Department for Transport

Bus Retrofit Performance Report

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Executive summary

This report documents the Joint Air Quality Unit's (JAQU) investigation into the effectiveness of retrofitted Selective Catalytic Reduction (SCR) technology in reducing emissions of nitrogen oxides (NO_X) from buses.

SCR exhaust after-treatment technology has been retrofitted to approximately 8,800 buses in England to support compliance with legal limits for nitrogen dioxide (NO_2). Evidence began to emerge in late 2021 indicating that SCR retrofit technology was not reducing NO_X emissions from buses to the levels expected. Real-world emissions monitoring conducted in late 2022 confirmed that there was considerable variation in the performance of retrofitted buses which required further investigation.

JAQU initiated a programme of work in spring 2023 to assess the operational performance of the technology, investigate the factors which may be affecting performance, and assess the scope for achieving and maintaining greater performance. The Bus Retrofit Expert Group (BREG) was convened in April 2023 to provide independent scientific advice in support of this programme of work.

Performance of the retrofitted bus fleet

The effectiveness of retrofitted SCR systems in delivering real-world NO_X emission reductions when installed on buses has been assessed in two ways:

1. Comparing tailpipe emissions from retrofitted and non-retrofitted buses.

2. Using NO_X measurements from sensors before and after the retrofitted SCR system to calculate the percentage NO_X reduction.

Evidence indicates that **real-world performance of the retrofitted bus fleet is highly variable**; some Euro V buses retrofitted with SCR technology produced greater NO_X emissions than non-retrofitted Euro V buses under the same conditions, while other retrofitted buses produced lower emissions. Overall, **SCR retrofit technology is delivering a small average reduction in tailpipe NO_X emissions compared to non-retrofitted Euro V buses. NO_X emissions from retrofitted Euro V buses are however considerably higher than emissions from Euro VI buses.**

The retrofitted SCR systems have been accredited by the Clean Vehicle Retrofit Accreditation Scheme (CVRAS) to produce Euro VI equivalent emissions at the tailpipe. In real-world operation, CVRAS requires an 80% reduction of NO_X emissions between the engine and tailpipe to deliver emissions approaching those of Euro VI buses.

It is important to note that the CVRAS NO_X reduction requirement only applies to periods when on-board NO_X sensors are recording, and not to an entire journey. NO_X sensors do not record when faulty, when SCR temperatures are low, and during sensor warm up in cold start conditions. This performance metric does not guarantee that emissions at the tailpipe are within acceptable limits for the total journey.

In real-world operation, **retrofitted buses are achieving the 80% NO_X reduction requirement infrequently**. For a sample of just over 3,500 buses retrofitted with SCR systems from four different suppliers, around a third achieved the required 80% NO_X reduction.

There is strong evidence to indicate that compared to non-retrofitted buses, a greater fraction of NO_X is emitted as NO_2 from buses with retrofitted SCR systems. Analysis of ambient NO_2 measurements suggests that in certain local situations where retrofitted buses comprise a large proportion of the local fleet, greater NO_2 emissions from retrofitted buses could lead to increased roadside NO_2 concentrations. There is a medium level of confidence in this, however evidence is currently limited to one location and further analysis is needed.

An assessment of the impact of retrofitted SCR systems on other pollutants is beyond the scope of this work, however testing of a small number of vehicles highlighted a potential risk that adjustments to improve NO_X reduction could result in increased ammonia emissions. Ammonia is a precursor for $PM_{2.5}$, so care must be taken to ensure retrofitted SCR systems do not unintentionally increase ammonia concentrations in urban environments.

Further evidence collection and air quality modelling is required to assess the full impacts of SCR retrofitting on air quality.

Factors affecting performance

The causes of underperformance of SCR retrofit technology are multifactorial and interacting. To function effectively, SCR systems have three key requirements – a sufficiently high temperature, the correct dosing of urea and a fully functioning SCR catalyst.

The condition of the bus engine, diesel particulate filter (DPF) and diesel oxidation catalyst (DOC) can play a role in the effective operation of an SCR system. A lack of maintenance of these upstream systems can affect the efficiency of the SCR system and increase engine out emissions (particularly soot) and oil consumption which can accelerate its degradation.

1. Temperature

For effective operation an SCR system requires a high exhaust temperature. At lower temperatures, there is minimal NO_X reduction. **A substantial proportion of retrofitted buses are not maintaining sufficiently high exhaust temperatures for effective SCR operation**. Temperature is influenced by a multitude of factors, including route characteristics such as gradients and frequency of stops. Ambient temperatures may have a small influence. Low temperatures can also negatively affect other system components such as DPFs which can become blocked with soot and affect the vehicle engine and performance of the SCR.

The CVRAS testing cycle which formed part of the accreditation process for retrofitted SCR technologies was not fully representative of real-world conditions as testing allowed a substantial warm-up phase and the test itself used only the ‘hot’ part of the drive cycle.

2. The retrofit system

Urea serves as a source of ammonia which is essential for the reduction of NO_X. Urea is supplied in an aqueous solution marketed as AdBlue. The retrofit system is complex and contains many components to control the dosing of urea onto the engine exhaust gases. These components must be working well and in harmony to reduce NO_X. Strategies used by retrofit suppliers such as dosing control logics and controls on the activation of NO_X sensors also influence urea dosing.

NO_X sensors determine the appropriate dosing of urea based on engine exhaust gases. Sensors commonly malfunction and require frequent testing and replacement. Filters on tanks which hold AdBlue are susceptible to blockage from dirt and crystallised (unreacted) urea. Other components within the urea dosing system can also become blocked by crystallised urea so frequent servicing is required. **Component failure is common. One or more component failures can quickly lead to total systems failures.**

Scope for improvement

SCR retrofit technology can reduce NO_X emissions from Euro V buses to levels approaching those of Euro VI buses. However, multiple factors lead to variations in performance and widespread underperformance. As a result, **there is no single solution to improve the performance of the retrofitted bus fleet.**

1. Temperature

It would be technically possible to implement modifications to improve the ability of retrofitted SCR systems to achieve and maintain higher operating temperatures, and therefore reduce periods of poor performance. However, whether such modifications would be economically or practically feasible to implement at a fleet level is uncertain and would require exploration.

Where practical, redeployment of retrofitted buses away from bus routes where the conditions for low temperatures prevail may offer the most suitable solution. Whether this is economically or practically feasible has not been investigated and would require consideration at the local level.

Whilst there may be potential for technical modifications to reduce periods of sub-optimum SCR temperature, the feasibility and effectiveness of such interventions requires further investigation. Such modifications are likely to be costly, and as **such maintaining optimum SCR temperature may remain a fundamental limitation of some SCR retrofit technology that in certain circumstances cannot be overcome.**

2. The retrofit system

Retrofitted buses demonstrating the very poorest performance typically exhibit problems with the urea dosing system. **It is likely that more effective maintenance of retrofitted SCR systems could improve performance of the poorest performing buses**.

Enhanced maintenance practices could reduce the occurrence and persistence of faults with the urea dosing system. Further testing is needed to identify the type and frequency of maintenance required as well as to quantify the level of improvements that could be realistically achieved. This will need to take account of operational factors at the local level that limit the amount of maintenance possible.

Maintaining retrofitted SCR systems to enable effective NO_X emission reductions is more challenging and costly than had been anticipated by bus operators. **Fixes for components in the urea dosing system are typically not complex though diagnosing faults can be practically challenging to achieve, particularly with limited engineer capacity and technical expertise.**

Enhanced routine provision and monitoring of telematics data could play a key role in facilitating timely, targeted maintenance. Sensors within the retrofit system report information via telematics which can be useful in identifying sub-systems where faults may lie. However, **the existence and capabilities of telematics are not known to all bus operators**. More investigation is also required to assess the accuracy of telematics data and how it is processed and reported by suppliers.

The landscape within which retrofitted buses are operating is complex. There are multiple actors facing competing challenges and with differing motivations. There is a shortfall in the capacity of retrofit suppliers and engineers in bus depots to diagnose and fix faults quickly. Future maintenance may be at risk if buses are a dwindling market for retrofit suppliers.

Urea dosing and NO_X sensor release strategies deployed by suppliers could also be adjusted to optimise NO_X reduction, though these require further investigation.

Considerations of future use of SCR retrofit technology

SCR remains an effective application for lowering real-world NO_X emissions for the latest diesel passenger cars and vans. In considering whether SCR is the appropriate retrofit technology for NO_X emission reductions across a wider range of transport and machinery applications, it will be important to carefully consider the expected duty cycle of that machinery and whether the typical exhaust temperatures experienced in real-world use are likely to be conducive to good NO_X reduction performance. Consideration should also be given to whether vehicle operators will be able to sufficiently maintain the vehicles and retrofitted SCR systems such that effective NO_X reduction can be achieved and maintained in real-world operation.

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1. Introduction

In late 2021, the Joint Air Quality Unit (JAQU) commissioned an evidence review to obtain evidence on the performance of Selective Catalytic Reduction (SCR) bus retrofit technology in reducing emissions of nitrogen oxides (NO_X; the collective term for NO and NO_2). NO_X is emitted from combustion processes including those in road transport. At the roadside, NO rapidly converts into nitrogen dioxide (NO_2), an air pollutant which is a respiratory irritant and associated with negative health impacts[1]. In some roadside locations, the UK is in breach of the legal limit value for annual mean NO_2. SCR technology has been used for several decades by the automotive industry to control NO_X emissions. The technology has been applied to buses more recently. Several Government funding schemes have supported the retrofit of the technology in buses as a means of improving air quality and meeting legal limits for NO_2. There are approximately 8,800 buses with SCR retrofit technology in England.

This evidence review was evaluated in spring 2022 and indicated underperformance of the technology in reducing NO_X emissions, but the evidence was limited. JAQU commissioned a remote sensing emissions campaign in three English cities between September and December 2022 to confirm whether there was an issue with performance of the technology. The campaign obtained over 2,800 measurements of emissions from retrofitted buses. The measurements from this initial campaign showed that SCR on retrofitted buses is not consistently reducing emissions as expected. Instead, there is considerable variation in performance - in some cases retrofitting has reduced NO_X emissions, while in others, emissions from retrofitted buses are comparable to or greater than emissions from non-retrofitted buses. In addition, the fraction of NO_X emitted as NO_2 (f-NO_2) is higher on average in retrofitted buses. These findings were consistent with findings from Transport Scotland in 2021 and provided strong evidence that there was an issue with the technology which required further investigation.

The observational evidence obtained showed a large variation in the performance of retrofit technology that could not be explained by a single causal factor. JAQU therefore initiated a programme of work in spring 2023 to answer two research questions:

1. Why have NO_X and NO_2 emissions from retrofitted buses not reduced as much as expected?

[1] Air Pollution in the UK 2022, available at: https://uk-air.defra.gov.uk/library/annualreport/.

2. What is the scope for achieving and maintaining greater NO_X and NO_2 emissions reductions from retrofitted buses?

The questions focus the scope of the programme of work on NO_X (as opposed to other pollutants emitted at the tailpipe) and on the original expectation of performance as described in the Clean Vehicle Retrofit Accreditation Scheme (CVRAS) (Section 2.2).

JAQU identified the problem as a complex one. There are multiple stakeholder perspectives and interests, at both local and national scales. There are multifactorial and interacting causes, with potentially unpredictable relationships between cause and effect of SCR technology on levels of NO_X and NO_2 emissions. In response, the programme adopted a systems approach, seeking multiple perspectives and combining technical investigations with quantitative and qualitative evidence gathering, to build a holistic understanding of the nature of the problem and potential points of intervention to improve performance.

Chief Scientific Advisers in the Department for Environment, Food and Rural Affairs (Defra) and Department for Transport (DfT) convened an expert group – the Bus Retrofit Expert Group (BREG) – to provide independent scientific advice in support of this programme of work. The focus of the BREG was on explaining the factors causing underperformance through an assessment of existing and new evidence.

Consideration was given to the following sub-questions which accompany the two overarching research questions:

1. Does retrofitting reduce NO_X emissions to the levels expected under the CVRAS?

2. How do emissions from retrofitted buses compare with emissions from non-retrofitted buses in real-world conditions?

3. What are the root causes of underperformance?

4. How do emissions from retrofitted buses vary under different conditions in the real-world?

5. Why is there variation in the performance of retrofit technology?

6. Can retrofit performance be improved?

The structure of this report reflects these questions – firstly by providing new evidence on performance of the retrofitted bus fleet in England, then by explaining the factors causing underperformance, and finally by setting out the scope for improvement in performance of the existing retrofitted bus fleet.

2. Background

2.1 Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) is an exhaust after-treatment technology used primarily in diesel vehicles to reduce NO_X emissions. It works by injecting diesel exhaust fluid (an aqueous solution of urea marketed as AdBlue) into the exhaust gases from the engine[2] (Figure 1), where is it hydrolysed into ammonia. Ammonia is a reactive compound that in the presence of a catalyst selectively reduces the NO_X in the exhaust gases into nitrogen (N_2) and water (H_2O). These are inert and harmless and pass out through the vehicle tailpipe.

Both the NO_X reduction reaction and the urea hydrolysis are highly dependent on the temperature of the exhaust gases – temperatures between 200°C and 450°C give optimum SCR performance. The SCR control system also influences actual NO_X reduction; the system takes inputs from engine sensors that represent engine conditions (including key parameters such as exhaust temperature and mass flow). These inputs are processed inside an electronic control unit (ECU) which monitors and reports faults in the system and determines the optimal urea mass to inject at any time to reduce emissions to required levels. These include ammonia emissions from incomplete reactions (‘ammonia slip’). The process of optimal urea injection requires the functioning of several components within the SCR system; these components must be in good working order and must function in harmony.

[2] Alternative ‘dry’ SCR systems exist that operate under similar principles to those described here, though these are less common.

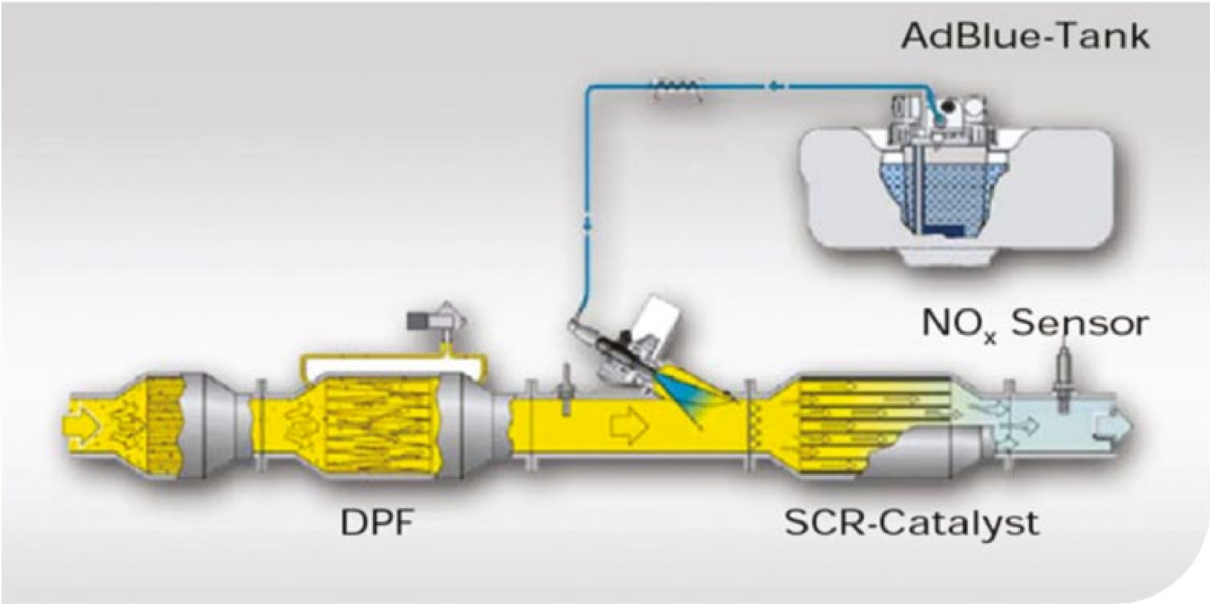


Figure 1 Illustration of an SCR system
Source: The Clean Retrofit Technology Guide 2021 published by the Zemo Partnership. Note: 'DPF' refers to Diesel Particulate Filter.

