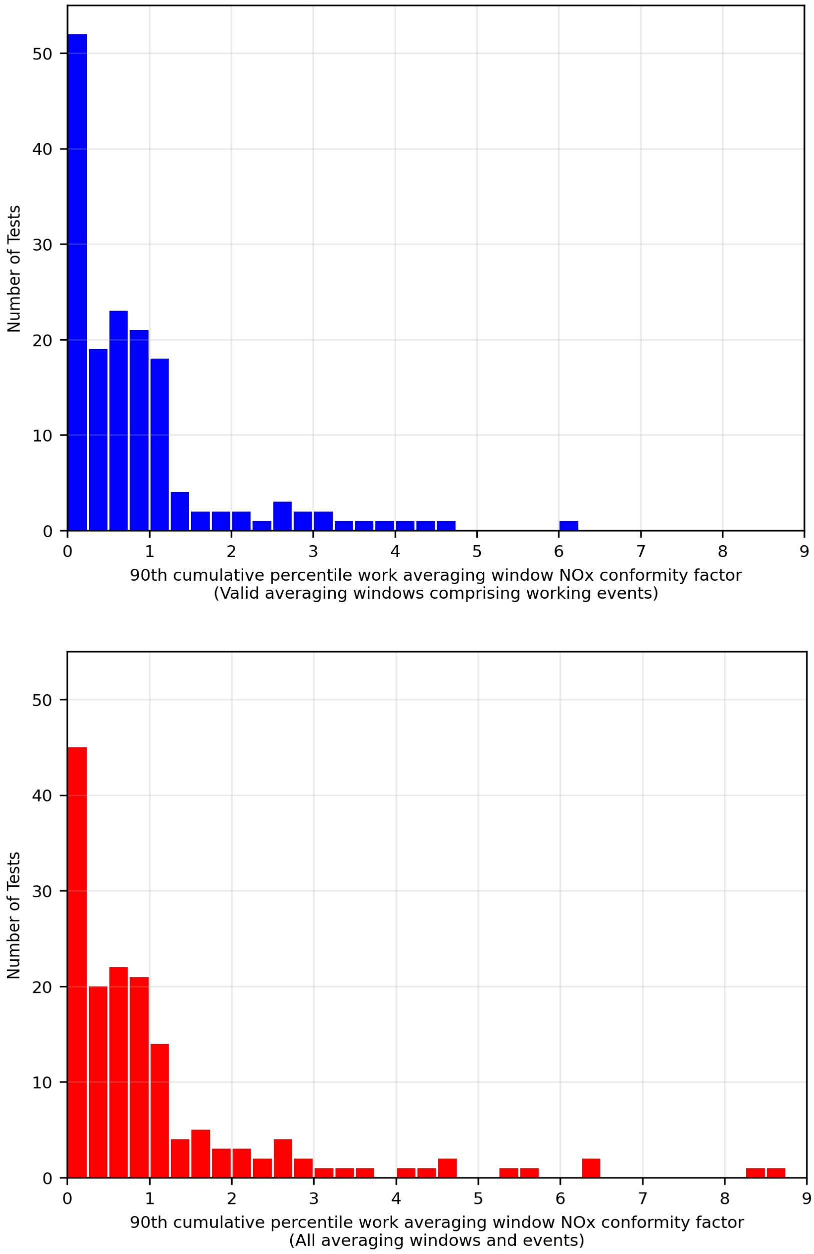
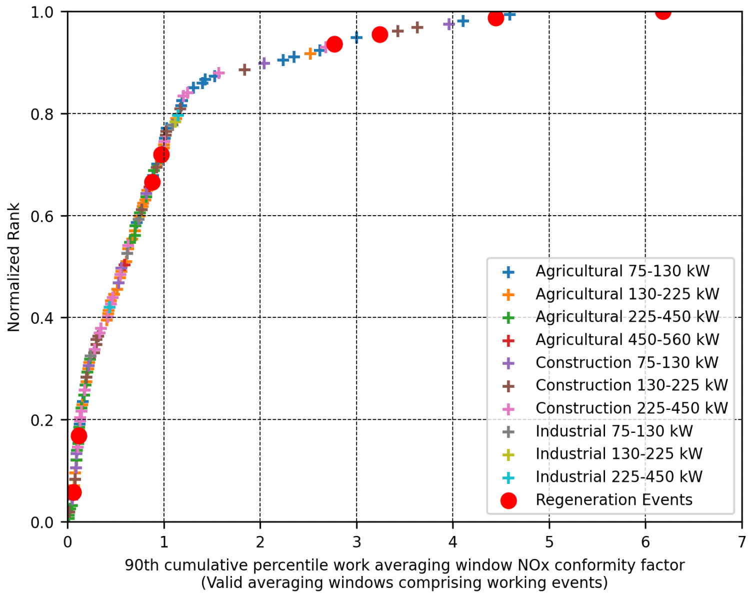


