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Evaluating low NO_x hydrogen engines designed for off-road and construction applications†

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Hydrogen internal combustion engines offer a near-term decarbonisation pathway for hard to electrify sectors such as non-road mobile machinery (NRMM). However, few hydrogen-specific engines have ever been developed with the twin-goals of maximising low carbon energy efficiency and delivering air quality co-benefits. We present analyses of dynamometer-derived nitrogen oxides (NO_x) tailpipe emissions from four variants of a ∼55 kW four-cylinder port fuelled injection spark ignition hydrogen internal combustion engine (H2ICE) suitable for a range of uses within the NRMM industry. Engine out (pre-aftertreatment) emissions are also reported for one of the H2ICE variants. The emissions were compared over the Non-Road Transient Cycle (NRTC) with an equivalent contemporary Stage V emissions compliant 55 kW diesel engine. All four H2ICE variants were configured to operate under lean burn conditions generating substantially lower NO_x exhaust emissions over the NRTC when compared to the diesel engine. Lowest NO_x emissions were observed for a spark ignition H2ICE with selective catalytic reduction and particulate filter (SCRF) aftertreatment. Tailpipe NO_x emissions over the full NRTC for this configuration were 1.90 mg kWh^{-1}, a greater than 99% reduction compared to diesel (3340 mg kWh^{-1}) with lower average NO_x emissions observed for the H2ICEs over all power, torque, and speed settings. The frequency and magnitude of transient (<20 ms) increases in NO_x were also compared between diesel and H2ICE. A H2ICE using a hydrogen slip catalyst, but without SCRF aftertreatment, also emitted significantly lower tailpipe NO_x than the diesel equivalent (63.7 mg kWh^{-1}), a factor of greater than 50 times improvement over the NRTC. This creates a systems level dilemma: whether the additional small absolute reductions in NO_x achieved using SCRF would have a net benefit that outweighed the broader financial and environmental costs of the SCR and exhaust fluid manufacture, distribution and possible small in-service ammonia slip from exhaust. Irrespective of aftertreatment system, the adoption of low NO_x emitting H2ICE in NRMM, and particularly construction equipment, would appear to offer much greater near-term air quality benefits for cities when compared to switching to other low carbon alternatives such as biodiesel or hydrotreated vegetable oil.

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Environmental significance

The United Kingdom has committed to reach net zero by 2050. Non-road mobile machinery is often 'hard to electrify' due to duty cycles, power demands and use in off grid remote and environmentally harsh conditions. Hydrogen internal combustion offers a plausible strategy for decarbonisation however there is a legacy association with air pollution disbenefits, specifically increased nitrogen oxide emissions. NO_x emissions of four variations of a specifically designed hydrogen internal combustion engine were evaluated. These were found to be significantly lower than a diesel counterfactual, including engine systems without selective catalytic reduction, and indicate that substantial NO_2 air quality improvements might be delivered as a co-benefit if hydrogen internal combustion engines are adopted widely in cities.

Introduction

The effectiveness of different technical decarbonisation strategies is dependent on the end-use and must also consider issues such as component cost, weight and supply chain availability. Whilst electric battery technology may be a viable technology to replace fossil fuels and internal combustion engines in passenger and light commercial vehicles, it is not an optimal strategy for some industrial sectors that currently rely on

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medium to large sized diesel engines. This includes non-road mobile machinery (NRMM), where machines may be used continuously for long periods, have repetitive and demanding power and torque cycles and operate in challenging conditions away from infrastructure, *e.g.* off-grid, exposed to extreme temperatures and/or high levels of dust. The term 'NRMM' envelopes a broad range of machinery and is defined and regulated in the European Union and the UK according to regulation (EU) 2016/1628 as 'any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads'.[1] A decarbonisation pathway that offers a feasible, near-term and cost competitive option for current diesel NRMM powertrains is the hydrogen fuelled internal combustion engine (H2ICE). H2ICE is by no means a new concept, but there has been more limited research and development activity when compared to battery drivetrains. Much literature on air quality emissions from H2ICE is now rather dated, often referring to 1980s and 1990s conversions of gasoline or diesel engines to a different fuel.[2–4]

Whilst a possible strategic industry transition from diesel powertrains to H2ICE is motivated by the need for sector-wide decarbonisation, the air quality implications of any replacement systems are also important to consider. In the UK alone, between 29 000 and 43 000 deaths annually are associated with outdoor air pollution.[5] NRMM manufacturers are particularly cognisant of air quality-relevant emissions, given that equipment is often used within cities in close proximity to people. Urban planners can specify a minimum level of emissions performance of construction equipment when they permit new building projects and developments. This presents an incentive for the adoption of lower-polluting machinery, encouraging a quick turnover of the construction fleet and therefore the potential for a rapid improvement in air quality.

NRMM equipment can emit a range of different air quality pollutants including particulate matter, NO_x (NO_x, the sum of NO + NO_2), unburned hydrocarbons (from fuel and lubricants), and carbon monoxide. NO_x impacts air quality both directly, *via* the effects on inhalation of NO_2 molecules, and indirectly as a precursor for secondary inorganic particulates (*e.g.* as ammonium nitrate). Additionally, the oxidation of volatile organic compounds (VOCs) in the presence of NO_x and sunlight causes tropospheric ozone formation which has been estimated to cause greater than 1 million premature deaths globally per year.[6] Whilst many NO_x pollution sources are linked with combustion in urban centres, the formation, and eventual breakdown, of long-lived intermediate species such as peroxyacetyl nitrate provides an effective mechanism for transporting NO_x to cleaner rural regions,[7] impacting ecosystems through a wide variety of mechanisms such as eutrophication.[8]

The introduction of progressively more stringent NO_x emission standards for road transport has led to a decrease in NO_x emissions of 84% from this sector since 1990.[9] Other sectors have also reduced their emissions to varying degrees and over the decades there has been a change in the relative proportion of NO_x coming from different sectors. The difference between the 1990 and 2021 distribution of NO_x emissions between major sectors for the UK are shown in Fig. 1. Of relevance to NRMM are the manufacturing and construction, and non-road transport sectors, which in 2021 contributed 20% and 13% of the UK's NO_x emissions. The exact impact of NRMM on NO_x emissions is difficult to evaluate as the broad nature of machinery included within NRMM, and its mobile and transitory use patterns, can lead to potential inclusion in several different categories within the National Atmospheric Emissions Inventory (NAEI). Estimates are often limited to the industrial off-road mobile machinery category (Nomenclature for reporting, 1A2gvii). Desouza *et al.*[11] proposed a revised methodology for NRMM emissions and calculated that the NRMM 1A2gvii fleet emitted 36.6 kilotonnes of NO_x in 2018, compared to the NAEI estimate of 27 kilotonnes,[9] highlighting the uncertainty in estimates. Just as for road transport, the decarbonisation of NRMM should ideally be accompanied by air quality co-benefits, particularly particulate matter (PM) and NO_x reduction. Here, we assess the emissions from contemporary H2ICE designed for NRMM use and evaluate the potential of H2ICE to deliver air NO_x quality co-benefits alongside decarbonisation.