2.2 Overview of the CVRAS

The Low Carbon Vehicle Partnership (Low CVP, now the Zemo Partnership) was commissioned in 2016 to develop an accreditation scheme for retrofit technologies that could reduce NO_X emissions from buses to Euro VI levels. The focus was largely on buses but with several pilot projects carried out on other vehicle types including coaches and refuse collection vehicles. The aim was to facilitate solutions to bridge the gap towards zero emission vehicles. The scheme – the Clean Vehicle Retrofit Accreditation Scheme (CVRAS) – is technology neutral but most technologies accredited use SCR. The CVRAS and accreditation process is managed by the Energy Savings Trust (EST) and the Zemo Partnership.

The scheme drew on evidence from the 2014 Clean Vehicle Technology Fund (CVTF) and 2013 and 2015 Clean Bus Technology Fund (CBTF) to develop guidance and a two-stage accreditation process:

- Accreditation of retrofit suppliers: Checks on the trading and financial aspects of retrofit suppliers and quality assurance checks on the retrofit technology (and component parts) to provide 'approved supplier status'.

- Accreditation of retrofit technology: Testing of retrofit technologies either on a chassis dynamometer or using Portable Emissions Measurement Systems (PEMS). Once accredited, the technology can be applied to any bus though the specification of the technology should be tailored to the model, engine, and weight class of the vehicle.

2.2.1 Emissions limits

Low CVP obtained evidence from emissions testing of retrofitted (Euro II to V) and non-retrofitted buses from several pilot studies between 2013 and 2015. Most pilot studies showed significant NO_X emissions reductions from SCR technologies. In particular, Euro V retrofitted buses operated by Transport for London (TfL) achieved around 95% NO_X reduction under testing in a laboratory. COPERT[3] emission factors were also considered alongside emissions data from five Euro VI buses that achieved NO_X emissions below 500mg/km. Pilot studies showed that 6 months after fitment, in-service performance maintained good conformity with that achieved in initial testing. This evidence was collated into a 2017 evaluation report[4].

Evidence from 21 buses across 15 local authorities was used to decide emissions limits for accredited technologies. These were agreed by a Technical Advisory Group (TAG)[5]. To be accredited, retrofit technologies are required to achieve a maximum permitted emission limit for four primary and three secondary pollutants, and a reduction performance for NO_X of >80% between the engine and the tailpipe (Table 1). The maximum permitted limit of <500mg/km for NO_X was considered challenging but attainable.

On the back of findings from the pilot studies, an additional in-service daily average NO_X reduction requirement of 80% for the lifetime of the system was agreed. This ensures that 80% NO_X reduction (which can deliver emissions approaching Euro VI levels) is maintained during the lifetime of the retrofit system. Monitoring performance in-service is achieved using NO_X sensors at the engine and tailpipe which record and report data via telematics systems.

[3] A software tool used to calculate air pollutant emissions from road transport.

[4] Low Carbon Vehicle Partnership - Low CVP (2017) Clean Vehicle Technology Fund and Clean Bus Technology Fund Programmes - Evaluation Report.

[5] The TAG included representatives from Low CVP, the Energy Savings Trust (EST), Vehicle Certification Agency (VCA), Driver and Vehicle Standards Agency (DVSA) and industry associations including the Freight Transport Association (FTA), Road Haulage Association (RHA), and Society of Motor Manufacturers and Traders (SMMT).

Exhaust emission parameter		Maximum permitted limit	Reduction performance
Primary emissions			
Mixed oxides of nitrogen	NO_X	500mg/km	>80%
Nitrogen dioxide	NO_2	100mg/km	
Particulate matter	PM	10mg/km	
Number of particles	PN	6 x 10^{11}/km	
Secondary emissions			
Nitrous oxides/methane	N_2O/CH_4 (as CO_2e)	< 5% of CO_2	
Carbon dioxide	CO_2	< 1% increase	
Ammonia	NH_3	10ppm average, 25ppm peak	
In service			
Mixed oxides of nitrogen	NO_X		> 80% daily average

Table 1 - Emission limits applying to buses after installation of retrofit technology.
Source: Clean Vehicle Retrofit Accreditation Scheme (CVRAS) - Chassis dynamometer test procedures for approval of low emission adaptations to comply with Clean Air Zones (CAZ), Low Emission Zones (LEZ) and Ultra-Low Emission Zones (ULEZ).

2.2.2 Testing cycles

Candidate retrofit technologies were tested for attainment of these emission limits. This was typically done with the bus on a chassis dynamometer following a velocity profile, and at a constant temperature of 18°C +/- 2°C. Testing procedures were agreed by the TAG and incorporated two critical design elements with the aim of developing an independent testing protocol using real-world drive cycles:

- Vehicle emission test procedures: Adapted from existing well recognised procedures such as those developed at recognised tests centres, and established data developed in the UK and in Europe.

- Drive cycles: Cycles were adapted from 1996 onwards into the Revised 2017 Low CVP UK Bus Cycle. This cycle includes three phases – an inner London phase and an outer London phase which matched a route operating between Streatham and Trafalgar Square, and a rural section derived from European bus operations. The London cycles were developed in 1996 and have since been verified to ensure they represent city centre bus operations.

2.3 Assessment of the CVRAS

In summer 2023, JAQU commissioned testing of three buses fitted with retrofit SCR technology at a vehicle testing centre. The limitations and real-world application of the CVRAS test procedures were explored as part of this testing. Full details of the analysis can be found in Annex B.

2.3.1 Limitations of the CVRAS

There are several limitations of the CVRAS. Firstly, the CVRAS emission limits and in-service performance criteria were derived using a limited sample of Euro II to V emissions data, with no standard method of testing provided.

Secondly, as detailed in Annex B, the testing cycle does not include a cold start. Emissions are only assessed when a vehicle is hot. Whilst this was considered within the development of the 80% daily NO_X reduction target, this limitation still exists in the accreditation process. Moreover, the evidence from the CVTF and CBTF used to develop the scheme was limited with all tests being undertaken on hot vehicles.

Thirdly, the drive cycle used for accreditation has not been updated since the revised 2017 LUB test cycle. Whilst there have been several reviews of the drive cycle by relevant stakeholders, it may be that more representative drive cycles are required to reflect the latest real-world conditions, for example including more periods of stop-start driving where temperatures are expected to be low.

These limitations suggest that the CVRAS in its current form does not have the capacity to ensure that retrofit technologies are performing to the required standard in-service under real-world driving conditions.

The in-service NO_X reduction metric relies on the use of telematics systems. There are additional limitations with these systems. Firstly, there are often significant periods of a bus journey when NO_X sensors are not recording. This is necessary to some extent to protect the sensors from damage when moisture forms on the heating elements at low temperatures. It is expected that NO_X reduction is minimal during these periods, yet non-recording periods are not included when assessing the daily average NO_X reduction requirement.

Secondly, not all buses have functioning telematics systems as some bus operators have not subscribed to the service. Currently 20% of CVRAS accredited retrofitted buses in England and Wales do not have any telematics data available. Performance of a retrofit SCR system cannot be monitored in-service without this data. **The current configuration of bus telematics systems and associated services is not fit for purpose to enable effective oversight of performance of retrofit technologies in-service**. Work is continuing to improve telematics coverage and the reporting of poor performing buses.

2.4 Science Programme Design

The programme of work initiated by JAQU in spring 2023 sought to assess the effectiveness of SCR retrofit technology in reducing NO_X emissions from buses and explain the factors affecting performance[6]. It was necessary to determine whether the technology is fundamentally not fit for purpose or whether there are specific factors at play that are causing variation in performance and which, if understood, could enable improved

[6] The performance of hybrid buses with SCR retrofit technology has not been directly investigated; rather the focus in this programme of work has been on buses with conventional internal combustion engines. However, many of the findings are applicable to retrofitted hybrid buses.

performance. The science programme adopted a systems approach, to understand and engage with the complexity the problem presented - both in terms of the many possible causes that it aimed to investigate, as well as the many methods used to collect and analyse data.

A long list of 38 potential factors to investigate (Figure 2) was developed by JAQU and assessed by the BREG. Some factors were considered likely to have a stronger influence than others, and it was acknowledged that there were many relationships between factors. The factors were described in two broad categories – technical and human. This categorisation enables the identification of the separate potential causative factors, technical and human, as well as considering the interactions between factors.

1. Technical: What are the physical factors relating to a) the design and b) the integration of the technology with the engine, that could affect performance?

2. Human: If the technology works (in some or all conditions), what are the human factors at play in the real-world, encompassing installation, maintenance, and use, that are causing performance to drop off?

The programme of work sought to obtain new evidence across both the technical and human categories to answer the programme's research questions. A summary is provided here of the methods used for quantitative and qualitative data collection, and the statistical analysis and modelling processes to reveal findings from this data.

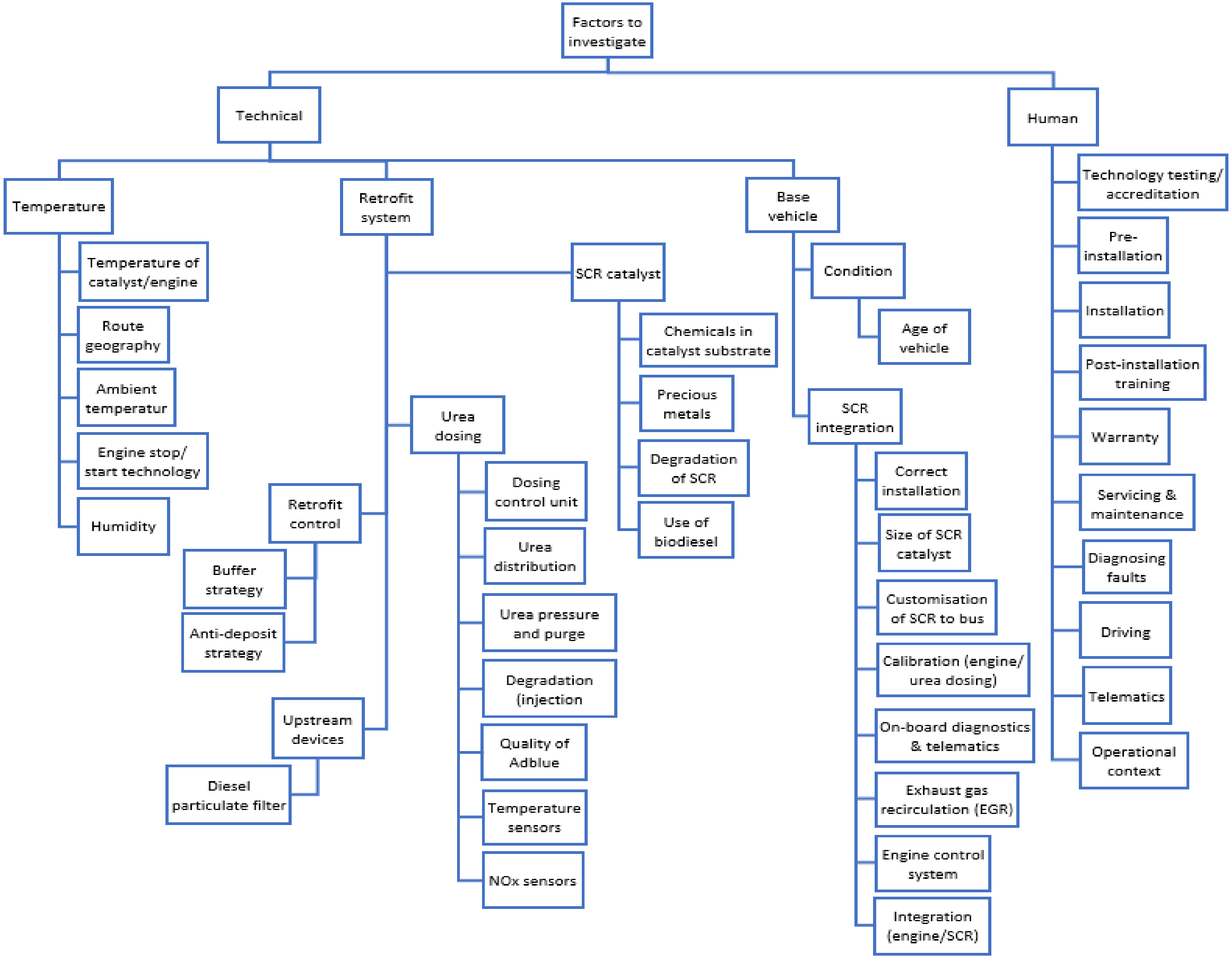


Figure 2 A long list of factors potentially affecting the performance of bus retrofit technology.

2.4.1 Evidence Collection

Detailed below are the evidence collection projects within the programme of work.

2.4.1.1 Remote Sensing

Remote sensing equipment measures tailpipe emissions at a fixed point on the road. This means that emissions are captured at a fixed point in the drive cycle but there is often variability in vehicle speeds, acceleration and weather conditions during the measurement campaign. When used correctly, remote sensing has been shown to provide robust emission estimates with quantifiable uncertainty[7].

A remote sensing monitoring campaign was undertaken in summer 2023 to measure real-world emissions from retrofitted and non-retrofitted buses. The 2023 campaign built on evidence from a similar study undertaken in late 2022. The aims of the 2023 remote sensing campaign were to:

1. Investigate variations in retrofit performance at different points on a typical bus route. Two sensors were set up in two cities running simultaneously, one in the city centre and one in the outer urban area. The aim was to capture some of the same buses at different points on their routes. In the city centre the retrofit technology is expected to be performing more poorly with more start-stop movements and idling periods, than in the outer urban area.

2. Investigate the impact of ambient temperature on retrofit performance. The 2022 monitoring campaigns were undertaken in late autumn and winter; the 2023 campaign took place in summer.

3. Gain more insight into the factors influencing retrofit performance by matching remote sensing data to telematics data from the observed buses.

4. Provide a like-for-like comparison of emissions from non-retrofitted Euro V and Euro VI buses and retrofitted Euro V buses under the same conditions.

[7] Minimum sample sizes for on road measurements of car emissions; Environmental science and technology 53, 22, 2019: https://pubs.acs.org/doi/abs/10.1021/acs.est.9b04123.