Figure 3 reproduces the data from the blue line of Figure 1, but in this case the richness of the evaluation has been enhanced by assigning individual test results according to their general application (agricultural, construction or industrial), and various power sub-classes. It is apparent that the different applications and power sub-classes are well interspersed though no statistical evaluation has been attempted. Lastly, this figure identifies the tests where regeneration of the after-treatment system was reported to have taken place during the ISM test. Regeneration may interrupt the normal operation of the emission control system.

Under laboratory test conditions the impact of infrequent regeneration is time-weighted in the results, reflecting the fact it is not occurring continuously during engine operation. However, there is no such time weighting in the ISM results, so the overall impact of regeneration may appear greater than is the case were it to be time weighted.

Figure 3. Normalised Ranks – All Group A categories, applications and power classes (valid averaging windows comprising working events): NOx (90th percentile)



Although it is not possible to provide conclusive evidence, the existence of test results with a range of conformity factors is most likely to be related to the conditions under which the NRMM were operating. All known engine types within ISM Group A utilise a selective catalytic reduction (SCR) system to reduce NOx after the exhaust leaves the engine cylinder. Put simply, high NOx is most likely to be due to the exhaust temperature falling to a level whereby the SCR system is unable to convert the NOx in the exhaust into nitrogen (N_2), water (H_2O) and carbon dioxide (CO_2). Consequently, the same engine, when used in different NRMM, or even in the same NRMM performing different tasks, may give different results.

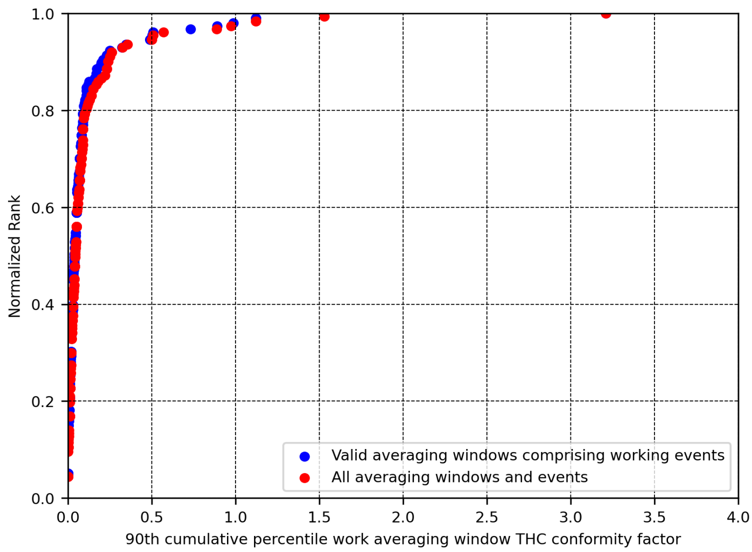
<u>THC</u>

Figure 4 shows the 90th percentile THC conformity factors for the entire test cohort, reported both for valid averaging windows comprising working events (blue), and all averaging windows and events (red), arranged in normalised rank order. The very steep line indicates that most results have a very low conformity factor. The statistical evaluation shows that the minimum conformity factor was 0.00, with 25% of the results having a conformity factor of less than 0.01. The average result for the blue and red lines was 0.11 and 0.13 respectively, with 75% of the tests returning a conformity factor no higher than 0.08 and 0.09 respectively.

Figure 5 reproduces the data from the blue line of Figure 4 but assigning individual test results according to their general application and power sub-class. The different applications and power sub-classes are well interspersed though no statistical evaluation has been attempted.