Hydrogen as a fuel

Hydrogen can be used as powertrain energy source in two distinct ways; in an electrochemical fuel cell or as a combustion fuel. Fuel cells offer superficially the most optimal air quality benefits since they generate only steam as a by-product (although there may be some hydrogen gas slip). However, they are currently very costly and require expensive supporting power batteries of which there is limited global supply.[12] Fuel

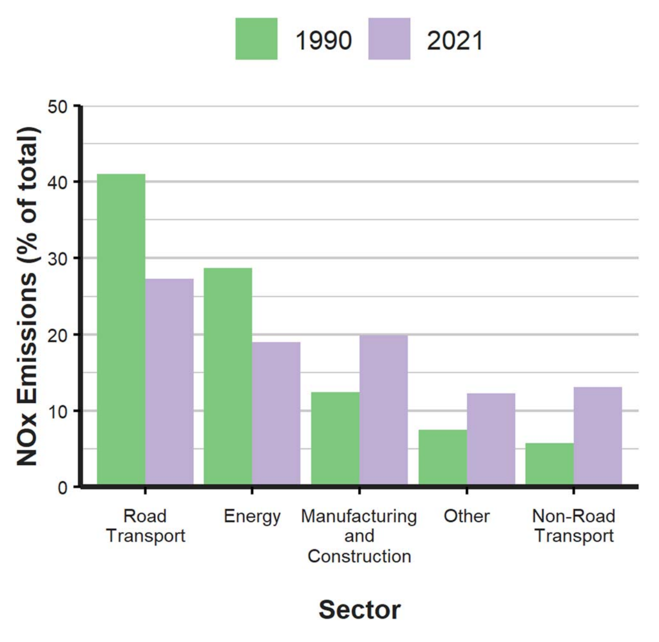

Fig. 1 Sector by sector percentage share of annual NO_x emissions for the United Kingdom 1990 *versus* 2021.[10] The category 'Other' includes other small stationary combustion and non-road mobile sources and machinery, fugitive emissions, industrial processes, agriculture, and waste.

cells are poorly tolerant of dirty working conditions, a particular drawback for use in NRMM. Importantly their efficiencies can be poor at high loads and a substantial fraction of the energy inputs to a fuel cell power train may need to be expended on thermal management cooling the stack.[13] The combination of cooling systems, power batteries and fuel cell may increase vehicle weight and therefore potentially also increase non-exhaust particulate matter emissions in on-road applications.[14]

The poor suitability of fuel cells for use in the NRMM sector means that industrial research focus has turned to using hydrogen as a combustion fuel. The combustion of hydrogen in an internal combustion engine is a well-established principle, if not widely adopted in practice. In contrast to engines using diesel or those burning 'low carbon' fuels such as biodiesel, methanol or hydrotreated vegetable oil, H2ICE produces no carbon dioxide at the tailpipe. Assuming that low carbon, ideally green, hydrogen (*i.e.* hydrogen produced by electrolysis using renewable electricity) is used, H_2 provides a more immediate climate benefit than biofuels. The relatively straightforward technological and consumer behavioural changes that would need to accompany adoption of hydrogen ICEs offer some advantages over other potential decarbonisation pathways, such as battery electrification or fuel cells.[15] The maturity of ICE technology provides some reassurance around reliability and affordability, and benefits from existing manufacturing and recycling infrastructure. In contrast to battery electric vehicle (BEV) technology, rare earth elements are not required.

Hydrogen has a long history as a fuel extending back to the start of the 19th century, when Francois Isaac de Rivaz used a hydrogen and oxygen fuel mix to power what is claimed to be the world's first automobile powered by an ICE.[16] In the centuries that have followed, scientific understanding of the chemistry and engineering controls that govern this relatively simple combustion reaction has advanced. However, two major concerns are typically expressed around the adoption of hydrogen as an engine fuel. These centre around delivering good powertrain efficiency, the formation of nitrogen oxides (NO_x) as a waste product and the possible trade-off between these two factors.[17]

Efficiency is not the focus of this paper, however the H2ICE engines tested here operated in the range 45% peak brake thermal efficiency (BTE), comparable to the diesel equivalent. In some UK policy assessments relatively low efficiencies for H_2 engines are cited.[18] However, these often compare efficiencies for H_2 from literature referencing engines made in the 1990s, with reported diesel efficiencies from engines produced in the 2020s. In practice, if modern engine technologies, (*e.g.* design, fluid dynamics, engine control electronics, sensors, turbochargers and so on) are applied to hydrogen engines today, they have broadly similar efficiencies to their diesel counterparts. Indeed not all past literature shows lower efficiency: modelling by Verhelst and Wallner[19] demonstrated efficiencies greater than a gasoline equivalent for both port fuel injection and direct injection H2ICEs. In 2009, BMW claimed to have produced a peak H2ICE efficiency of 42%, which they cited as 'on par with that of the best turbodiesel engines'.[20] Furthermore, Matthias *et al.* were able to demonstrate a peak BTE of 45.5% for an optimised direct injection engine, with efficiencies remaining above 35% for over 80% of the operating range.[21]

The second area of concern cited for H2ICE, and the motivation for this paper, involves tailpipe NO_x. NO_x can be formed during the combustion of hydrogen (indeed all fuels) due to the presence of nitrogen within air, where sufficiently high temperatures (greater than 1300 °C) cause diatomic nitrogen molecules to decompose and react with oxygen, in accordance with the extended Zeldovich mechanism.[22] Rate constants for these reactions have an exponential dependence on temperature[23] and as the hydrogen adiabatic flame temperature is greater than that of natural gas or diesel fuel, hydrogen combustion has historically been associated with higher NO_x emissions.[17,24–26]

However, elevated NO_x is not inevitable. A feature of hydrogen is its wide flammability range (4–75% in air)[27] meaning that combustion is possible over a wide range of air to fuel ratios (frequently referred to as lambda, λ, or sometimes as the equivalence ratio expressed as a ratio of fuel to air). Lean-burning hydrogen (an excess of air, deficit of fuel) generates lower combustion temperatures, which limits NO_x formation. It is possible to burn hydrogen in engines under leaner conditions than diesel or gasoline giving a greater potential to reduce NO_x formation in-cylinder than for either of those fuels. A reliance on aftertreatment systems is then also reduced, or potentially eliminated. A summary of the options for managing H2ICE emissions through both pre-intake and post combustion controls was provided by Syed and Renganathan.[28]

Significantly lower NO_x emissions when using hydrogen (compared with the equivalent diesel engine) have been reported by Wallner *et al.*,[29] Takagi *et al.*[30] and Luo *et al.*[31] Whilst numerous studies have tested incorporation of hydrogen into the fuel mix (so called co-fuelling), this has typically been *via* retrofitting pre-existing diesel or petrol engines (such as Dimitriou and Tsujimura,[32] Wright and Lewis[33] and references therein). There has been limited literature on multi-cylinder engines designed from first principles to run purely on hydrogen; the cost of their development has limited research and development to only a few major engine manufacturers, and beyond the reach of university laboratories.

Methods

Dynamometer driven emissions were measured in accordance with the non-road transient cycle (NRTC) for four variants of a 4.8 litre 55 kW hydrogen ICE. The same basic H2ICE engine was used in all four test variants. The engine was custom designed for hydrogen fuel through its design and nature of operation, in broad terms using high lambda conditions coupled with fast responsive turbocharging to maintain lean combustion even during load transients. Engines with different aftertreatment systems were tested in the study; a hydrogen slip catalyst (HSC) or selective catalytic reduction with particulate filter (SCRF). Whilst the hydrogen engines were port fuel injection spark ignition engines, two were tested in accordance with the compression ignition (CI) NRTC, with the remaining

Table 1 Characteristics of engines and test cycles evaluated. NRTC CI is the compression ignition non-road transient cycle. NRTC LSI is the large spark ignition test cycle

Engine	Test cycle	Abatement technologies	Engine maturity	Measurement location	Referred to as
JCB 430 Stage V compliant diesel	NRTC CI	Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF)	Production	Tailpipe	Diesel Stage V
JCB 448 PFI hydrogen	NRTC CI	Selective Catalytic Reduction with Particulate Filter (SCRF)	Prototype	Tailpipe	H2ICE with SCRF
JCB 448 PFI hydrogen	NRTC CI	NA	Phase 1	Engine	H2ICE engine out
		Hydrogen Slip Catalyst (HSC)	Phase 1	Tailpipe	H2ICE with HSC
JCB 448 PFI hydrogen	NRTC LSI	Selective Catalytic Reduction and Particulate Filter (SCRF)	Phase 2.1	Tailpipe	H2ICE with SCRF SI TC
JCB 448 PFI hydrogen	NRTC LSI	Hydrogen Slip Catalyst (HSC)	Phase 1	Tailpipe	H2ICE with HSC SI TC

two engines tested against the large spark ignition (LSI) NRTC. The different tests reflect engines at different timepoints in the research and development process and engine maturity which includes the refinement of engine management software and calibration, summarised in Table 1. The ‘phase 1’ description indicates that some engine parts are production intent, whereas ‘phase 2.1’ represents the latest iteration of engine development. Also included in the dataset is the H2ICE with SCRF, classified as ‘prototype’. The H2ICE with SCRF run under the spark ignition test cycle is phase 2.1, representing a maturer version.