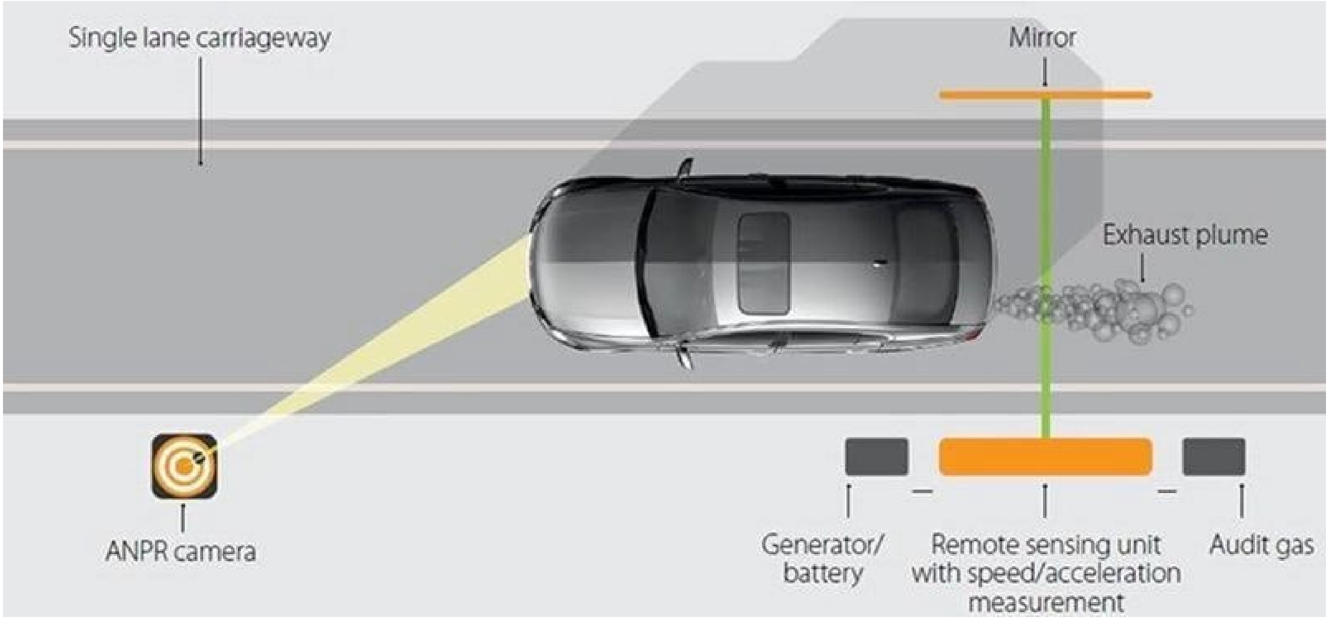


Figure 3 Real-world remote sensing monitoring equipment set up (image provided by Ricardo Energy & Environment).

2.4.1.2 Testing and physical inspection at a vehicle test centre

The physical inspection and testing of three buses at a vehicle testing centre enabled a detailed assessment under controlled conditions of some of the technical factors influencing retrofit performance. A key principle was to link observations from in-service telematics data to specific causes of poor performance; inspect and undertake maintenance if required; and then retest in a repeatable way to assess the impact of maintenance on emissions. The testing was composed of three parts:

1. CVRAS testing: To benchmark the in-service performance of the retrofit system and determine next steps. This was completed for all vehicles.

2. Root cause analysis: To understand why expected emissions reductions were not achieved by the vehicles selected for testing. This consisted of deep dives into the retrofit systems with physical inspections and emissions analysis. Retrofit suppliers undertook targeted maintenance with component faults isolated. This testing was completed on two buses which exceeded the benchmark CVRAS emissions limits.

3. Emulation testing: The retrofit technology on one bus was stress tested to identify boundary conditions and study system reactions to unfavourable conditions, and the accuracy of telematics outputs. This testing was undertaken on a chassis dynamometer on a vehicle that performed reasonably well on the CVRAS test (albeit recording marginal exceedances of the CVRAS emissions limits).

Buses with in-service telematics data showing low NO_X reduction were prioritised for testing to explore the causes of underperformance. Telematics data was also used to identify trends and correlations between NO_X emission reductions and other reported metrics such as SCR temperature, urea rail pressure and average urea consumption. Remote sensing data collected during the 2022 campaign was used to check for agreement with the NO_X emissions outputs from the telematics data.

The analysis of telematics data was used to establish and target groups of buses with reoccurring faults which could indicate a systematic issue with the retrofit systems or maintenance, rather than that of an individual bus. A series of exclusion criteria were identified to apply to the bus selection to ensure buses with obvious unique faults were excluded. For example, buses were excluded if they had unresolved intermittent faults or warning lights. These exclusion criteria were applied where possible within telematics data first, and then shared with bus operators.

The selection of buses was limited to Cummins ADL Enviro 400, the most common engine type on the CVRAS whitelist, as a controlled variable. Operators were asked to provide vehicles in their current in-service condition. Annex C details the buses selected for testing at the testing centre and the emission tests completed on each. A detailed analysis of the results of the testing was undertaken by Vehicle Certification Agency (VCA) and JAQU.

2.4.1.3 Portable Emissions Measurement System (PEMS) testing

JAQU commissioned real-world PEMS testing to explore how NO_X emissions from retrofitted and Original Equipment Manufacturer (OEM) buses varied throughout a real-world drive cycle. How geographical factors experienced on typical bus routes impact SCR temperature and retrofit performance was also explored along with the accuracy of telematics data recorded across the drive cycle.

PEMS equipment records tailpipe out emissions of pollutants such as NO_X and NO_2 during real-world drive cycles. Figure 4 shows a PEMS kit installed on the exhaust of a bus to collect exhaust outputs, with the corresponding measurement equipment located inside the bus.

Figure 4 PEMS equipment in use (taken on a bus in Bath, September 2023).

Real-world PEMS testing was conducted on retrofitted Euro V buses and a Euro VI OEM bus on bus routes in Sheffield and Bath in early autumn 2023. Test results from Bath were not available in time to include in this report.

The rationale for the selection of buses for PEMS testing and the tests completed on each bus is provided in Table 8 in Annex C. Retrofitted Euro V buses achieving good levels of

NO_X reduction (>80% average NO_X reduction) were prioritised for testing, with bus operators asked to confirm the vehicles had no known faults. Testing well performing buses on challenging routes (such as those with frequent idling and steep gradients), would stress test the technology to understand the conditions under which NO_X reductions are high and low, and whether the technology can perform well in all conditions. The findings of the testing are detailed in Section 3.

PEMS data obtained from the Zemo/EST Partnership's 2021-2 ongoing retrofit performance monitoring campaign is also presented in Section 3. Zemo/EST has tested 10 retrofitted buses, six on a test track and four on real-world bus routes, as well as two OEM Euro VI buses and 2 OEM Euro V buses both on the track and on real-world bus routes.

2.4.1.4 Telematics data collection

Telematics provides detailed information on retrofitted SCR performance, collected through continuous on-board monitoring of information such as NO_X reduction, AdBlue consumption and SCR temperature. This data can provide valuable insight into the performance of the retrofit technology which could guide diagnostics, and how performance is influenced by factors such as vehicle speed. It does not provide information on the fraction of NO_X which is NO_2. The telematics monitoring is made available by retrofit suppliers who provide access for bus operators through an online portal. Consumers of telematics include operators, Government and third-party organisations.

Retrofit suppliers provided JAQU with several batches of detailed telematics data for buses captured during the remote sensing campaigns in autumn/winter 2022 and summer 2023. The data analysed in this report is predominantly from two major retrofit suppliers, covering around 1,200 days of data for around 350 different buses. To look at retrofit performance more widely, 24-hour performance summaries for over 3500 buses across the UK were provided by Zemo/EST who also have access to this high-level data from their own portal.

2.4.1.5 Human Factors

JAQU commissioned behavioural research consultants to investigate the human factors that might be influencing performance of SCR retrofit technology throughout its lifecycle. The research sought to ground findings from the quantitative evidence collection activities above in a real-life context and obtain new insights. These factors focus particularly on the ongoing maintenance and monitoring of the technology. They involve many actors from different organisations such as those who supply the retrofit systems and those in bus depots who maintain them. The research sought to understand the drivers of any relevant behaviours and unpick the influence of the organisational context within which individuals sit.

A key principle in the human factors research is that of 'work as done' versus 'work as imagined' – do the real-life practicalities of installing, maintaining and operating retrofitted buses mean that achieving ongoing 80% NO_X reduction is implausible? And are there sufficient resources and incentives for 'work as imagined' or are there shortcuts taking place which led to 'work as done'? The research identified the key individual, social and material factors driving behaviours that appear to deviate from the ‘work as imagined’ journey.

Ten interviews were carried out with individuals from different bus operators, retrofit suppliers, the Confederation of Passenger Transport (CPT) and the Zemo Partnership. Interviews explored broad contextual factors at play, decision-making processes and overall perspectives on SCR retrofit technologies. Four visits were made to bus depots in England where the technology is in use, including one that undertook maintenance on behalf of depots across a wider region. Activities were observed and a range of individuals with different responsibilities spoken to. Reported responses are not attributed to individuals or settings. The qualitative evidence obtained was examined using behavioural analysis tools. Evidence reflects differing viewpoints that may be rooted in the motivations of different stakeholders and does not necessarily represent the views of the wider industries.

2.4.1.6 Statistical analysis and modelling

The statistical analysis and modelling workstream sought to answer the research questions through analysis of the data available. There were three key components to this work:

1. Analysis of remote sensing data:
   This analysis sought to understand how real-world NO_X emissions measured through remote sensing for retrofitted buses compared to that from OEM Euro V buses and OEM Euro VI buses. It also looked to understand how emissions varied by a range of other factors, such as bus make and model, operator, and city. Being able to make fair comparisons across, for example bus operators or cities, is challenging because there are many different factors that could impact the NO_X emissions measured. For example, the emissions for buses in a particular city may appear higher than another, but measurement sites may have different ambient temperatures, average speeds and gradients, making it hard to draw clear conclusions on the key factor driving any difference. To address this, statistical modelling techniques were explored which seek to model the underlying relationships between various factors to allow their effect on emissions to be separated and quantified. Generalised additive models (GAMs) were used for much of this analysis.

2. Analysis of telematics data:
   This sought to understand how retrofit performance, particularly the percentage NO_X reduction between the engine and tailpipe, were influenced by factors such as SCR temperature and the performance of the urea dosing system. These findings were used both to assess performance across the fleet and to inform how telematics data might be used more effectively to monitor in-service performance and identify specific problems. It also looked to understand the amount of time that NO_X sensors do not record.

3. Analysis of remote sensing data matched to telematics:
   By matching the remote sensing measurements with telematics data, this component looked at how NO_X emissions from buses with retrofitted SCR systems compared to emissions from the wider fleet, both when retrofitted buses were performing well and when they were performing poorly.

3. Performance of the fleet

3.1 Early evidence on NO_X emissions

Real-world remote sensing emission monitoring data was collected at the roadside within three cities in England in 2022. The data showed that, in the sample studied, retrofitting SCR technology to buses was not reducing NO_X emissions as expected (i.e. to Euro VI levels). Performance was variable; in some cases, retrofitting appeared to reduce NO_X emissions (although not to Euro VI levels), while in other cases NO_X emissions from retrofitted buses were comparable to or greater than emissions from non-retrofitted Euro V buses.

Figure 5 shows the variation in the NO_X emissions measurements captured during the remote sensing monitoring campaign for both non-retrofitted (OEM) and retrofitted buses. Most retrofitted buses captured during the measurement campaign were Euro V buses, but a number of retrofitted Euro IV buses were captured. The range in NO_X emission measurements was larger for retrofitted buses than for non-retrofitted buses. Emissions from Euro VI OEM buses were low and the variation in measurements was much smaller than for the other categories shown in Figure 5.

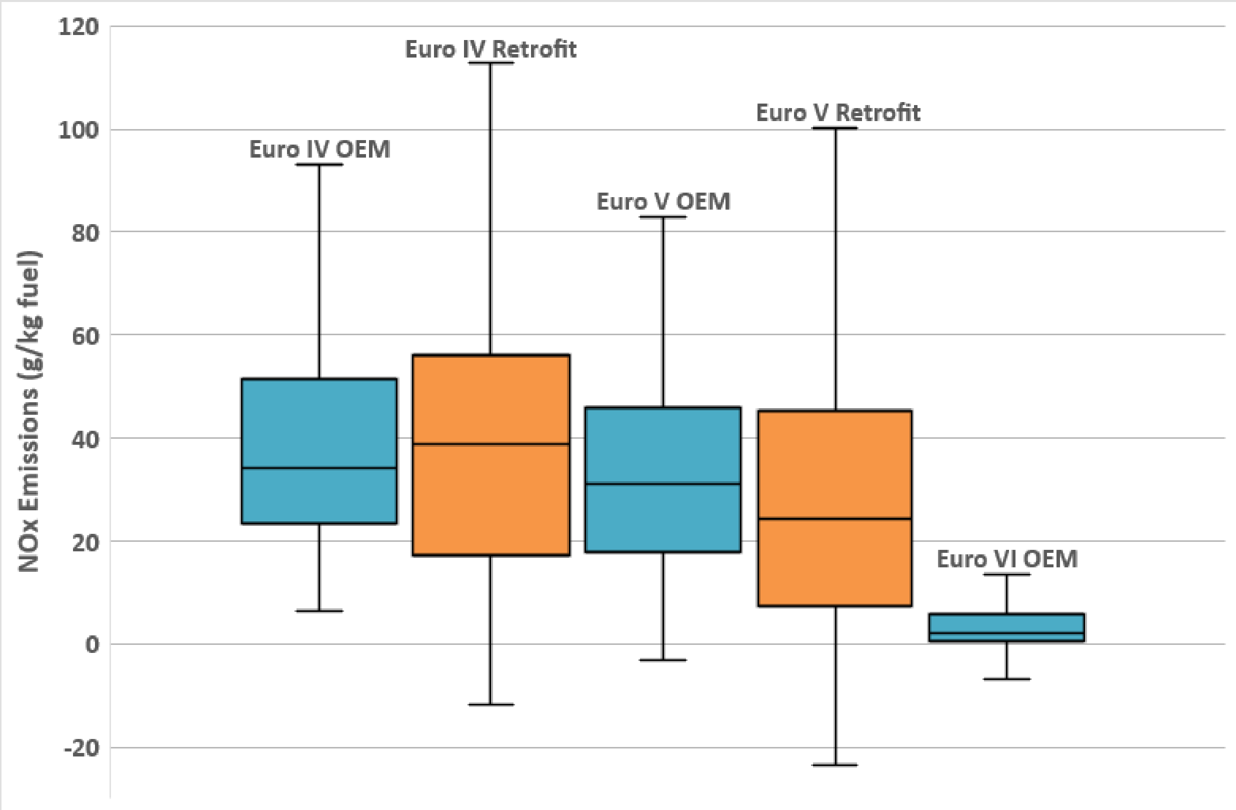


Figure 5 Box and whisker plot summarising the variation in NO_X emission measurements during the remote sensing monitoring campaign in autumn/winter 2022 in all measurement locations. The boxes show the upper and lower quartiles of the emissions measurements, the horizontal line shows the median and the whiskers present the 5th to 95th percentiles of the data. Negative emissions can arise when emissions are low, and this reflects uncertainties in the background subtraction procedure[8].

Transport Scotland reported comparable findings from a remote sensing monitoring campaign undertaken in 2021[9]. Both studies also found that the fraction of NO_X being emitted directly as NO_2 (f-NO_2) is greater for retrofitted buses than for non-retrofitted buses.

PEMS tests undertaken by Zemo/EST on behalf of JAQU as part of their ongoing monitoring programme in 2021 and 2022 showed that SCR retrofits were not reducing emissions to Euro VI levels across the whole measurement period. However, the data showed that the buses tested on the test track at the Millbrook vehicle test centre were producing low levels of NO_X during the CVRAS test cycles. The PEMS sample size was limited to ten retrofitted buses, two OEM Euro V buses and two OEM Euro VI buses. Further evidence which captured the performance of the technology over the whole drive cycle was needed.

[8] Background subtraction procedure explained in Annex 1 TRUE – The Real Urban Emissions Initiative London 2017-2018 Fieldwork and methodology report https://theicct.org/wp-content/uploads/2022/01/OPUS-RSE_ICCT_TRUE-London_2017-2018_Field_report_180710.pdf.