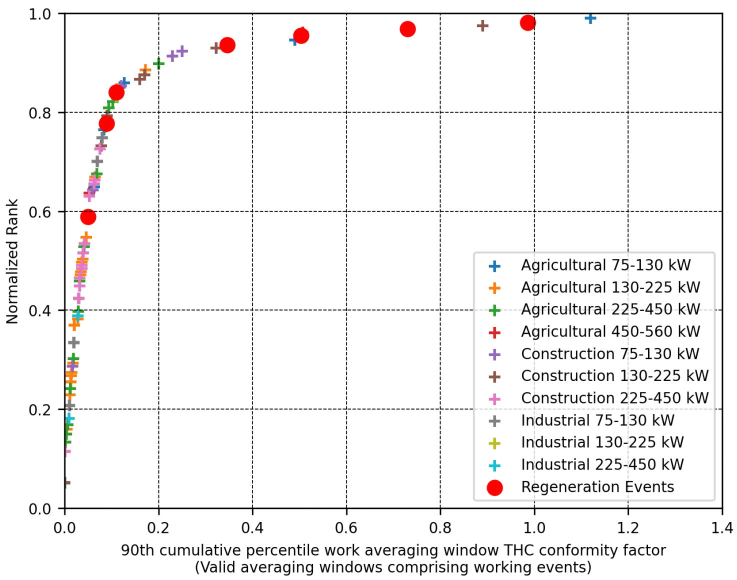
Regeneration is associated with a number of the highest results, which could be related to unburned fuel from the process to create additional heat for that regeneration.

Figure 4. Normalised Ranks – All Group A categories, applications and power classes: THC



90th cumulative percentile work averaging window THC conformity factor	Count	Min	25th Percentile	Avg	50th Percentile	75th Percentile	Max
Valid averaging windows comprising working events	158	0,00	0,01	0,11	0,04	0,08	3,21
All averaging windows and events	158	0,00	0,01	0,13	0,04	0,09	3,21

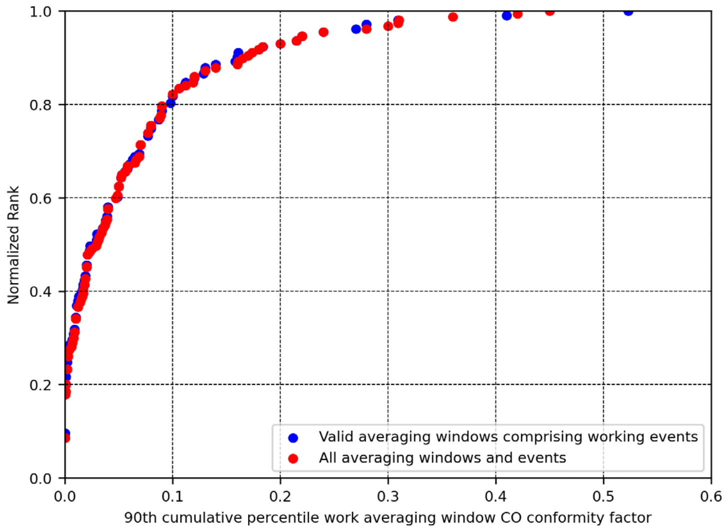
Figure 5. Normalised Ranks – All Group A categories, applications and power classes (valid averaging windows comprising working events): THC (90th percentile)



CO

Figure 6 shows the 90th percentile CO conformity factors for the entire test cohort, reported both for valid averaging windows comprising working events (blue), and all averaging windows and events (red), again arranged in normalised rank order. Although the line is more curved, nevertheless all the results have a conformity factor of less than 1.00. In this case the difference between the blue and red lines is almost indistinguishable. The statistical evaluation shows that the minimum conformity factor was 0.00, with 25% of the results also having a conformity factor of 0.00. The average result for both the blue and red lines was 0.06, with 75% of the tests returning a conformity factor no higher than 0.08.

Figure 6. Normalised Ranks – All Group A categories, applications and power classes: CO



90th cumulative percentile work averaging window CO conformity factor	Count	Min	25th Percentile	Avg	50th Percentile	75th Percentile	Max
Valid averaging windows comprising working events	158	0,00	0,00	0,06	0,03	0,08	0,52
All averaging windows and events	158	0,00	0,00	0,06	0,03	0,08	0,45

Figure 7. Normalised Ranks – All Group A categories, applications and power classes (valid averaging windows comprising working events): CO (90th percentile)