The counterfactual for performance is a current production JCB 55 kW diesel engine. This engine when combined with the aftertreatment system (diesel oxidation catalyst and particulate filter) meets the Stage V emissions control requirements when tested against the CI NRTC. Stage V was introduced through Regulation (EU) 2016/1628 [1] and is the most stringent global emission standard for NRMM as well as the incumbent standard within the EU and UK for new NRMM equipment. Comparison using the CI NRTC allowed for direct point-for point instantaneous comparison between the diesel and hydrogen engines at 10 Hz resolution. Differing combinations of engine maturity and test cycles means that the data presented does not allow for exact like-for-like comparison of different aftertreatment performances. NO_x emissions were measured at the tailpipe for all engines, with an additional measurement taken before the aftertreatment system specifically for the H2ICE with HSC engine tested in accordance with the compression ignition non-road transient cycle. This allows for an assessment of the ‘NO_x benefit’ arising from applying aftertreatment solutions to the H2ICEs.

As there are, as of 2024, no hydrogen-specific emission standards, the NRTC offers the likely regulatory test that would be applied at least initially for type approval. The certification for diesel engines is also supplemented by Not to Exceed (NTE) testing, where humidity, temperature and altitude are altered to test overall system compliance, as well as testing to determine the potential for diesel exhaust fluid (DEF) dilution. Stage V regulation also stipulates the requirement to collect in-service Portable Emission Measurement System (PEMS) data and a consideration for aftertreatment deterioration. None of these additional tests were replicated in this analysis. Particulate matter emissions that may occur due to the combustion (restricted to those deriving from lubricating engine oils, since there is no carbonaceous fuel) was also out of scope but are anticipated to be substantially lower than the diesel equivalent.[34]

NO_x measurements

Emissions data is reported here in micrograms of NO_x emitted per second since this measure is most directly relevant to ambient air quality. This was calculated from the measured instantaneous gas mole fraction corrected for mass flow of exhaust gas (which typically increases as speed and load increase). A commercially available AVL AMA i60 instrument was used to measure the exhaust emissions of NO_x at 10 Hz frequency using a chemiluminescence technique and has a quoted instrument uncertainty of $\leq 0.5\%$. The machine is intermittently calibrated with a span gas of concentration 500 ppm and data had not been corrected for potential analyser drift. The limit of quantification (LOQ) was therefore estimated to be 2.5 ppm. Values above −2.5 ppm were retained as from true (non-negative) emissions but with observations below this value excluded in the analysis. Negative NO_x values were measured for approximately 50% of observations for the H2ICE with SCRF, likely reflecting concentrations approaching or at this limit of detection of the instrument. The lowest value of NO_x measured was −3 ppm for H2ICE with SCRF SI TC. No negative gas phase mole fractions (ppm) were recorded for the H2ICE with HSC SI TC but negative NO_x emissions rates (μg s^{-1}) were calculated due to a negative exhaust mass flow, indicating that the engine was briefly drawing air from the exhaust. These negative mass flow measurements constituted 2.67% of the total dataset for H2ICE with HSC SI TC.

Analysis was extended beyond what would be required for engine type approval to examine the full spectrum of potential NO_x emissions from H2ICE. Emissions were evaluated as a function of operational parameters: torque, speed, and power. Potential different emission profiles that arise from different machine uses, since different machines have different power and torque requirements, were also evaluated. Additionally, extreme values, those in the top 5th percentile, were analysed to determine whether rapid changes in load can lead to significant transient increases in NO_x production.

Results

NRTC mean NO_x performance

For regulatory purposes, type approval is based upon the average NO_x emission value normalised for power output taken across the test cycle with weightings for hot and cold starts, shown in Table 2.

Table 3 shows mean values in terms of the raw gas mole fraction and emission rate for all engines tested. These figures demonstrate the several orders of magnitude reduction in mean NO_x produced from the hydrogen engines in contrast to diesel, with the H2ICE with SCRF measured on the SI TC representing a 99.96% reduction compared to the counterfactual diesel engine.

Density functions

Fig. 2a shows the frequency distribution of tailpipe emissions generated over the course of a NRTC test. Due to the order of magnitude differences between engines $\log_{10} NO_x$ values were used. This logarithmic translation means that whilst these plots are not probability density functions, they do highlight the large differences in spread and distribution of the data. It is important to note that this translation distorts the shape of the distributions by spreading data at the lower end of NO_x emissions and condensing data at the higher end. Consequently, sharp peaks at high NO_x values in Fig. 2a span a large range, whereas broad peaks at low NO_x values represent sharp peaks over a very minimal range. This effect can be seen in Fig. 2c and d, where the distribution of NO_x values for the H2ICEs is plotted without logarithmic translation and inclusive of negative emission rates.

In Fig. 2b, three engines are compared: the Stage V diesel engine, H2ICE with a hydrogen slip catalyst (HSC) and H2ICE with selective catalytic reduction and particulate filter (SCRF) and illustrates that the performance of both diesel and H2ICE is broadly similar between a cold and hot start test. The distribution of emissions from the H2ICE with HSC also shows that it is possible to achieve emissions that fall within a tightly defined band – the narrower the band the less sensitive the emissions are to operating demands.

Table 2 Mean NO_x emissions weighted for power taken across the non-road transient cycle (NRTC). Data has been weighted 90% to the hot start and 10% to cold as required by the NRTC

Engine	NO_x weighted over NRTC (mg kWh^{-1})
Diesel Stage V	3340
H2ICE with HSC	63.7
H2ICE with SCRF	1.90

The efficacy of the hydrogen slip catalyst as a post-combustion aftertreatment can be seen in Fig. 2c. Even without aftertreatment, NO_x emissions reductions remain substantial in comparison to the diesel counterfactual highlighting the robust combustion control technologies of the H2ICE.

Weighted cold start and hot start data was combined for the CI test cycles when producing Fig. 2d since the spark ignition test cycle runs continuously. To compare how the different CI and SI versions of the test impact emissions, data from the H2ICE with HSC can be directly compared since both engines were 'phase 1' maturity when tested under the different cycles, see Fig. 2d. Since the H2ICE is a SI engine it is reasonable to assume the SI test would more directly replicate real-world emissions. The test cycle median emission rate for the H2ICE with HSC under SI test (200 μg s^{-1}) was lower than the CI test (213 μg s^{-1}) albeit it with a distribution with a longer tail of higher instantaneous outliers – discussed in the section 'Transient high NO_x emission events'.

Power specific emissions

In Fig. 3 instantaneous 10 Hz emissions data was placed into six data bins representing different bands of engine power outputs. The box and whisper plots represent the median, interquartile, 5th and 95th percentile values. The six power bins cover the full range of engine operating conditions with the 50–60 kW bin representing emissions when the engines were operating at close to, or at, maximum rated power output. For both fuel types (diesel and H_2), NO_x emissions increase as power output increases. In this figure, 'SI TC' represents data collected under the spark ignition test cycle which differs from the compression ignition cycle and does not include the highest 50–60 kW power bin.