[9] Assessment of real-world vehicle emissions in Scotland in 2021: Emissions testing campaigns in Edinburgh and Glasgow https://theicct.org/wp-content/uploads/2023/06/true-scotland-remote-sensing-jun23.pdf.

3.2 New evidence on NO_X emissions

A second real-world remote sensing monitoring campaign was undertaken in the summer of 2023. This study repeated roadside measurements in Manchester and Sheffield at two of the same sites as the autumn/winter 2022 campaign. Measurements took place concurrently at an additional site within each city to capture variation in emissions across the route.

Figure 6 shows a comparison of measured NO_X emissions at the same sites in autumn/winter 2022 and summer 2023. The left-hand panels present emissions from OEM buses and the right-hand panels present emissions from retrofitted buses. Only individual buses that were captured in both monitoring campaigns have been included in the figure. In total there were 522 individual buses captured during both monitoring campaigns.

The data shows no meaningful difference in the measured mean NO_X emissions between the two campaigns for both retrofitted and non-retrofitted buses. However, there is some evidence of difference between different retrofit technology suppliers. Buses with retrofit technology from Suppliers 1 and 3 tend to have higher NO_X emissions than buses with retrofit technology from Suppliers 2 and 4, although there is limited data on retrofit performance from Suppliers 3 and 4. Some retrofits from Supplier 2 in Sheffield have higher median emissions in 2023 than in 2022.

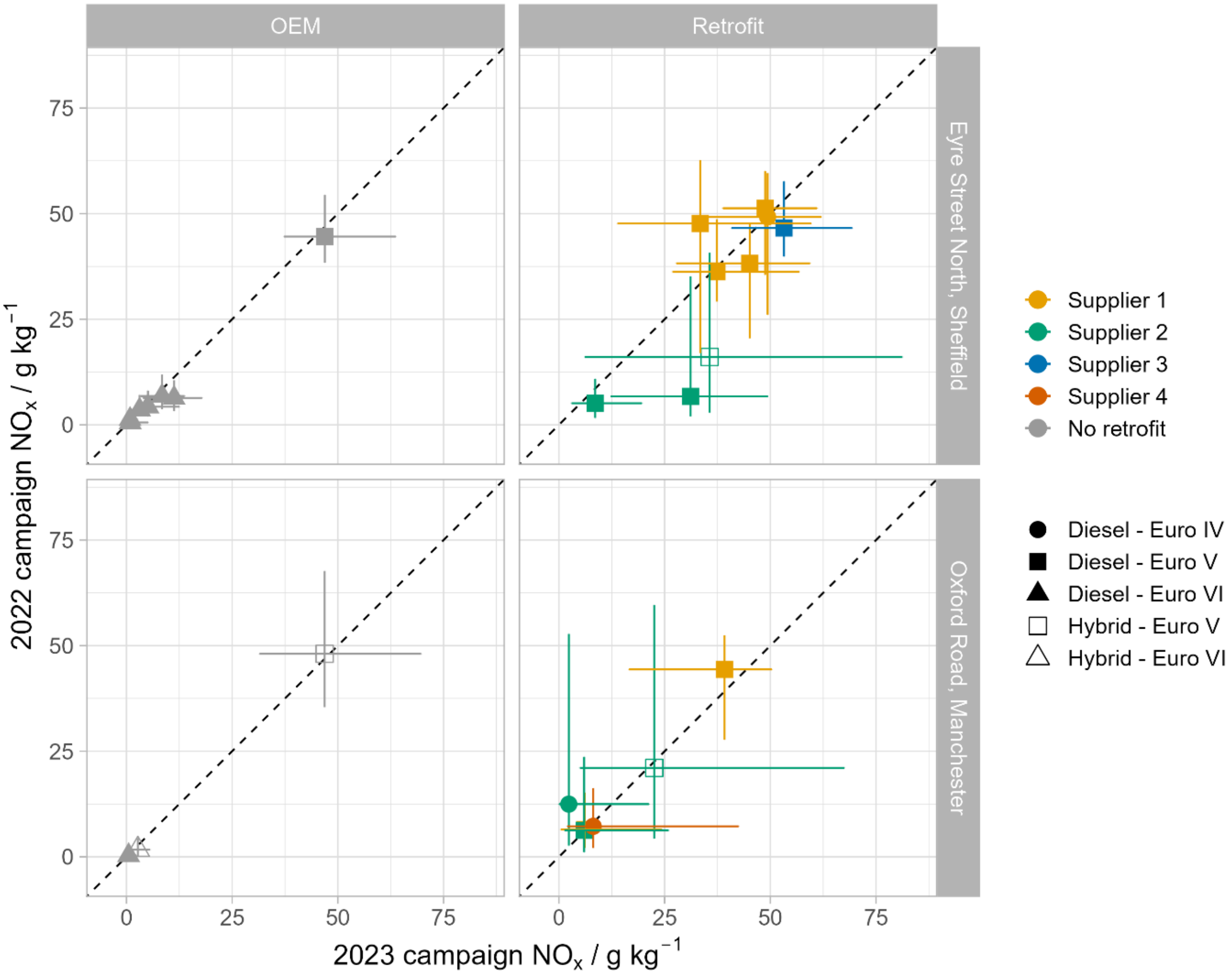


Figure 6 Comparison of NO_X emissions at the two common sites between the 2022 and 2023 campaigns. Each point represents the median NO_X emissions from a bus group, grouped by vehicle make, model and Euro standard. The error bars represent the interquartile ranges. Only common bus groups and only common buses within each group between the two campaigns have been plotted. Where points are close to the x=y line this shows that there is no meaningful difference between the measurements. Total number of buses: 522. Total number of 2022 measurements: 2,965. Total number of 2023 measurements: 3,734.

Figure 7 and Figure 8 show the comparison of NO_X emissions at the two different monitoring locations in Manchester and Sheffield, respectively. The left-hand panels present emissions from OEM buses and the right-hand panels present emissions from retrofitted buses.

Oxford Road in Manchester is a city centre site where bus speeds are generally lower (18 kph) and buses stop more frequently due to congestion and the number of bus stops. Wilmslow Road is an outer urban site where bus speeds are generally higher (25 kph) and the buses stop less frequently. Figure 7 shows that emissions of NO_X are closely aligned between the two sites for both non-retrofitted buses and retrofitted buses, except for Supplier 1 retrofitted buses which had higher emissions on Oxford Road.

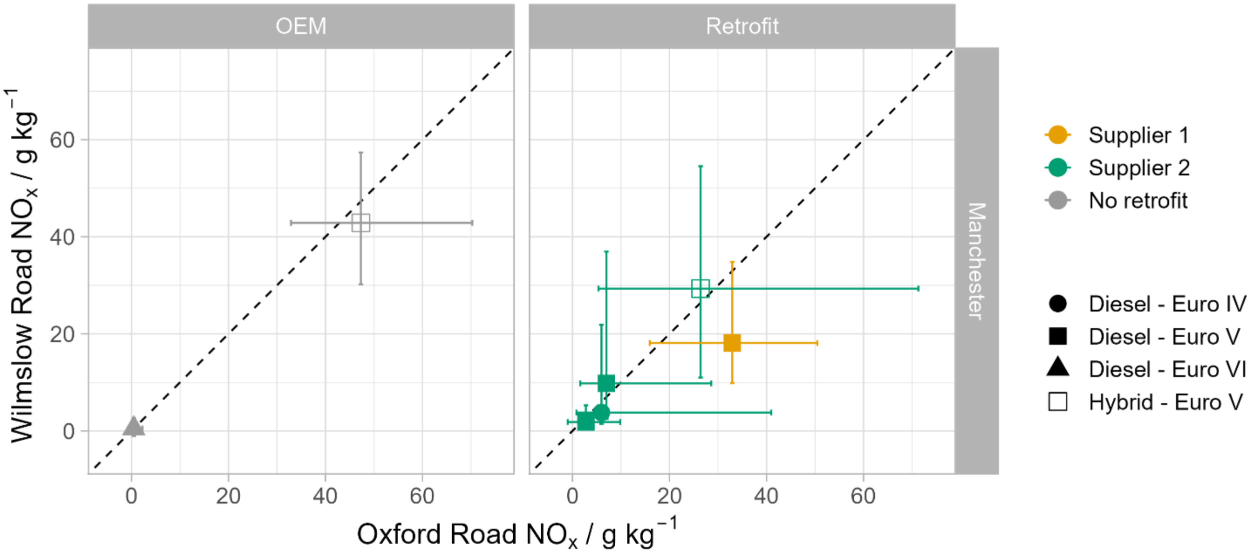


Figure 7 Comparison of NO_X emissions at the two measurement sites in Manchester during the summer 2023 campaign. Each point represents the median NO_X emissions from a bus group, grouped by vehicle make, model and Euro standard. The error bars represent the inter quartile ranges. Only common bus groups and only common buses within each group between the two sites have been plotted. Where points are close to the x=y line this shows that there is no meaningful difference between the measurements. Total number of buses: 232. Total number of measurements at Oxford Road: 1,459. Total number of measurements at Wilmslow Road: 1,035.

Eyre Street in Sheffield is a flat, city centre site. Barnsley Road is an outer urban site and has a steep gradient. The monitoring equipment was positioned so that the buses captured were travelling uphill. Average bus speeds were similar (22 kph and 21 kph, respectively). Figure 8 shows that emissions from retrofitted buses tended to be slightly lower at Barnsley Road than at Eyre Street, while emissions from Euro VI buses tended to be slightly higher.

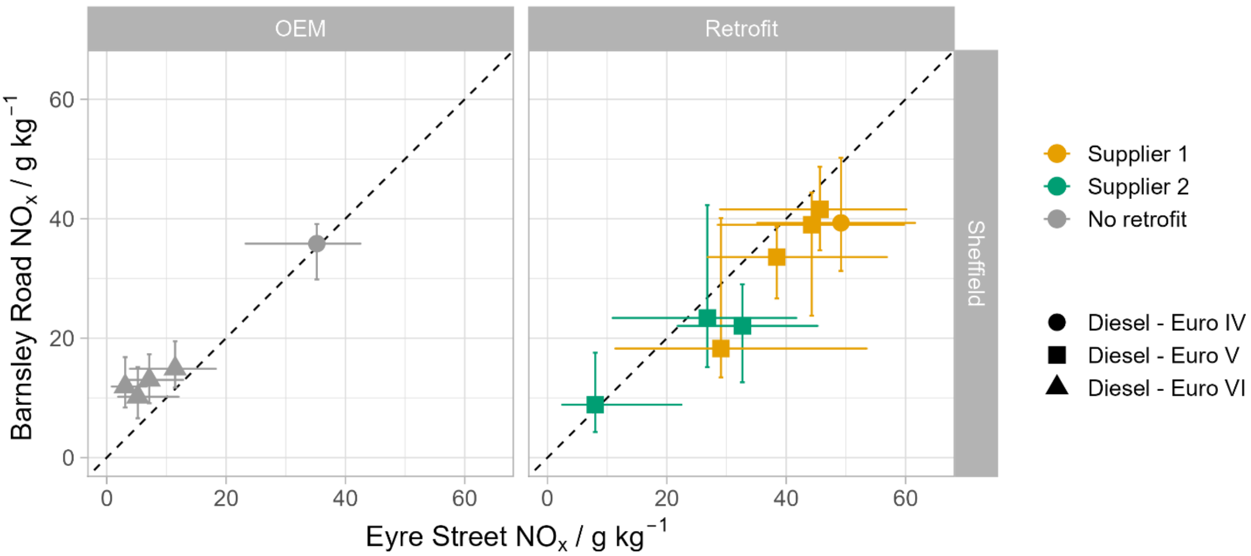


Figure 8 Comparison of NO_X emissions at the two measurement sites in Sheffield during the summer 2023 campaign. Each point represents the median NO_X emissions from a bus group, grouped by vehicle make, model and Euro standard. The error bars represent the interquartile ranges. Only common bus groups and only common buses within each group between the two sites have been plotted. Where points are close to the x=y line this shows that there is no meaningful difference between the measurements. Total number of buses: 199. Total number of measurements at Eyre Street: 1,999. Total number of measurements at Barnsley Road: 1,002.

Overall, the monitoring campaigns in Manchester and Sheffield suggest that the SCR technology on retrofitted buses is not, in the sample studied, reducing NO_X emissions to the levels expected. The variation in median emissions and the interquartile ranges show that **retrofit performance is highly variable**. In general, there is little variation in the median measured emissions between the 2022 and 2023 monitoring campaigns - the difference in ambient temperature between the two monitoring campaigns seems to have had little impact on the results. NO_X emissions in the inner and outer urban locations in Manchester showed very little difference for both OEM buses and the majority of the retrofitted buses. Route geography can be seen to have had some impact on NO_X emissions from retrofitted buses. NO_X emissions were lower when the bus was travelling up the steep hill at Barnsley Road, Sheffield than compared to on Eyre Street which is flat.

3.3 Statistical analysis of remote sensing data

Exploratory data analysis showed large heterogeneity in areas that are important for isolating factors that influence exhaust emissions. For example, there is no location/operator combination that has enough buses from the two main retrofit suppliers to make valid comparisons (both the unique number of buses, and the overall sample size are too low). Despite this, it was possible to address some questions such as the impact of speed on retrofit NO_X emissions according to age and location.

NO_X emissions from retrofitted buses show varying dependence on speed based on their location, despite being identical in their make, model and retrofit manufacturer. NO_X emissions from buses in Newcastle show a positive, linear relationship with speed. NO_X emissions from buses in Manchester vary negatively and nonlinearly if retrofitted in the last two years, and linearly if retrofitted over two years ago. Euro VI performance appears unaffected by these factors.

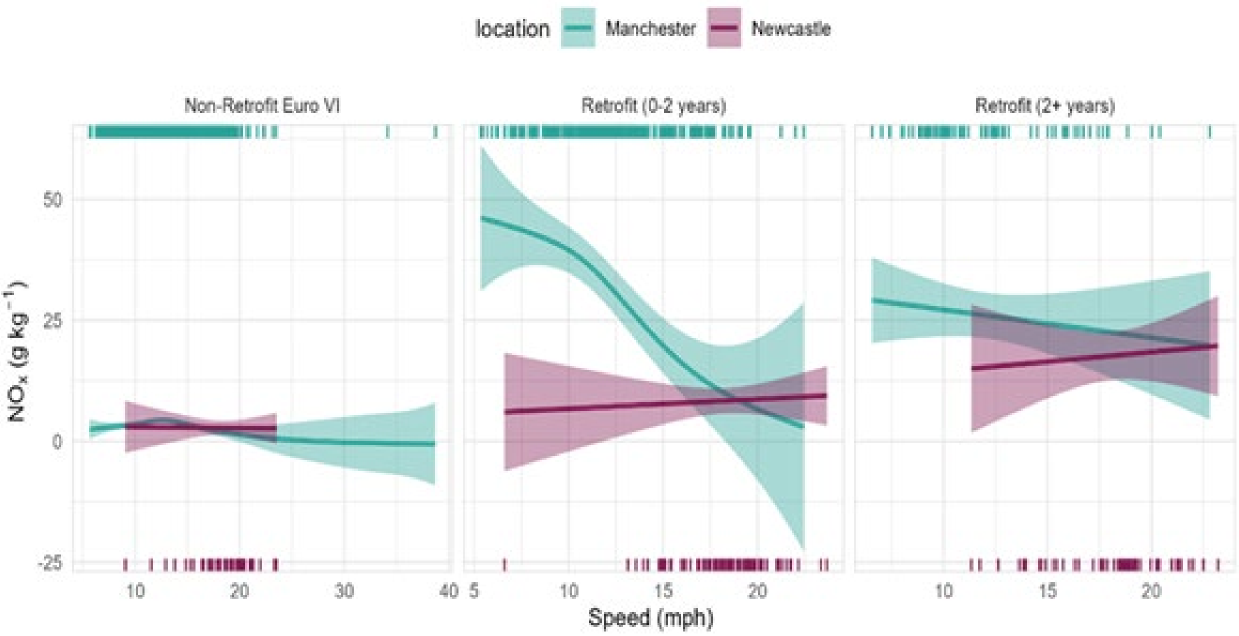


Figure 9 Influence of speed on emissions by location and age of retrofitted SCR system.