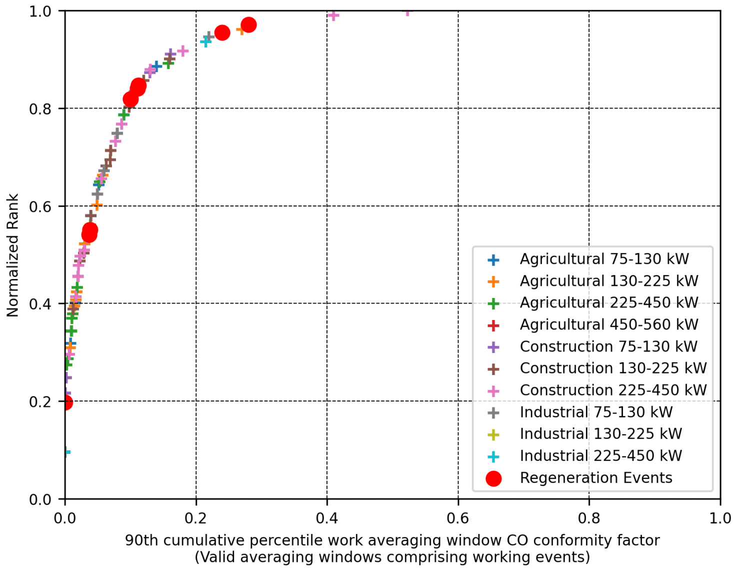


Figure 7 reproduces the data from the blue line of Figure 6 but again assigning individual test results according to their general application and power sub-class. The different applications and power sub-classes are well interspersed though without statistical evaluation. Regeneration is apparent in some results.

Conclusion

This technical report contains anonymised ISM test results from EUROMOT member companies collected in the period May 2021 to August 2024. The reported results are a summary from tests independently conducted by the manufacturers concerned and submitted to EU approval authorities according to the requirements of the Regulation for engine (sub-)categories NRE-v-5 and NRE-v-6, i.e., variable speed engines of category NRE with a range of reference power from 56 to 560 kW (ISM Group A); This technical report solely covers those (sub-)categories. At the time of publication this is the largest known cohort of non-road in-use emission test results ever compiled into a single analysis.

In general, the results show that in the absence of any mandated pass-fail criteria the in-use gaseous emissions of NOx, THC and CO are nevertheless well-controlled when evaluated on the basis of the current EU ISM Regulation (EU) 2017/654. It recognized that there will still be some cases of higher than average in-use NOx emissions under certain operating conditions due to naturally occurring phenomena or to the limitations of the emission control system.

It is apparent that more generally the existence of test results with high NOx conformity factors is most likely to be related to the conditions under which the NRMM was operating. All known engine types within ISM Group A utilise a selective catalytic reduction (SCR) system to reduce NOx after the exhaust leaves the engine cylinder.

High NOx is most likely to be due to the exhaust temperature falling to a level whereby the SCR system is unable to convert the NOx in the exhaust into nitrogen (N_2), water (H_2O) and carbon dioxide (CO_2). Consequently, the same engine, when used in different NRMM, or even in the same NRMM performing different tasks, may give different results.

For more information please contact

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THIS IS EUROMOT

Founded in 1991, EUROMOT is the European association of internal combustion engine and alternative powertrain manufacturers. Representing the key global manufacturers for over 30 years, we provide an invaluable centre of expertise for businesses, authorities, regulators and public stakeholders worldwide. We are the industry's united voice to drive smart and gold standard global regulations for sustainable mobile machinery and stationary applications, helping the manufacturers shape innovations and markets for the future.

With an ecosystem of working groups spanning current and future power and mobility systems, we facilitate cross-fertilisation of innovation across industries. EUROMOT provides an essential gateway to the EU Single Market and forms a bridge for the transition from traditional to alternative energy and advanced powertrains.

Since our foundation, we have been facilitating ever increasing environmentally friendly and sustainable products as well as the decarbonization of our sector and its transition to low/zero-carbon emissions and renewable energy. With a membership encompassing all major ICE and alternative powertrain manufacturers and well-established connections to regulators, EUROMOT is uniquely positioned to decarbonise entire industries from agriculture to construction and from land-based to marine alongside stationary power for heat and electricity.

Headquartered in Brussels, EUROMOT is a European interest group, and our profile is registered in the EU Transparency Register under the identification number 6284937371-73. We have been granted consultative status at the United Nations IMO (International Maritime Organization, London) and United Nations ECE (Economic Commission for Europe - Geneva) and other relevant stakeholders.

OUR MEMBERS

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