Visual inspection shows immediately that for all statistics – median, interquartile, 5th and 95th percentile, the H2ICE engines emit substantially lower NO_x than the comparator Stage V diesel engine at the same power settings. The relationship between increasing power and NO_x does differ slightly

Table 3 Mean NO_x emissions expressed as the gaseous mole fraction (parts per million) and as a rate (micrograms per second)

Engine	Mean NO_x gas mole fraction (ppm)	Mean NO_x emission rate (μg s^{-1})
Diesel Stage V[a]	221	11 400
H2ICE with SCRF[a]	2	122
H2ICE engine-out[a]	7	389
H2ICE with HSC[a]	5	264
H2ICE with SCRF SI TC	<0.1	5
H2ICE with HSC SI TC	6	338

[a] Indicates taking a weighted mean across the hot and cold start cycles; 90% weighting to hot start and 10% to cold as required by the NRTC.

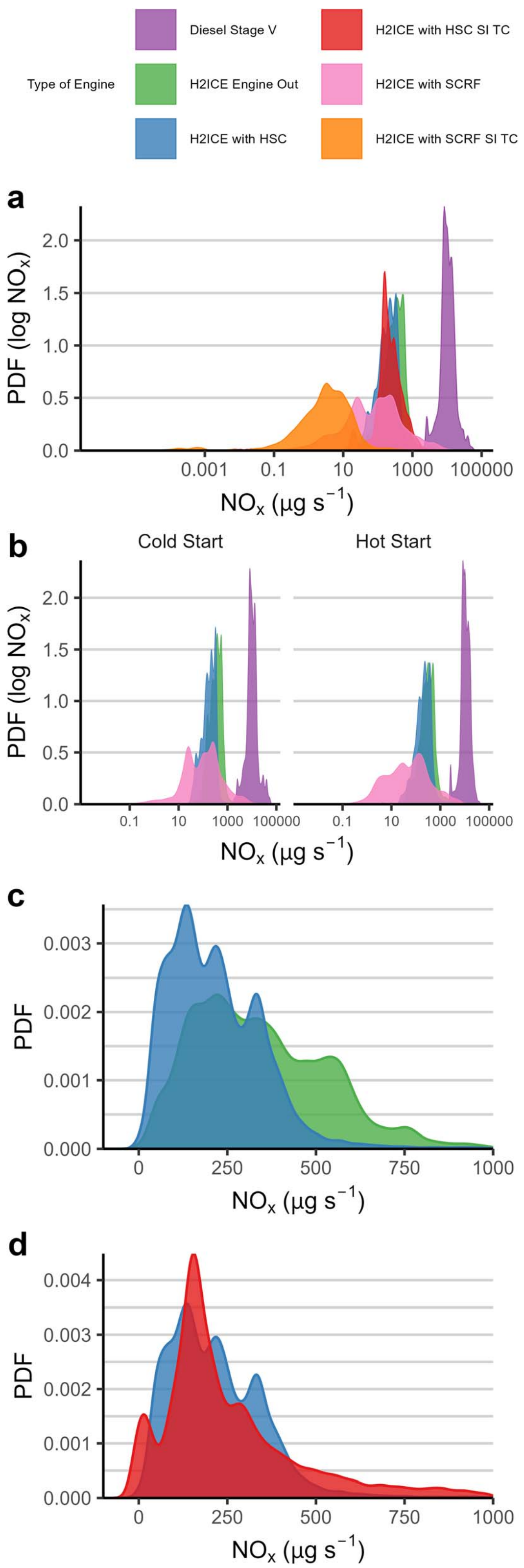

Fig. 2 (a) Frequency distribution of 10 Hz emissions data from non-road transient cycle (NRTC) compression ignition (CI) and NRTC spark ignition (SI) engine test cycles for a (i) diesel Stage V – purple, (ii) H2ICE engine out (CI test) – green, (iii) H2ICE with Hydrogen Slip Catalyst (HSC) (CI test) – blue, (iv) H2ICE with HSC (SI test) – red, (v) H2ICE with Selective Catalytic Reduction and Particulate Filter (SCRF) (CI test) – pink and (vi) H2ICE with SCRF (SI test) – orange. Note $\log_{10}$ x-axis scales (b). Frequency distribution of 10 Hz emissions data from the NRTC CI engine test cycle for a Stage V diesel, H2ICE Engine out, H2ICE with HSC and H2ICE with SCRF shown for the separated hot and cold start cycles. Note $\log_{10}$ x-axis scales. (c) Probability density function comparing the pre and post-HSC aftertreatment emissions for the H2ICE. (d) Probability density function comparing the H2ICE with HSC performance on the CI and SI NRTC test cycles.

between engines however this may represent different maturity for engine calibration rather than necessarily being a phenomenon arising from the test cycles or aftertreatment systems.

For speed and torque binned data, there were also no modes of operation where the hydrogen engines produced greater NO_x than the diesel counterfactual. Figures for the speed and torque binned data are included in the ESI (Fig. S1 and S2).†

It is useful to consider H2ICE performance both in terms of the absolute amounts of NO_x emitted from the engine, but also as the relative emissions improvement compared to a current Stage V diesel engine. In Fig. 4 a by-difference plot is shown as both a box and whisper and frequency distribution for six equally spaced power bins, comparing the Stage V diesel emissions data against a single H2ICE variant, in this case H2ICE with HSC under the NRTC CI cycle. The x-axis shows the H2ICE NO_x emissions as a percentage of the diesel counterfactual.

At the highest power setting (50–60 kW), the H2ICE with HSC variant compared in Fig. 4 emitted ~2.5% of the NO_x that would have been emitted from the Stage V diesel, in other words it is a ~40-fold improvement. At low loads the H2ICE median emission rate is around 80 times lower than the Stage V diesel. For some engine and power combinations, *e.g.* H2ICE with SCRF at low loads, the improvement over diesel, in terms of the median value, exceeded a factor of 1000 (see Fig. S3 and S4†).

Application and equipment-specific emissions

The NRTC was developed to capture emissions from engines that might be used in a broad range of non-road activity and different equipment types. The cycle comprises representative duty cycles from seven different nonroad applications: agricultural tractor, backhoe loader, crawler dozer, arc welder, skid-steer loader, rubber-tire loader and excavator. Using the cycle application and segment durations outlined in Fig. 4.2–6 of the Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines,[35] separated emissions from testbed data were generated for the seven different use cases.

Fig. 5 shows a comparison of NO_x distributions from seven use-cases comparing H2ICE with HSC and H2ICE with SCRF with Stage V diesel. As for Fig. 2, the base-10 logarithm of NO_x ($\mu g\ s^{-1}$) was used to plot density functions of the separated applications. The mean NO_x value across the individual application cycle was also calculated for each engine, see Table 4.

Table 4 includes a substantial number of negative emission values for the H2ICE with SCRF; these may reflect exhaust gas concentrations at or below the detection limit (generating noise distributed around zero). It is also possible that NO_x concentrations in the air intake were higher than those found in the post-aftertreatment exhaust – the H2ICE system under some