3.4 Comparisons to non-retrofitted (OEM) Euro V and VI buses

PEMS data from 2021/22 was used to provide estimates for Euro V and VI buses and buses retrofitted with SCR systems from two different suppliers (Table 2). All undertook the CVRAS cycle on track and with a cold start due to practicalities. For comparison, the PEMS testing undertaken by JAQU included a retrofitted bus tested in service on a typical route in Sheffield. The emissions were 4.7 g/km.

CVRAS PEMS (NO_X)	Euro V (2 buses, 5 runs)	Euro VI (2 buses, 3 runs)	Retrofitted Euro V (4 buses, 12 runs)
Mean (g/km)	9.0	1.8	5.2
Range (g/km)	6.4 – 11.9	0.4 – 4.2	2.2 – 12.6

Table 2 Distance specific emissions from PEMS data.

In this small set of data, mean NO_X emissions from retrofitted buses sit between those from Euro V and Euro VI buses. It is worth noting the upper end of the retrofit range does seem atypical; all other runs were lower by several g/km. The lower end of the retrofit range shows performance better than one Euro VI bus.

3.4.1 Euro V comparison

The 2022 remote sensing campaign reported NO_X emission measurements from OEM Euro V buses, as well as buses retrofitted with SCR technology from the two main suppliers. The data was collected across three cities and covered a range of bus operators and vehicle ages.

The remote sensing emission measurements were variable, however analysis of covariance to account for ambient and categorical factors produced a statistically significant value for differences in NO_X emissions from retrofitted Euro V buses compared to those from OEM Euro V buses. The variance accounted for in the model is low, due to the variability associated with remote sensing measurements and factors unaccounted for.

On average, emissions from retrofitted Euro V buses are approximately 4g NO_X/kg lower than those from OEM Euro V buses. The model met underlying assumptions reasonably well. Figure 10 shows the relationship of speed and emissions. For each group the data is quite dispersed but the trends for each indicated by the lines are quite different. The grey bands indicate 95% confidence intervals. Overall, retrofitted buses (brown line) tend to perform better with increasing speed unlike OEM Euro V buses (blue line). This may be because higher speeds cause the SCR temperature to increase so increasing NO_X reduction. Note at the lowest speeds retrofits may perform slightly worse than OEM Euro V buses.

In summary, **a statistical model showed NO_X emissions from buses with retrofitted SCR systems from the two largest retrofit suppliers were on average 11% lower than emissions from OEM Euro V buses**. This was statistically significant ($P<0.05$).

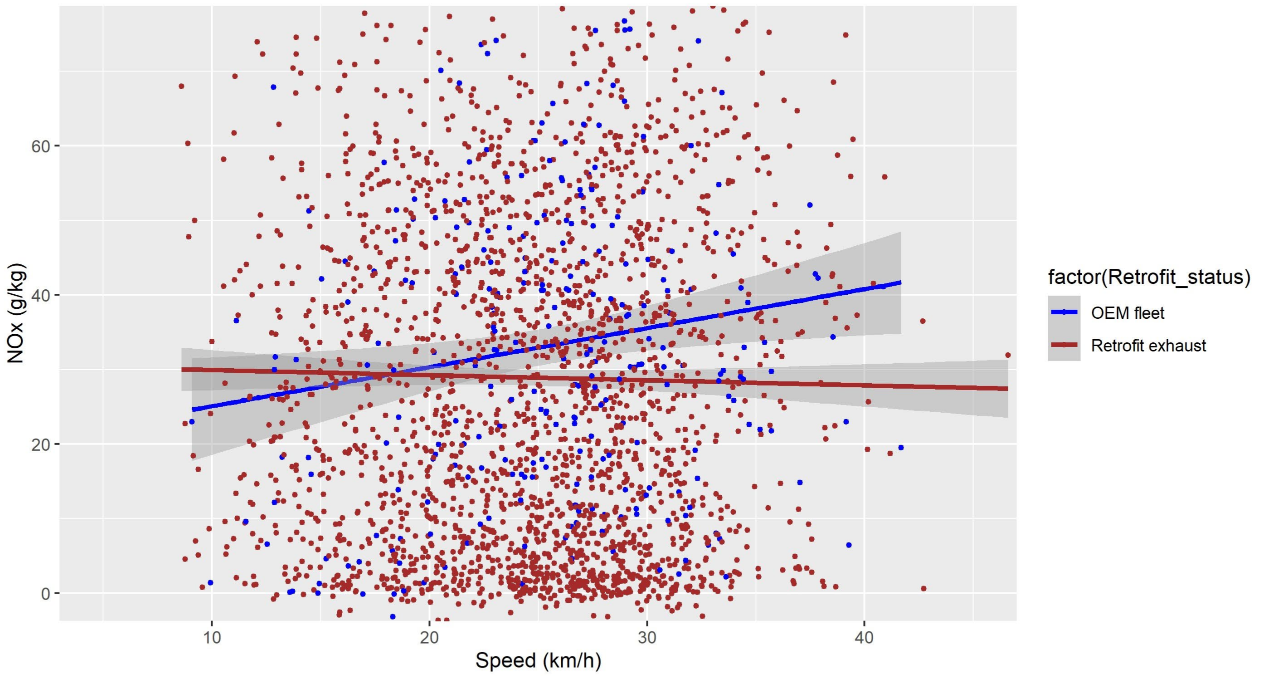


Figure 10 The relationship between speed and NO_X emissions for retrofitted and non-retrofitted (OEM) Euro V buses.

Tables 3 and 4 present the mean NO_X emissions measurements at Oxford Road (Manchester) and Eyre Street (Sheffield) during the 2023 remote sensing monitoring campaign for retrofitted Euro V buses and non-retrofitted Euro V and VI buses. The monitoring campaigns on Wilmslow Road, Manchester and Barnsley Road, Sheffield did not capture enough non-retrofitted Euro V buses to provide a robust comparison.

At Oxford Road, mean NO_X emissions from retrofitted Euro V buses were lower than those for non-retrofitted Euro V buses. The standard deviation calculations show that for retrofitted buses, the variation around the mean value was much higher than for non-retrofitted buses.

At Eyre Street mean NO_X emissions from retrofitted buses were similar to those for non-retrofitted Euro V buses. The standard deviation calculations show that for retrofitted buses, the variation around the mean value was much higher than for non-retrofitted buses.

At Oxford Road, the mean NO_X emissions from retrofitted buses was 6g/kg fuel lower than the mean emissions from non-retrofitted Euro V buses. At Eyre Street the mean NO_X emissions from retrofitted buses was 0.2g/kg fuel higher than the mean emissions from non-retrofitted Euro V buses.

NO_X	Retrofitted Euro V	OEM Euro V	OEM Euro VI
Mean (g/kg fuel)	18.8	24.8	1.7
Standard deviation (g/kg fuel)	24.8	12.4	6.7
Number of measurements	412	34	553

Table 3 Manchester Oxford Road 2023 remote sensing campaign statistics.

NO_X	Retrofitted Euro V	OEM Euro V	OEM Euro VI
Mean (g/kg fuel)	34.8	34.6	7.2
Standard deviation (g/kg fuel)	25.6	18.6	8.9
Number of measurements	1018	97	1135

Table 4 Sheffield Eyre Street 2023 remote sensing campaign statistics.

3.4.2 Euro VI comparison

Tables 3 to 6 present a comparison of the emissions from retrofitted Euro V buses against non-retrofitted Euro VI buses. **Mean NO_X emissions from Euro VI buses are consistently lower than those from retrofitted buses**. The emissions from Euro VI buses vary by location; mean emissions were much lower in Manchester than in Sheffield.

NO_X	Retrofitted Euro V	OEM Euro V	OEM Euro VI
Mean (g/kg fuel)	18.0	14.1	1.5
Standard deviation (g/kg fuel)	22.0	10.2	4.3
No. of measurements	172	9	162

Table 5 Manchester Wilmslow Road 2023 remote sensing campaign statistics.

NO_X	Retrofitted Euro V	OEM Euro V	OEM Euro VI
Mean (g/kg fuel)	27.1	33.3	14.9
Standard deviation (g/kg fuel)	16.4	19.4	39.7
No. of measurements	396	10	439

Table 6 Sheffield Barnsley Road 2023 remote sensing campaign statistics.

Euro VI buses contain similar exhaust after-treatment technology as that used in retrofitted SCR systems. However, there are number of differences which mean that in certain conditions, the performance of retrofit technology will inevitably be lower. Principally, in a Euro VI bus, control of the after-treatment technology is integrated into the engine's on-board diagnostics (OBD) system. This enables the temperature of the SCR catalyst to be maintained more effectively. For example, during periods of lower engine load the system can artificially raise the catalyst temperature by increasing the amount of fuel in the engine.

3.5 In-service NO_X reduction

3.5.1 Comparison of telematics data to roadside remote sensing monitoring data

The exploratory data analysis showed good correlation between the roadside remote sensing NO_X emission measurements and the percentage NO_X reduction recorded by telematics systems (Figure 11). High tailpipe NO_X emissions are associated with recorded levels of poor NO_X reduction in the telematics and vice versa.

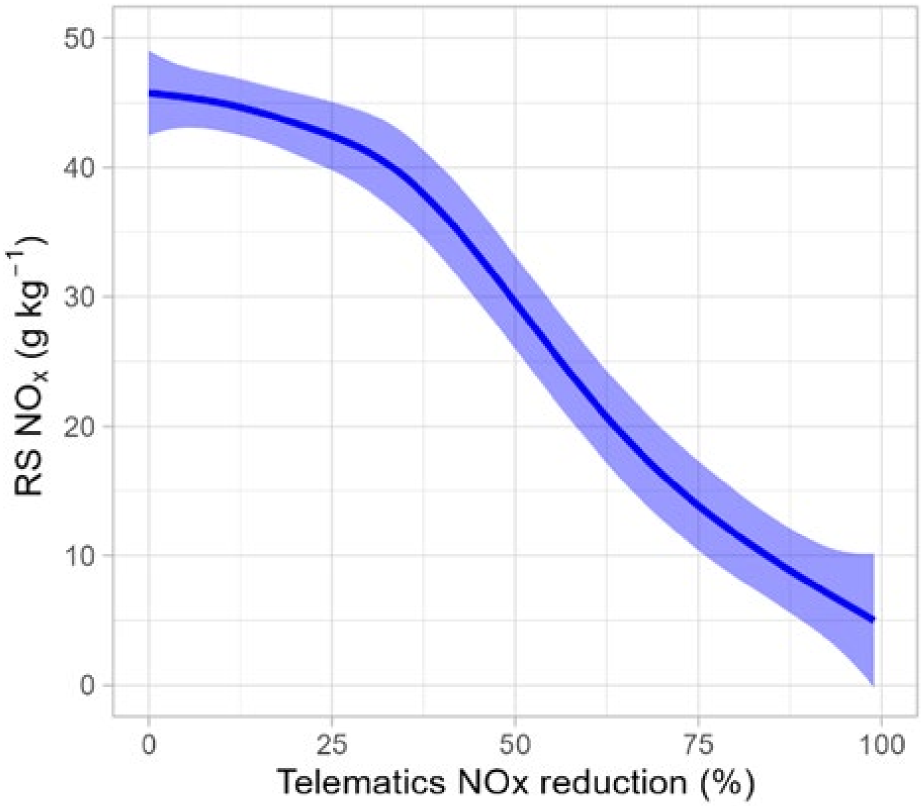


Figure 11 Relationship between observed tailpipe NO_X emissions from remote sensing (y-axis) and telematics percentage NO_X reduction (x-axis) from 1,201 remote sensing measurements.

Analysis also showed that NO_X reduction error codes in telematics data tend to be associated with high remote sensing NO_X emission measurements. **This suggests that gaps in NO_X reduction within the telematics data correspond to higher NO_X emissions which are not captured by the daily averages. Hence average NO_X emissions reported by telematics tend to over-estimate NO_X reductions and under-estimate NO_X emissions.**

It is noteworthy that the two independent estimates of performance, one from the vehicle telematics and the other from roadside remote sensing emission monitoring adhere to expectations and increase confidence in each data set.

3.5.2 NO_X reduction performance of the fleet

SCR retrofit technologies should reduce NO_X between the engine and tailpipe by a daily average of 80%. Matching the roadside emission measurement data from remote sensing to telematics provides an insight into the level of NO_X reduction achieved at the moment the measurement was taken. Figure 12 shows the average 24 hour % NO_X reduction recorded by telematics for 3,548 buses on 12 May 2023, covering a range of bus operators, bus makes and models, cities and SCR retrofit technology suppliers. Only 38% of buses achieved the required 80% NO_X reduction. Figure 13 shows how NO_X emissions measured by remote sensing (y-axis) varies with the % NO_X reduction achieved by the retrofit (x-axis). This shows that at the moment the roadside emission measurements were taken, most buses were not consistently achieving an 80% reduction[10].

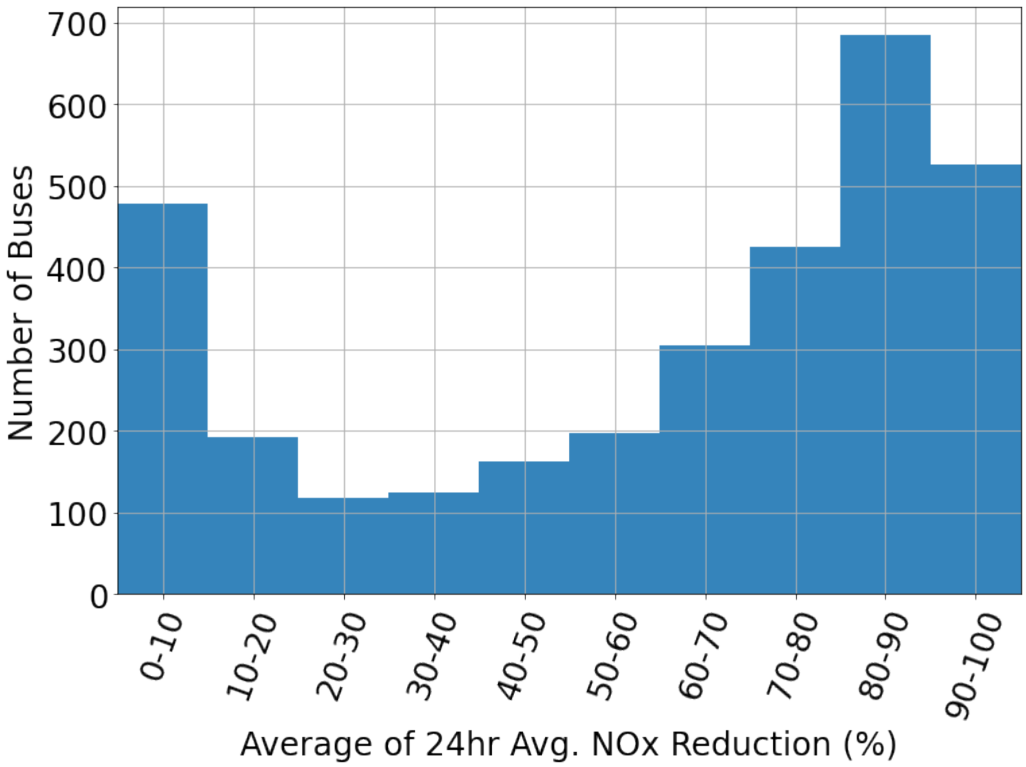


Figure 12 A histogram showing the average 24 hour % NO_X reduction for approximately 3,500 buses where telematics was available for 12 May 2023. Some buses showed negative NO_X reduction which is likely due to faulty NO_X sensors and are therefore not included in this figure. Data was provided by Zemo/EST.

[10] The quality of this data is still being verified, but these levels of reduction broadly agree with those seen in detailed telematics analysed internally by JAQU. Data that is clearly incorrect, such as when the NO_X reduction is reported as negative or greater than 100%, are not included in this figure. These cases are likely due to malfunctioning NO_X sensors.

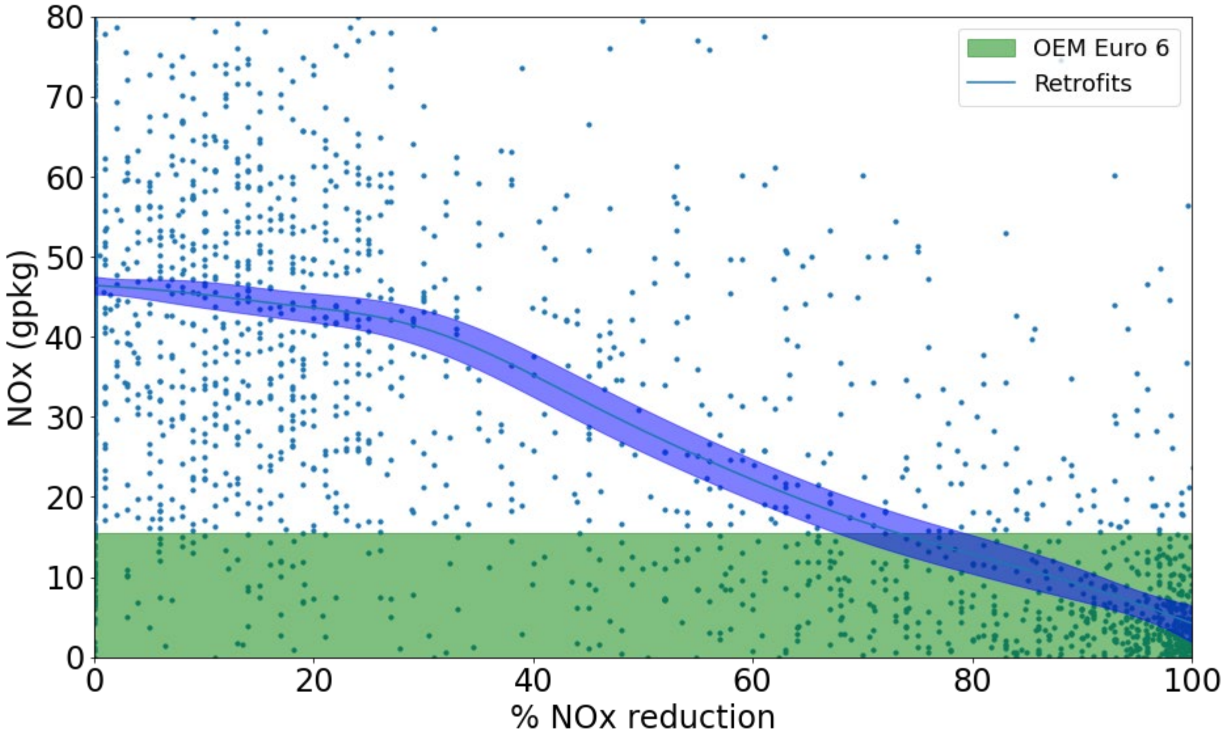


Figure 13 NO_X measured by remote sensing (in grams per kilogram) plotted against the % NO_X reduction measured by telematics data at the point the measurement was taken. Each blue point represents a single measurement. The blue line shows a generalised additive model (GAM) fit to this data, with the blue shaded region showing the 95% confidence interval in this fit. The green shaded region shows the distribution of measured NO_X emissions from Euro VI buses for comparison (covering two standard deviations). This shows that when retrofitted buses are achieving 80% NO_X reduction, they are emitting comparable levels of NO_X to Euro VI buses.

Figure 13 also shows that when buses with retrofitted SCR systems are performing poorly and achieving low NO_X reduction, they emit significantly higher levels of NO_X at the tailpipe than Euro VI buses. When buses with SCR retrofits are performing well and achieving NO_X reduction greater than approximately 75%, NO_X levels are approaching those from OEM Euro VI buses. **This evidence indicates that when a retrofitted SCR system is achieving 80% NO_X reduction this should lead to tailpipe emissions similar to OEM Euro VI buses**. This is in line with the CVRAS in-service 80% daily average reduction requirement.

3.5.3 NO_X emissions during warm up

The daily average NO_X reduction requirement applies only to periods where NO_X sensors are active and reporting, rather than across a whole journey. Emissions will be underestimated where NO_X sensors are faulty and not recording. Emissions will also be underestimated when SCR temperatures are low or during sensor warm up in cold start conditions. NO_X reporting is switched off in these conditions to avoid damage to sensors if moisture forms on heating elements at low temperatures. **Analysis of telematics data shows that the percentage of time the NO_X sensors are not recording varies significantly, but on average is approximately 27% of the day.**

PEMS measurements can be used to assess the scale of underestimation in emissions during NO_X sensor warm up. On comparison of PEMS data to reported telematics for one bus, NO_X sensors did not report until 8 minutes into the cycle. This was despite SCR temperatures rising to 200°C after 6 minutes. Figure 14 shows NO_X emissions summed as journey time progresses (cumulative NO_X). Approximately 50g of NO_X was emitted during those 8 minutes. Later in the cycle, discrepancies reduced significantly. No other sensor outages were observed over the remaining 3 hours.

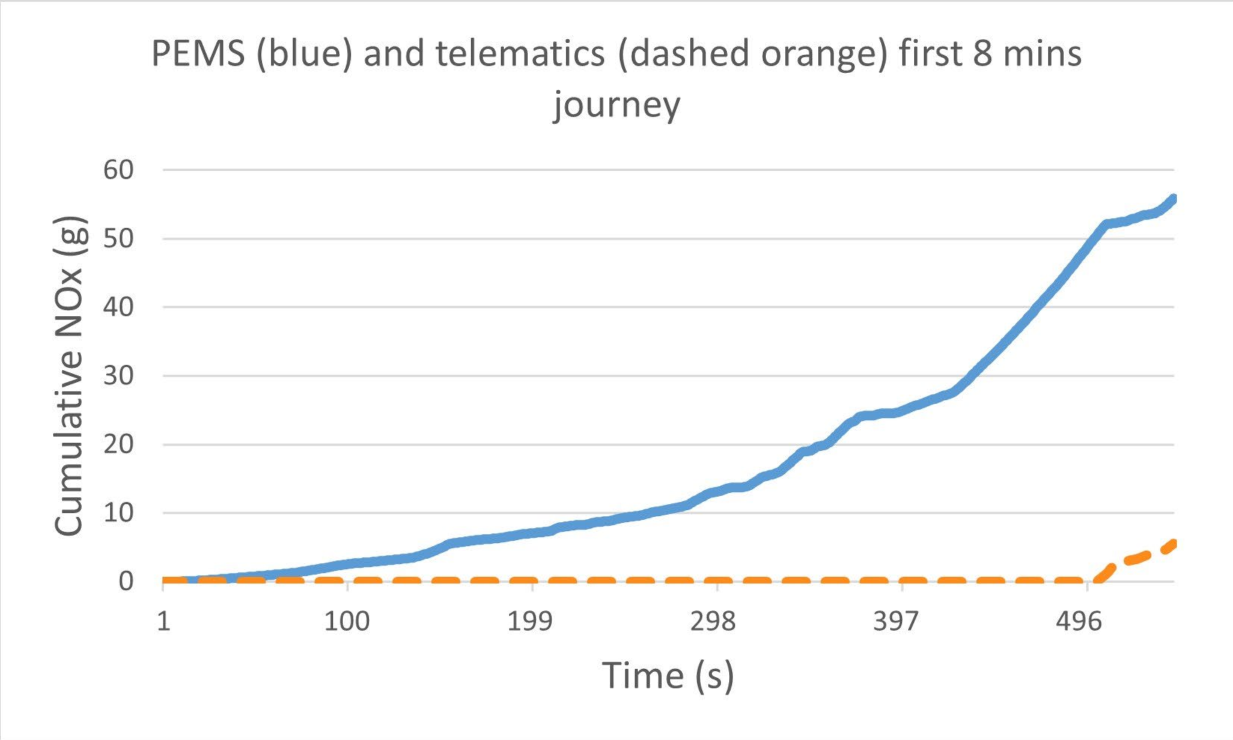


Figure 14 The impact of NO_X sensor warm up on NO_X emissions.

3.5.4 NO_X emissions during idling periods

To understand the underestimation of NO_X during periods of idling and associated low SCR temperatures, analysis of seven PEMS tests on four different buses commissioned by Zemo/EST as part of the ongoing CVRAS monitoring programme was undertaken.

The analysis showed a variation in emissions during the 10-minute extended idling period, but generally emissions were low. All buses showed a significant spike in emissions after the idling period although some variation in NO_X emissions between buses was identified. Further detail can be found in Annex D.

This evidence on the impact of idling is not likely to be fully representative of that incurred by buses moving in heavy traffic in urban centres where idling periods are likely to be shorter but far more frequent. **More evidence is required to assess the impacts of idling in real-world conditions in urban centres.**

4. Factors influencing performance

4.1 Overview

The analysis of remote sensing emission measurement data matched to telematics also reveals that to function effectively the SCR system has two key requirements: a sufficiently high temperature and the correct dosing and good mixing of urea into exhaust gases.

Data from telematics illustrates the importance of these requirements in achieving good NO_X reduction. Figure 15 shows a histogram of the average daily NO_X reduction for 766 days of telematics data for 198 buses recorded in 2022. All buses had been retrofitted with SCR technology from the same supplier. This shows that SCR retrofitted buses can be broadly separated into two groups: those that are achieving over 40% NO_X reduction and those that are not. The days are coloured corresponding to whether the SCR retrofits are reaching the temperatures required for NO_X reduction (defined as having an average SCR temperature over 200°C) and have functioning urea dosing systems (defined as using at least 3.5L of urea over a day and having a pressure difference between the rail and air pressure of >200kPa which indicates effective dosing). Buses that meet these requirements are coloured in green and all others are shown in red.

It is evident that for most SCR retrofits in this sample that are not achieving good NO_X reduction, the reason for this is that they are either not achieving a sufficiently high temperature, not achieving the correct dosing of urea, or both.

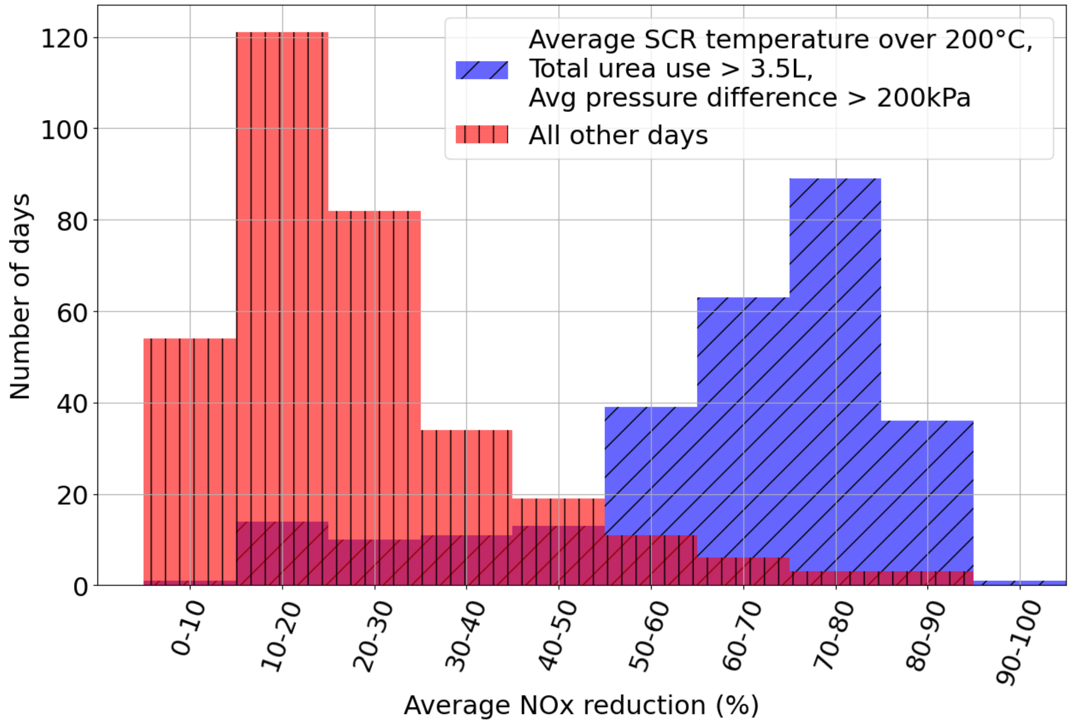


Figure 15 Average daily NO_X reduction for 766 days of telematics data for 198 buses recorded in 2022. Blue with diagonal stripes shows days where the buses are showing evidence of a working urea dosing system and achieving high SCR temperatures, red with vertical stripes shows those that are not. Dark pink with diagonal and vertical stripes is where the two overlap.

Figure 16 shows the interaction of urea use and SCR temperature in a statistical model. This demonstrates that the highest emissions (yellow) occur with low urea use under 0.1 units, and SCR temperatures below 190°C. Low emissions occur at high SCR temperatures and urea use above the threshold of 0.2 (dark blue).

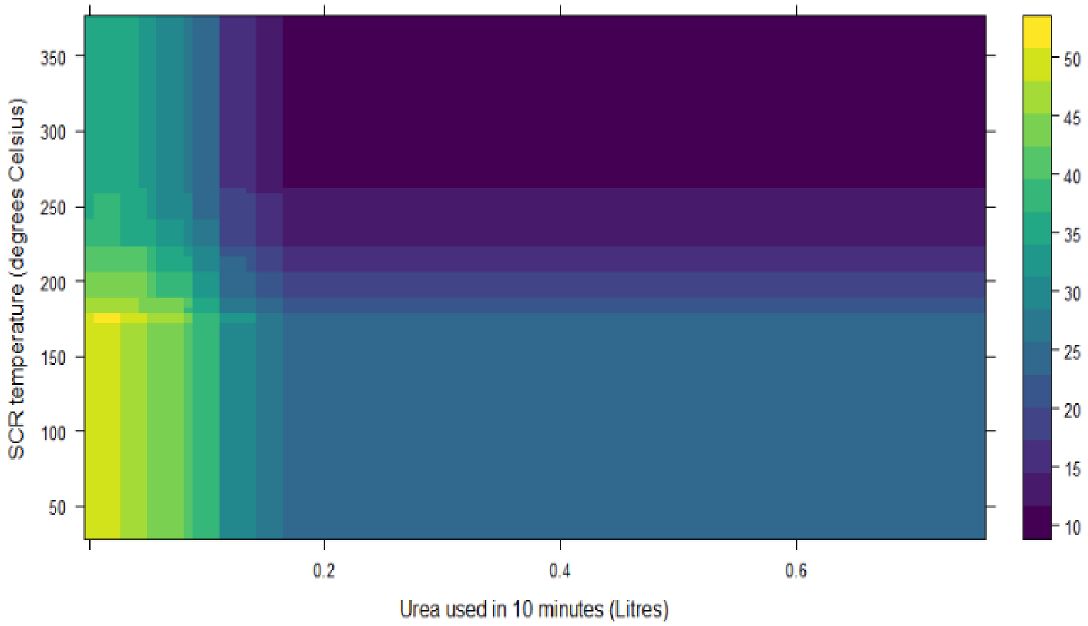


Figure 16 Statistical model showing the dependence of NO_X emissions (in g/km) on SCR temperature and urea consumption in the 10 minutes preceding the measurement.