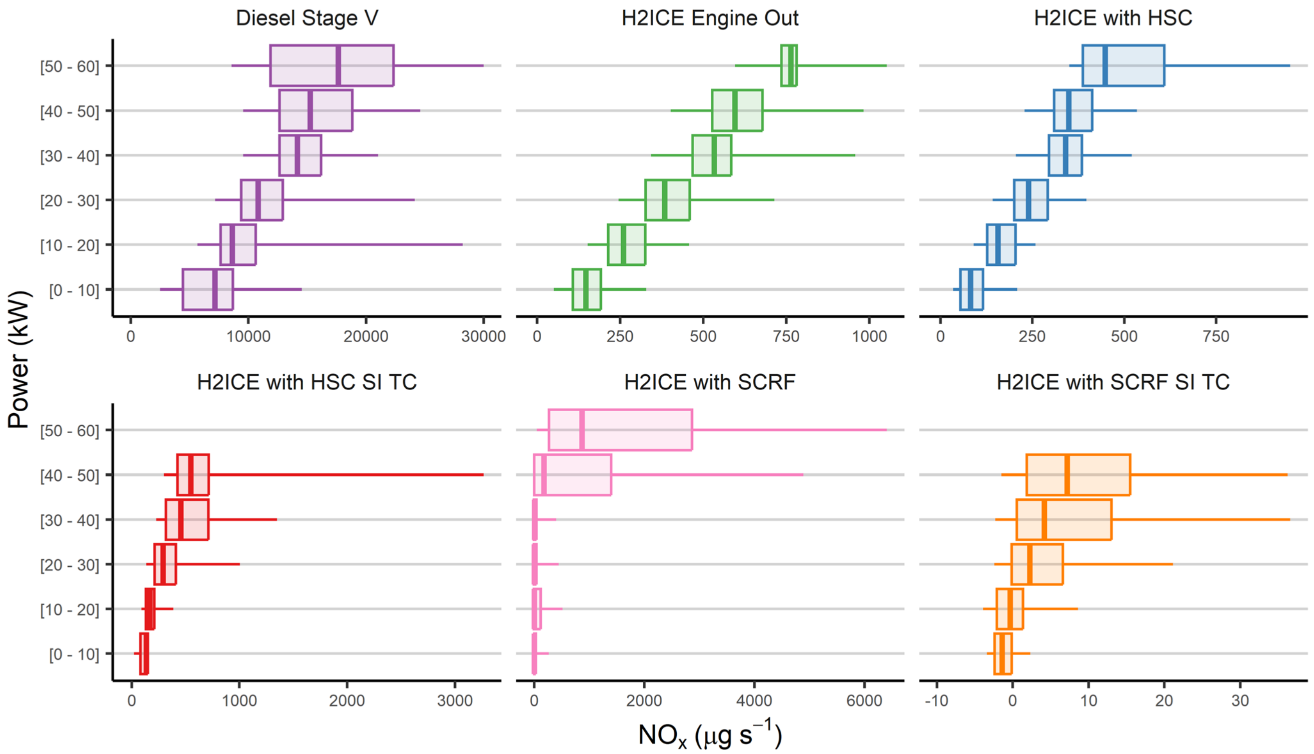

Fig. 3 Instantaneous NO_x emissions in μg s^{-1} for a Stage V diesel engine and five H2ICE datasets. Emissions have been separated into 10 kW-wide power bands. Upper whiskers show the 95th percentile, and lower whiskers illustrate the 5th percentile. Note the substantially different *x*-axis scales for the different engine and aftertreatment combinations *e.g.* diesel Stage V emissions are shown on a scale of 0–30 000 μg s^{-1}, whereas H2ICE SCRF SI TC is on a scale of 0–40 μg s^{-1}.

conditions may be a net loss process for NO_x, rather than a source. Improved calibration for low NO_x gas mole fractions is desirable to test this.

Fig. 5 shows that for all use cases within the NRTC, the H2ICE outperformed the Stage V diesel engine. For some applications such as the excavator, the difference in NO_x performance was very significant – the H2ICE with SCRF demonstrated a mean NO_x emission rate that was 1000 times less than the diesel equivalent. However, for the rubber-tire loader, the NO_x emission distributions of the H2ICE with SCRF and diesel engine overlapped. Looking in detail at the power probability distribution functions for the different applications and the NO_x emission rate for H2ICE with HSC, see Fig. 6, the rubber tire loader has the broadest spread with power demands that regularly oscillate between high and low output. In contrast, excavators in the test cycle operate in narrower power bands. This implies that whilst hydrogen engines may deliver improvements over diesel for all applications, the biggest gains would be in scenarios where there is lower variability in power demand. Generators are not one of the seven applications within the NRTC but are similar in operational cycle to the arc welder. The steady load for this application would suggest that significant NO_x benefits could be realised by switching to hydrogen. More direct testing is required to verify this, but it could be an important consideration in the supply of short-term dispatchable power in a renewable dominated electricity grid.

Transient high NO_x emission events

To maintain lean-burning conditions to limit NO_x formation during rapid increases in fuel input that occur in response to rising load, highly responsive turbocharging should be used. Whilst the NRTC averages shown in Table 3 capture any transient increases in the cycle average, in this section we look more in detail at outlier data, noting that Fig. 3 and 4 provided analysis of emissions falling within the 5th–95th percentile.

To investigate potential first order relationships between operating conditions and spikes in NO_x production, emissions were filtered to retain the highest 5% of emission rates for each engine and covariance and cross correlation tests were performed. This did not reveal any significant first order relationships between the operating variables (*e.g.* power, rate of change in power, *etc.*) and NO_x. Further investigation into the lag relationships that exist between changes in the operating conditions, NO_x formation and instrumental NO_x detection is required. Apparent multivariate complexity demonstrates that short-term high NO_x emissions may be difficult to mitigate. Additionally, although H2ICE transient increases in NO_x emission may be in absolute terms much smaller than the diesel equivalent, these events display a greater deviation from the test cycle mean in relative terms.

Shapiro–Wilk tests indicate that for each type of engine, the NO_x emissions are not normally distributed, $p \ll 0.05$. Although significance is likely when using a large number of

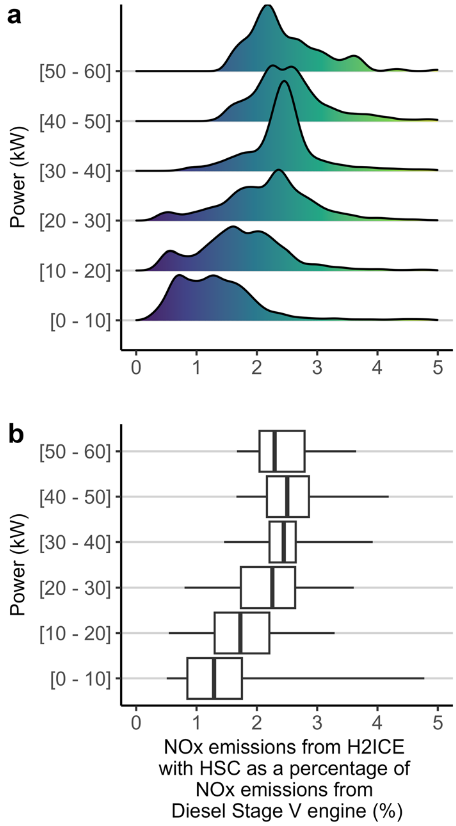

Fig. 4 The difference in instantaneous NO_x emissions as a function of power setting between H2ICE with HSC and Stage V diesel engine for the across the NRTC. (a) Shows the distribution as density plots and (b) shows data as a box and whisper plot with median, interquartile and 5th and 95th percentile ranges.

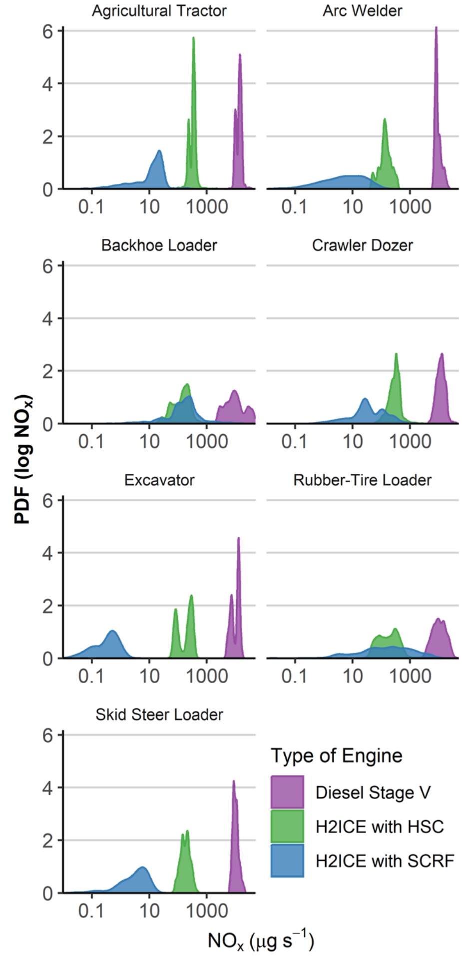

Fig. 5 NO_x emissions distribution for the seven applications within the NRTC for (i) diesel Stage V, (ii) H2ICE with hydrogen slip catalyst (HSC), and (iii) H2ICE with selective catalytic reduction and particulate filter (SCRF).

observations, $n = 5000$, this can be visually confirmed by plotting a quantile–quantile plot against the theoretical normal distribution, see Fig. 7. The distribution of NO_x emissions compared to the theoretical normal distribution demonstrates that whilst data is normally distributed around central NO_x values, all engines exhibit large relative displacements from a normal distribution at higher NO_x values. However, the hydrogen engines display greater departure from a normal distribution than the diesel engine at high NO_x values (up to seven times greater than emissions rates that would be anticipated if normally distributed). This demonstrates that any future hydrogen-specific emission standards should include tests that evaluate and limit outlier emissions.