4.2 Temperature

4.2.1 Impact of SCR temperature on NO_X conversion

Temperature plays a critical role in both the NOx reduction reaction on the SCR catalyst and the urea hydrolysis in an SCR system. Maintaining the right temperature range is essential for achieving efficient NO_X reduction whilst minimising ammonia slip and maintaining the durability of the catalyst.

Figure 17 shows how the variation in NO_X reduction over a real-world drive cycle is influenced by the temperature of the SCR; periods of high NO_X reduction generally correlate with SCR temperatures at the inlet of the catalyst of greater than 200°C.

Temperature is often regarded as satisfactory if a 200°C threshold is met or exceeded for a large proportion of a drive cycle. More ammonia than is instantaneously required to reduce NO_X can be injected and some then stored at lower temperatures (but still above 200°C). This can then provide a limited “buffer” to reduce NO_X during temperatures below 200°C and assist in NO_X reduction during highly transient conditions.

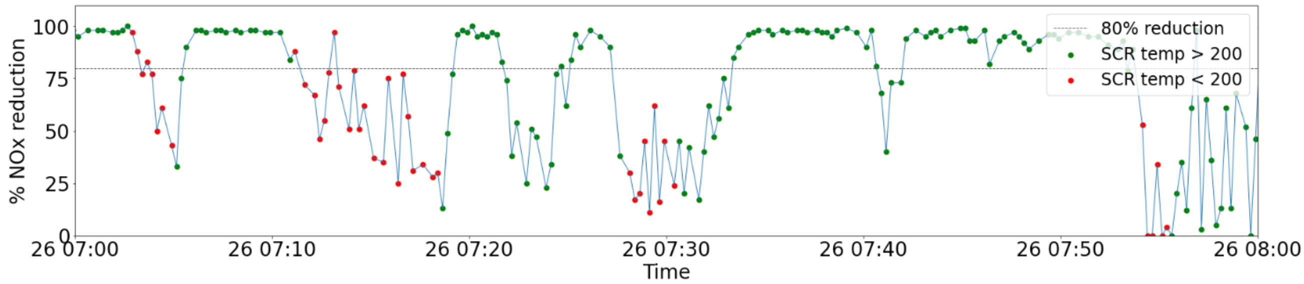


Figure 17 Variation in % NO_X reduction monitored through telematics over one hour of driving for a bus in Sheffield. Green and red points show periods where the SCR temperature is greater or less than 200 degrees respectively.

When the retrofitted SCR system is performing as designed, SCR temperature is the driving factor in determining NO_X reduction. Figure 18 shows how average daily NO_X reduction depends on how much of the drive cycle a bus spends with the SCR over 200°C.

This demonstrates that on average buses only achieve 80% daily NO_X reduction when the SCR is over 200°C for at least 90% of the drive cycle. **Analysis of approximately 1,200 days of telematics data covering around 350 buses with retrofitted SCR systems from the two largest UK suppliers found that 39% of buses spent over 90% of the drive cycle over 200 degrees.**

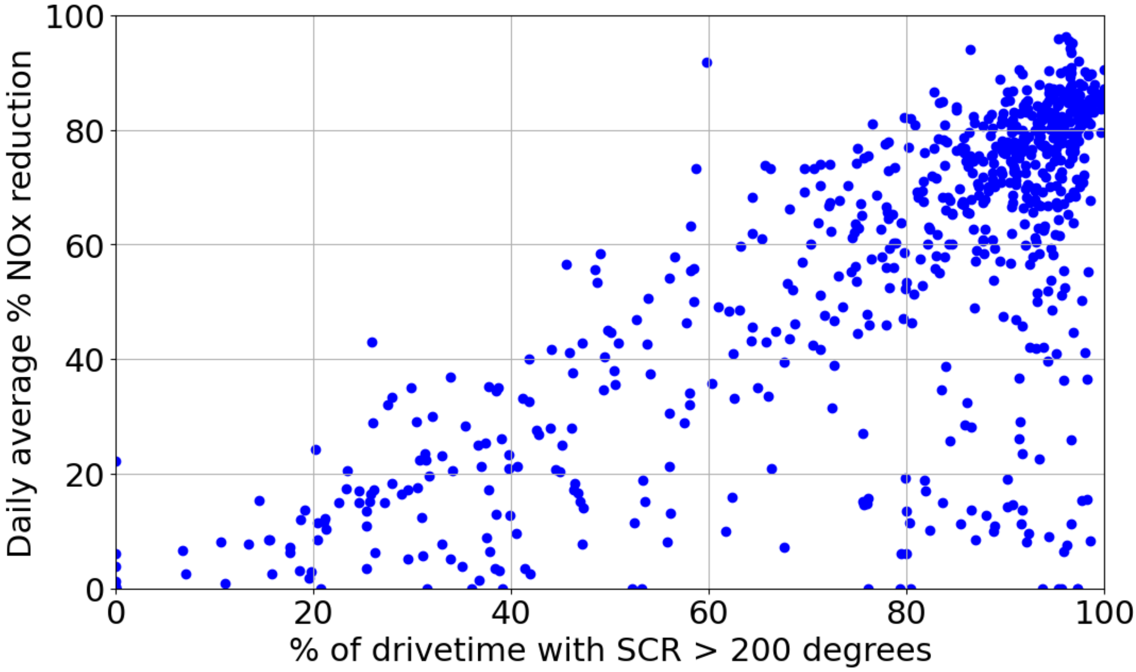


Figure 18 Average % NO_X reduction for each bus depends on the % of the day spent with the SCR over 200°C. 715 days of data from two different retrofit technologies is included. Buses with urea dosing issues have been removed to show the temperature dependence when urea dosing is working as expected.

There appear to be significant differences in SCR temperature between retrofit suppliers. Analysis found that retrofits from one supplier, “Supplier 1”, were spending 90% of the drive-cycle over 200 degrees on only 17% of days, compared to 78% of days for retrofits from a second supplier, “Supplier 2”, as shown in Figure 19.

It is not yet clear why this is the case. External factors such as differences in the routes driven have not been corrected for so could account for some or all of the differences in temperature. Inspection of a small number of buses indicates that Supplier 2 may use insulation jackets around the SCR and may position the SCR higher and closer to the engine which will help to achieve and maintain higher temperatures. However, evidence is very limited, and more work would be needed to fully understand these differences.

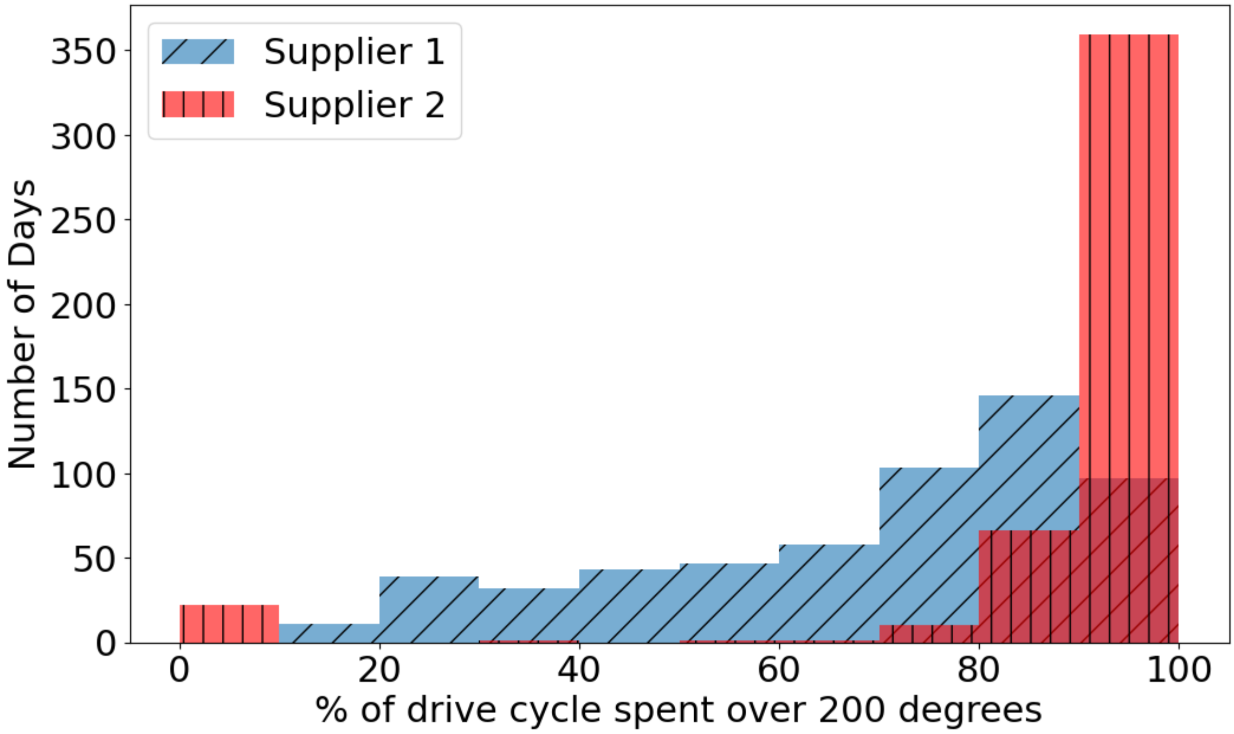


Figure 19 Histogram showing number of days where 90% of the drive-cycle was spent over 200 degrees for two different retrofit suppliers.

4.2.2 Factors influencing SCR temperature

Beyond any influences of insulation or positioning of the SCR in the bus chassis, there are four key factors affecting SCR temperature – ambient temperature, route geography, payload (passenger weight) and idling - as detailed below.

4.2.2.1 Ambient temperature

The NO_X emissions from common buses captured during both remote sensing monitoring campaigns in Sheffield and Manchester in 2022 and 2023 were compared to see if any impact due to changes in ambient temperature could be seen. No significant differences were observed.

Analysis identified a difference in NO_X emissions with respect to ambient temperature for retrofitted buses of varying ages. In two cities, increased temperature affected emissions negatively on newer retrofits, and positively on retrofits older than 2 years. Euro VI buses did not show the same dependency with emissions being well controlled across temperatures.

Emulation testing was conducted on a Euro V bus retrofitted with SCR technology ('Bus 1') at the vehicle testing centre to understand how varying ambient temperatures impacted SCR temperature and performance of the retrofit system. The complete CVRAS test was carried out at both 5°C and 18°C ambient temperatures including the warm-up phase. Figure 20 shows a 14% increase in tailpipe NO_X emissions during the 5°C test. NO_2 emissions do not show a marked difference. Ambient temperatures may have a small influence on the performance of retrofit technology although this observation is from one test only.

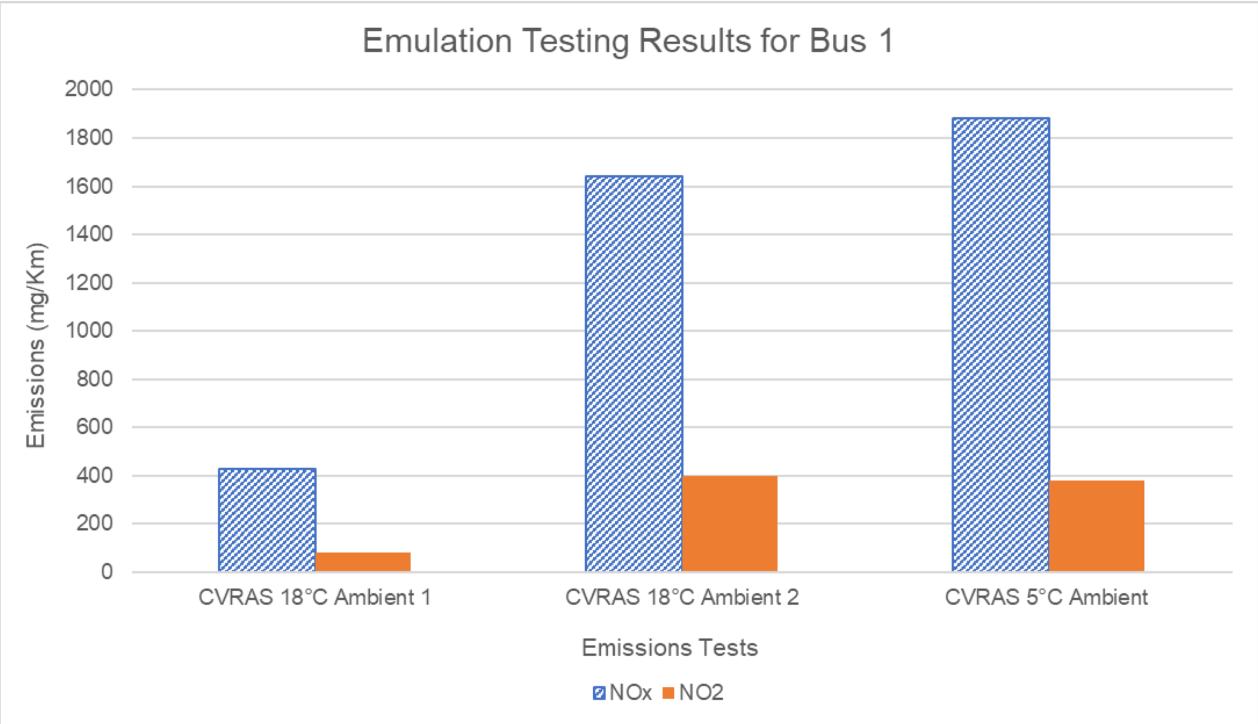


Figure 20 - NO_X and NO_2 emission outputs for CVRAS tests conducted at 18°C and 5°C ambient temperature conditions for one bus.

4.2.2.2 Route geography

Route geography, specifically gradients, can influence SCR temperatures over a real-world drive cycle. Figure 21 shows variations in altitude and SCR temperature over a journey undertaken by another retrofitted Euro V bus ('Bus 5'). As the bus travels uphill and engine load increases, SCR temperatures also increase. Whilst travelling downhill, the driver will be braking (where the engine will still inject fuel, but the load will be minimal) or using engine braking (where fuel is not injected, and the engine and exhaust will be constantly flushed with intake air). Both instances will lead to engine cooling.