Discussion

This analysis is not intended to rank different variants of the JCB H2ICE against one another since they are not directly comparable and represent different stages in the research and development process. Nonetheless the test data in its totality covers two potential aftertreatment configurations, includes hot and cold starts, evaluates emissions against CI and SI test cycles and compares engine out and tailpipe emissions. By examining data as a function of power (*e.g.* Fig. 3 and 4), or speed or torque (Fig. S1 and S2†) it is clear there are no individual modes of operation (*e.g.* particular power or speeds) where NO_x emissions would deviate substantially from performance inferred from NRTC mean value. There would likely be a substantial NO_x air quality benefit from adopting a H2ICE in place of a diesel

Table 4 Mean NO_x emissions for each application and engine combination. Negative measured mole fraction values create the negative emission rates for H2ICE with SCRF. A 90% weighting of hot start data and 10% to cold has been applied

	Mean NO_x ($\mu g\ s^{-1}$)		
Application	Stage V diesel	H2ICE with HSC	H2ICE with SCRF
Agricultural tractor	13 400	333	0.325
Arc welder	9600	152	−5.58
Backhoe loader	13 700	183	373
Crawler dozer	12 400	336	61.9
Excavator	10 200	198	−5.24
Rubber-tire loader	11 700	235	685
Skid steer loader	10 300	191	−7.08

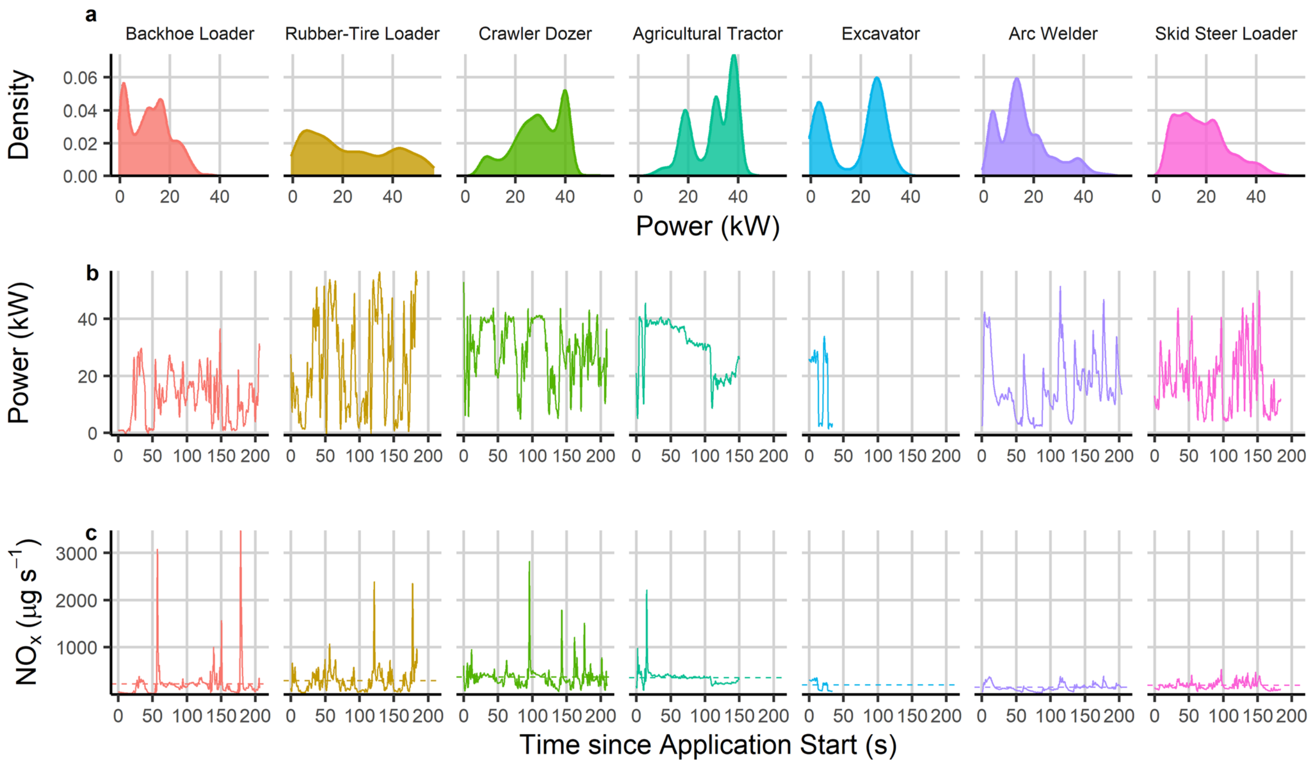

Fig. 6 H2ICE with hydrogen slip catalyst (HSC) for the hot-start non-road transient cycle. Showing (a) the density of the power, (b) the power (kW) during the application, and (c) the corresponding NO_x emissions where the dashed lines represent the mean value for each appliance.

equivalent in all the end-use scenarios – of the order a 40 times improvement as a minimum. The exact air quality 'advantage' of hydrogen engines over diesel would however be application and equipment-specific; this analysis suggests that the H2ICE advantage may be greatest in lower and/or steady load conditions. In some circumstances or applications, the air quality improvement over diesel Stage V could be greater than a factor of 1000.

Aftertreatment options

The substantial improvement in NO_x emissions performance of the H2ICE with HSC variant (and indeed the performance prior to aftertreatment at engine-out) compared to the counterfactual diesel engine is noteworthy. Whilst a H2ICE with Selective Catalytic Reduction and Particulate Filter (SCRF) ultimately delivered the lowest tailpipe NO_x of any engine tested here, the improvement the SCRF brings compared to only using a hydrogen slip catalyst as aftertreatment was modest in absolute terms. For two applications, backhoe and rubber tire loaders, the H2ICE with HSC outperformed its SCRF counterpart. Clearly refinement of the optimal aftertreatment and exhaust systems is a work in progress, but this raises an important question around whether pursuing 'lowest-possible' NO_x emissions in hydrogen-fuelled non-road mobile machinery (NRMM) would be proportionate when set against the 'costs' of adding and then using a SCR.

Further lifecycle analysis is needed to quantify the relative benefits and trade-offs of different aftertreatment systems for H2ICE. Factors that need considering include the possible additional capital costs of different approaches (and effects on rate of industry adoption) and the implications of in-use operation. The urea (as AdBlue) used as a reagent in SCR is currently derived from fossil fuel feedstocks and has its own greenhouse gas and air pollution footprint (including transport to point-of use).[36,37] The amount of urea consumed in an H2ICE aftertreatment system is very substantially less than is needed for a diesel engine (since exhaust fluid consumption is proportional to the amount of NO_x produced) but it still adds operational cost for the operator. Some slippage of ammonia in exhaust gases can occur from SCR, introducing a source of ammonia to urban regions and impacting particulate pollution.[38]

Nitrogen dioxide has rightly received significant media and regulator attention in recent years, but there is likely to be an inflexion point where the technical pursuit of ever-lower emissions might lead to unintentional environmental harms in other domains. The emergence of a new H2ICE engines that are by design very low in NO_x at engine-out may need to trigger wider debate about what proportionate targets for NRMM equipment might look like when considering system-wide environmental impacts (raw materials, consumables, air quality effects, and greenhouse gas emissions).

Machine location and operating hours

Of equal importance for air quality is where different engines might be used and for how long. Adopting hydrogen engines in place of diesel engines that are working long hours on construction sites in urban centres is likely to bring greater and

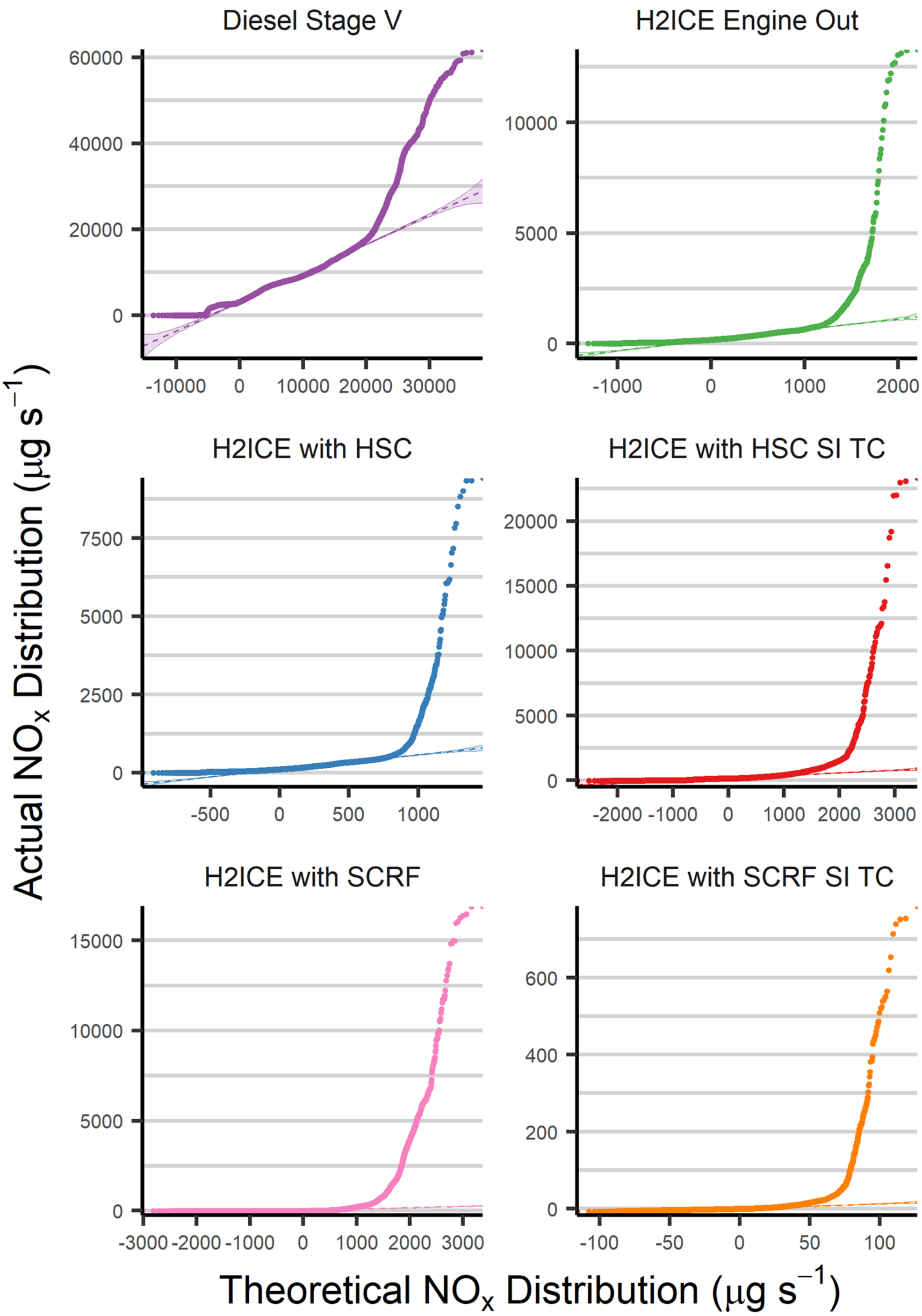

Fig. 7 Quantile–Quantile plots comparing the sample and theoretical normal distributions for the six datasets. The dashed line in each represents where sample observations would lie to match the theoretical normal distribution and thus is represented by the equation $x = y$. Therefore, all these lines have the same gradient, highlighting the more extreme departure from normality for the hydrogen data.

more immediate public health benefits than swapping in remote locations, or for engines only used occasionally, such as back-up generators. Whilst there is not currently a plentiful supply of green hydrogen within the UK, policy decisions regarding the introduction of hydrogen ICEs may wish to prioritise their early adoption in places where air pollution benefits would be greatest.

Conclusion

Hydrogen ICEs offer a viable decarbonisation option that is suitable for sectors where significant practical and logistical barriers limit other decarbonisation technologies, such as electrification. Emissions data from a 4.8 l 55 kW NRMM engine demonstrates that hydrogen combustion can be controlled to generate very low emissions of NO_x. Properly designed and optimised H2ICE engines are capable of substantially out-performing Stage V diesel engines on NO_x emissions (and likely other air pollutants, although not studied here). The absolute air quality advantage of H2ICEs compared to a diesel equivalent is variable by application with the greatest air quality benefits achieved for lower and constant load machines, although large benefits were seen in all applications considered.

Literature amply demonstrates that it is relatively easy to adapt diesel or gasoline engines to run on hydrogen fuel, but high NO_x is often a consequence. There is a risk of a missed opportunity to substantially reduce NO_x emissions if the introduction of hydrogen ICEs to market is not accompanied by ambitious hydrogen-specific tailpipe emission standards. Setting the regulatory bar for type approval of hydrogen engines at the existing Stage V diesel NRTC limits for NO_x would potentially allow poorer performing retro-fitted engines to emerge and disincentivise investment in custom designed low-NO_x H2ICEs. Creating bespoke NO_x (and PM) emission standards for hydrogen fuelled off-road engines would ensure substantial air quality and public health co-benefits were delivered alongside decarbonisation.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

RB, TB, TB, JH and JP are employees of JC Bamford Excavators Ltd, a manufacturer of construction equipment. Data was provided by the company to University of York with no restrictions on analysis, data use or publication.

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References

1 European Parliament and Council of the European Union, *Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No. 1024/2012 and (EU) No. 167/2013, and amending and repealing Directive 97/68/EC*, 2016.
2 C. A. MacCarley and W. D. Van Vorst, Electronic fuel injection techniques for hydrogen powered IC engines, *Int. J. Hydrogen Energy*, 1980, **5**, 179–203.
3 L. Sinclair and J. Wallace, Lean limit emissions of hydrogen-fueled engines, *Int. J. Hydrogen Energy*, 1984, **9**, 123–128.
4 L. Das, Hydrogen engines: A view of the past and a look into the future, *Int. J. Hydrogen Energy*, 1990, **15**, 425–443.
5 C. Mitsakou, A. Gowers, K. Exley, K. Milczewska, D. Evangelopoulos, and H. Walton, *Updated mortality burden estimates attributable air pollution' Chemical Hazards Poisons Report*, 2022.
6 C. S. Malley, D. K. Henze, J. C. I. Kuylenstierna, H. W. Vallack, Y. Davila, S. C. Anenberg, M. C. Turner and M. R. Ashmore, Updated global estimates of respiratory mortality in adults ≥30Years of age attributable to long-term ozone exposure, *Environ. Health Perspect.*, 2017, **125**, 087021.
7 H. B. Singh and P. L. Hanst, Peroxyacetyl nitrate (PAN) in the unpolluted atmosphere: An important reservoir for nitrogen oxides, *Geophys. Res. Lett.*, 1981, **8**, 941–944.
8 R. Aerts and R. Bobbink, in *The Impact of Nitrogen Deposition on Natural and Semi-natural Ecosystems*, Springer Netherlands, Dordrecht, 1999, pp. 85–122, DOI: 10.1007/978-94-017-3356-4_4.
9 National Atmospheric Emissions Inventory (NAEI), UK emissions data selector, https://naei.energysecurity.gov.uk/data/data-selector?view=air-pollutants, 2024.
10 Department for Environment Food and Rural Affairs (DEFRA), *Emissions of air pollutants in the UK – Nitrogen oxides (NO_x)*, 2023.
11 C. Desouza, D. Marsh, S. Beevers, N. Molden and D. Green, Emissions from the Construction Sector in the United Kingdom, *Emiss. Control Sci. Technol.*, 2024, **10**, 70–80.
12 A. Onorati, R. Payri, B. M. Vaglieco, A. K. Agarwal, C. Bae, G. Bruneaux, M. Canakci, M. Gavaises, M. Günthner, C. Hasse, S. Kokjohn, S. C. Kong, Y. Moriyoshi, R. Novella, A. Pesyridis, R. Reitz, T. Ryan, R. Wagner and H. Zhao, The role of hydrogen for future internal combustion engines, *Int. J. Engine Res.*, 2022, **23**, 529–540.
13 J. B. Benziger, M. B. Satterfield, W. H. Hogarth, J. P. Nehlsen and I. G. Kevrekidis, The power performance curve for engineering analysis of fuel cells, *J. Power Sources*, 2006, **155**(2), 272–285.
14 V. R. J. H. Timmers and P. A. J. Achten, Non-exhaust PM emissions from electric vehicles, *Atmos. Environ.*, 2016, **134**, 10–17.
15 I. A. Fernández, M. R. Gómez, J. R. Gómez and L. M. López-González, Generation of H2 on board LNG vessels for consumption in the propulsion system, *Pol. Marit. Res.*, 2020, **27**, 83–95.
16 S. Rațiu, The history of the internal combustion engine, *Ann. Fac. Eng. Hunedoara*, 2003, **1**, 145–148.
17 A. C. Lewis, Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NO x emissions, *Environ. Sci.: Atmos.*, 2021, **1**, 201–207.
18 N. H. A. Hadaya and R. Pearce-Higgins, *Industrial Non-Road Mobile Machinery Decarbonisation Options: Techno-Economic Feasibility Study*, 2023.

19 S. Verhelst and T. Wallner, Hydrogen-fueled internal combustion engines, *Prog. Energy Combust. Sci.*, 2009, **35**, 490–527.

20 BMW Press Release, BMW Hydrogen Engine Reaches Top Level Efficiency, **https://www.press.bmwgroup.com/usa/article/detail/T0020216EN_US/bmw-hydrogen-engine-reaches-top-level-efficiency?language=en_US**, accessed 13 May, 2024.

21 N. S. Matthias, T. Wallner and R. Scarcelli, A hydrogen direct injection engine concept that exceeds U.s. doe light-duty efficiency targets, *SAE Int. J. Engines*, 2012, **5**, 838–849.

22 Y. B. Zeldovich, in *Selected Works of Yakov Borisovich Zeldovich, Volume I*, ed. R. A. Sunyaev, Princeton University Press, Princeton, 1992, pp. 364–403, DOI: **10.1515/9781400862979.364**.

23 M. A. Psota and A. M. Mellor, *presented in part at the SAE Technical Paper Series, 2001/5/7*, 2001.

24 M. Nomura, H. Tamaki, T. Morishita, H. Ikeda and K. Hatori, Hydrogen combustion test in a small gas turbine, *Int. J. Hydrogen Energy*, 1981, **6**, 397–412.

25 R. Hoekstra, P. V. Blarigan and N. Mulligan, NO_x emissions and efficiency of hydrogen, natural gas, and hydrogen/natural gas blended fuels, *SAE Trans.*, 1996, **105**, 761–773.

26 P. Therkelsen, J. Mauzey, V. McDonell and S. Samuelsen, *Evaluation of a Low Emission Gas Turbine Operated on Hydrogen*, Proceedings of the ASME Turbo Expo 2006: Power for Land, Sea, and Air, Volume 1, Combustion and Fuels, Education, 2006.

27 K. Mazloomi and C. Gomes, Hydrogen as an energy carrier: Prospects and challenges, *Renewable Sustainable Energy Rev.*, 2012, **16**, 3024–3033.

28 S. Syed and M. Renganathan, NO_x emission control strategies in hydrogen fuelled automobile engines, *Aust. J. Mech. Eng.*, 2022, **20**, 88–110.

29 T. Wallner, H. Lohsebusch, S. Gurski, M. Duoba, W. Thiel, D. Martin and T. Korn, Fuel economy and emissions evaluation of BMW Hydrogen 7 Mono-Fuel demonstration vehicles, *Int. J. Hydrogen Energy*, 2008, **33**, 7607–7618.

30 Y. Takagi, M. Oikawa, R. Sato, Y. Kojiya and Y. Mihara, Near-zero emissions with high thermal efficiency realized by optimizing jet plume location relative to combustion chamber wall, jet geometry and injection timing in a direct-injection hydrogen engine, *Int. J. Hydrogen Energy*, 2019, **44**, 9456–9465.

31 Q.-H. Luo, J.-B. Hu, B.-G. Sun, F.-S. Liu, X. Wang, C. Li and L.-Z. Bao, Effect of equivalence ratios on the power, combustion stability and NO_x controlling strategy for the turbocharged hydrogen engine at low engine speeds, *Int. J. Hydrogen Energy*, 2019, **44**, 17095–17102.

32 P. Dimitriou and T. Tsujimura, A review of hydrogen as a compression ignition engine fuel, *Int. J. Hydrogen Energy*, 2017, **42**, 24470–24486.

33 M. L. Wright and A. C. Lewis, Decarbonisation of heavy-duty diesel engines using hydrogen fuel: a review of the potential impact on NO x emissions, *Environ. Sci.: Atmos.*, 2022, **2**, 852–866.

34 P. Xu, C. Ji, S. Wang, X. Bai, X. Cong, T. Su and L. Shi, Realizing low emissions on a hydrogen-fueled spark ignition engine at the cold start period under rich combustion through ignition timing control, *Int. J. Hydrogen Energy*, 2019, **44**, 8650–8658.

35 United States Environmental Protection Agency, *Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines*, 2004.

36 P. R. Gilbert and P. Thornley, *Energy and carbon balance of ammonia production from biomass gasification*, 2010.

37 S. K. Masjedi, A. Kazemi, M. Moeinnadini, E. Khaki and S. I. Olsen, Urea production: An absolute environmental sustainability assessment, *Sci. Total Environ.*, 2024, **908**, 168225.

38 R. Marten, M. Xiao, M. Wang, W. Kong, X.-C. He, D. Stolzenburg, J. Pfeifer, G. Marie, D. S. Wang, M. Elser, A. Baccarini, C. P. Lee, A. Amorim, R. Baalbaki, D. M. Bell, B. Bertozzi, L. Caudillo, L. Dada, J. Duplissy, H. Finkenzeller, M. Heinritzi, M. Lampimäki, K. Lehtipalo, H. E. Manninen, B. Mentler, A. Onnela, T. Petäjä, M. Philippov, B. Rörup, W. Scholz, J. Shen, Y. J. Tham, A. Tomé, A. C. Wagner, S. K. Weber, M. Zauner-Wieczorek, J. Curtius, M. Kulmala, R. Volkamer, D. R. Worsnop, J. Dommen, R. C. Flagan, J. Kirkby, N. McPherson Donahue, H. Lamkaddam, U. Baltensperger and I. El Haddad, Assessing the importance of nitric acid and ammonia for particle growth in the polluted boundary layer, *Environ. Sci.: Atmos.*, 2024, **4**, 265–274.