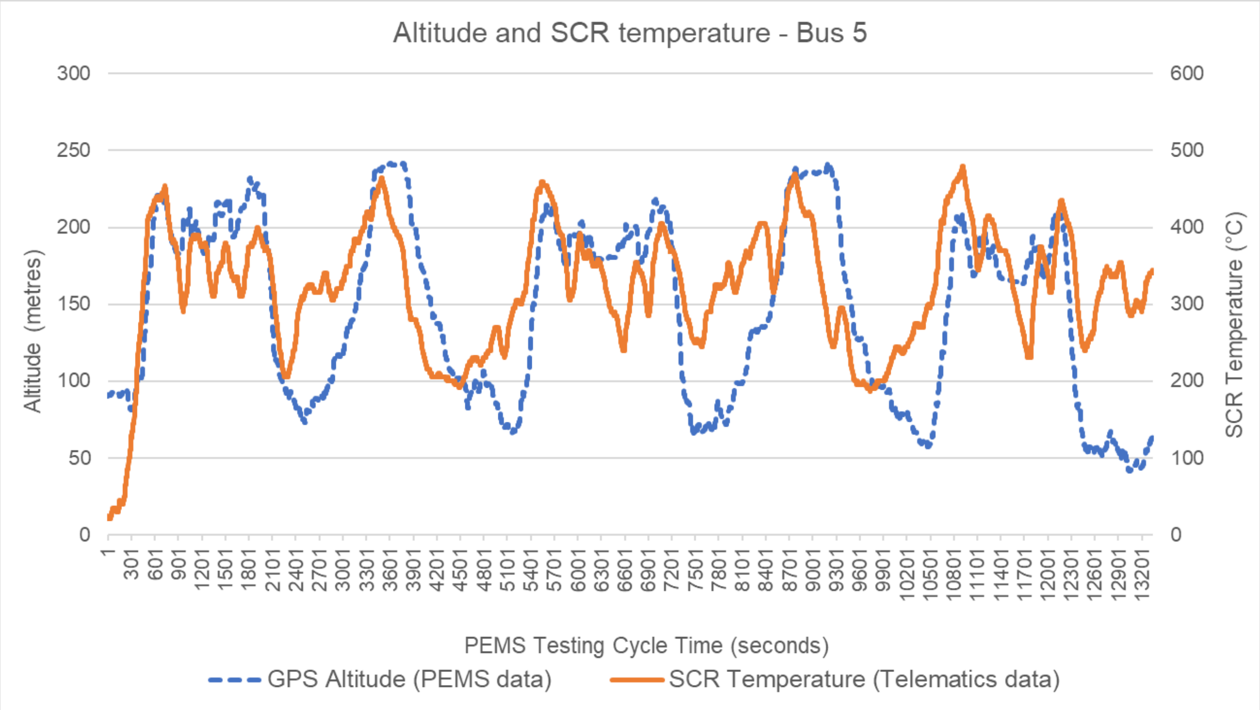


Figure 21 Relationship between SCR temperature (from vehicle telematics) and altitude from real-world PEMS testing conducted on Bus 5 in Sheffield.

The relationship between SCR temperature, NO_x reduction and altitude from the same PEMS test is explored further in Figure 22. The percentage NO_x reduction achieved by the retrofit system varies broadly in line with the recorded SCR temperature across much of the drive cycle. This graph therefore illustrates a potential link between varying topography over a real-world drive cycle, and the percentage NO_x reduction achieved by the retrofit system.

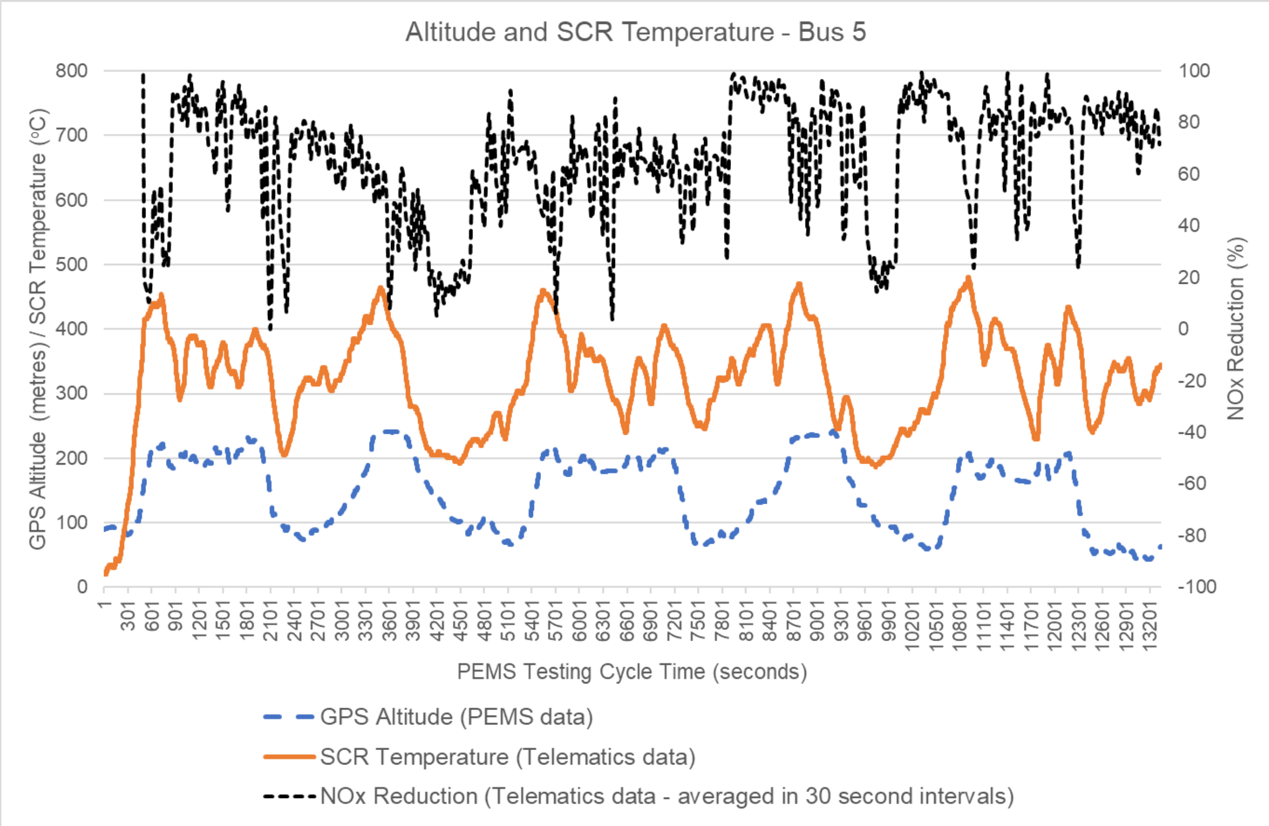


Figure 22 Recorded relationship between SCR temperature, altitude and percentage NO_X reduction recorded during a real-world PEMS test conducted on Bus 5 in Sheffield.

4.2.2.3 Payload (passenger weight)

Figure 23 shows a relationship between SCR temperature and payload from emulation testing on Bus 1. The 90% payload resulted in a higher SCR temperature throughout the CVRAS cycle compared to a 10% payload as engine load increased with weight.

Payloads vary under real-world conditions with buses experiencing variability in passenger loads across routes and at peak and off-peak travel times. Whilst higher SCR temperatures were recorded for Bus 1 during the CVRAS test at 90% payload, NO_X and NO_2 emissions recorded during the CVRAS cycle were also approximately 5% higher, with a similar percentage NO_X reduction noted for the different payloads. Increased vehicle payload increases cycle energy demand; therefore the engine is required to deliver more work done, which in turn typically increases engine-out NO_X emissions. However, this is in part offset by increased SCR efficiency in some parts of the drive cycle due to the extra heating effect, leading to relatively comparable NO_X control over the full cycle.

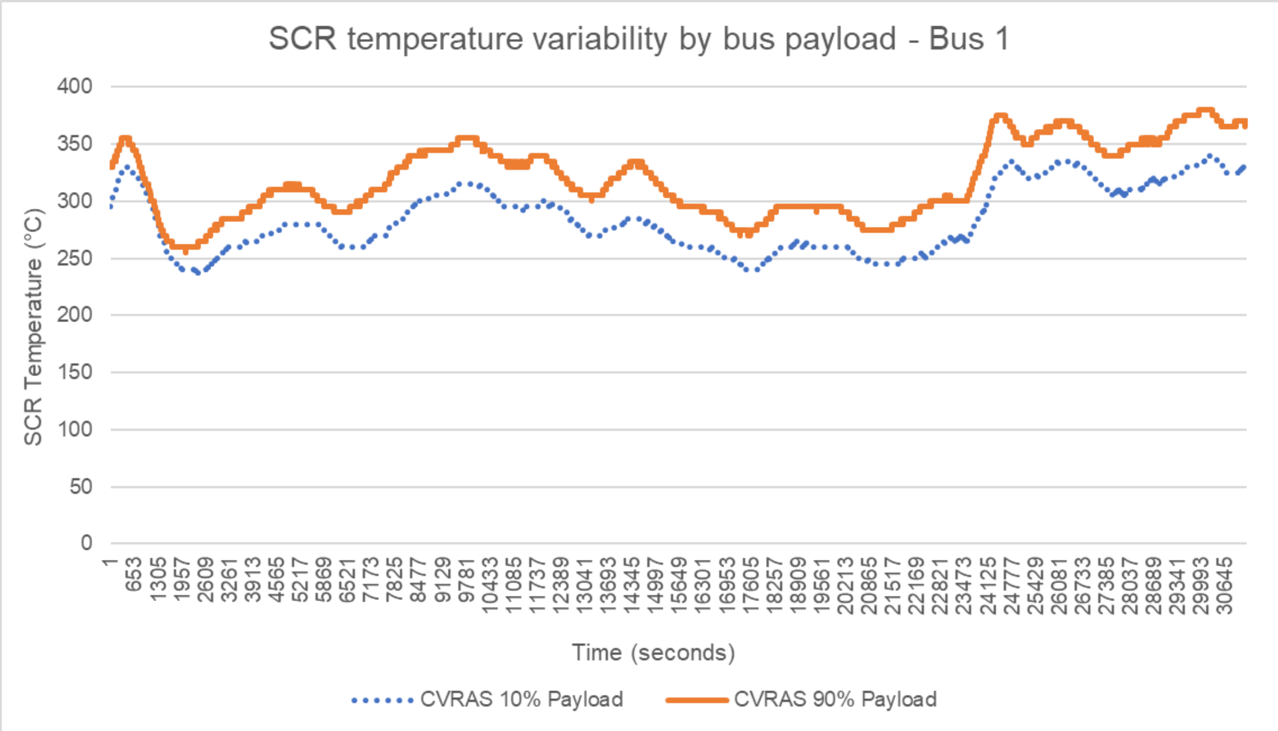


Figure 23 SCR temperature recorded by vehicle telematics for Bus 1 for CVRAS tests completed with 10% and 90% payloads.

4.2.2.4 Idling

As discussed in Section 3.5, idling in heavy traffic lowers internal temperatures. This is demonstrated through analysis of PEMS data for one bus. Data was sorted according to speed; continuous segments of 0km/h occurring for 20s to 188s were treated as representing periods of idling and were deemed suitable for analysis. Twelve idling segments were analysed covering the full range of the data. Whilst considerable variety exists in both the idling and average speed periods, cumulative NOx emissions during idling varied from 0.03 to 1.1g, with a mean of 0.4g for idling periods of 20 to 40s. It should be noted that not all retrofitted buses might behave in this way.

Other variables were influential during idling and could change emissions. A model for one tested bus was constructed to include these variables. Several variables were significant, but the greatest influence was SCR temperature. Figure 24 shows a non-linear relationship, with predicted high NO_X concentrations occurring at low SCR temperatures, then reducing rapidly as SCR temperature increases. At around 230°C concentrations start to level off.

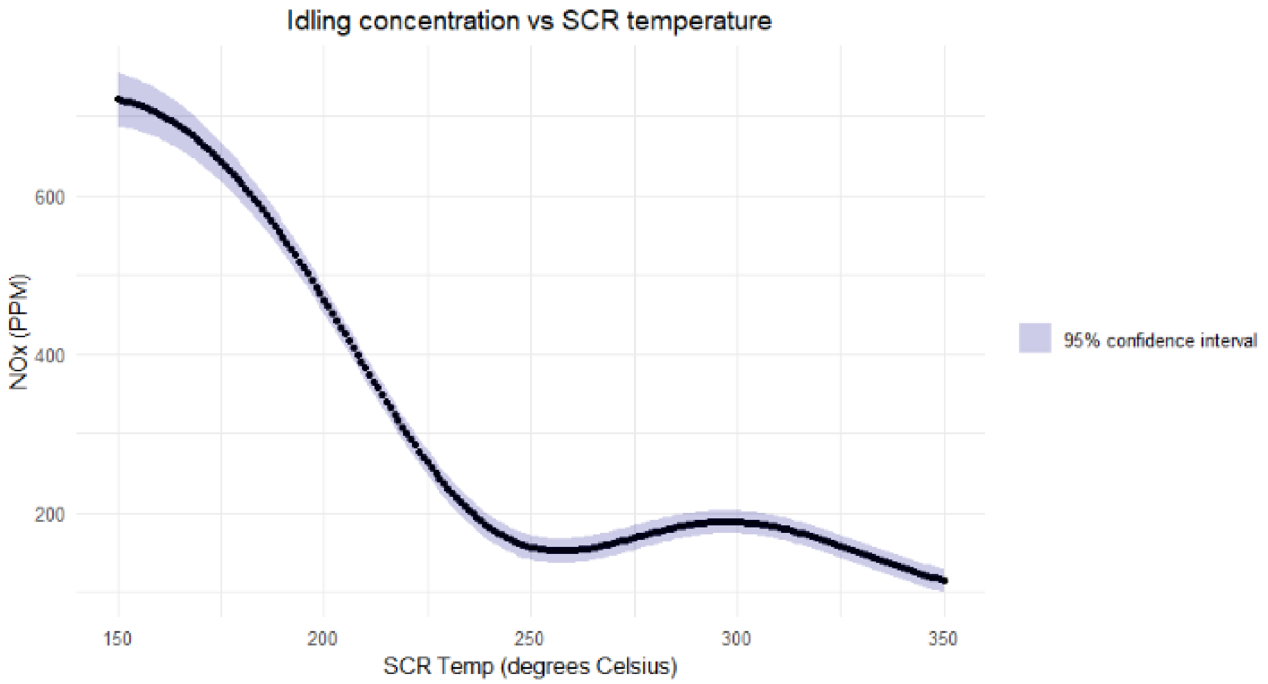


Figure 24 Impact of SCR temperature on NO_X concentrations at idle. Note that parts per million (ppm) NO_X is used in this figure.

The buses tested contained retrofitted SCR systems from two suppliers. The human factors research included a visit to a bus depot which used a third supplier. This supplier had provided retrofit systems with an additional feature – a separate heating element known as a "kettle" – which supports the hydrolysis of urea into ammonia at low temperatures. Engineers at the depot reported fewer problems with engine temperatures and high confidence in the technology performing as expected. There is no telematics data for any buses in the fleets to confirm this. Evidencing any improvements in performance from the application of the heating element would require further work.

4.2.3 Conclusions on temperature

Temperature is an important factor within the retrofit system, playing a critical role in both the chemical reactions within the SCR system and system durability. Temperature, and therefore performance of the retrofitted SCR system, can be influenced by a multitude of factors such as ambient temperature, route geography and driving conditions; with influences resulting in the production of hotter system temperatures often contributing to better system performance.

Whilst optimum operating temperatures of the SCR system can theoretically be encouraged with additional thermal management techniques such as insulation or heating elements, or improved driving techniques, temperature variability is a natural process often driven by seasonal variations and route topography. Therefore, **whilst there is potential for periods of sub-optimum SCR temperature to be reduced in existing systems, it is unlikely that this system limitation can be removed entirely.**

4.3 The retrofit system

The retrofit system as set out here covers the urea dosing system and the SCR catalyst. It also includes influences from upstream devices. Factors affecting performance within each sub-system are assessed below.

Fuel samples were taken from the buses tested at the vehicle test centre to explore the impact of fuel type on the performance of the retrofit system. The results of the fuel sample analysis were not available in time to be included in this report.

4.3.1 Urea dosing system

Urea serves as a source of ammonia which is essential for the catalytic reduction of NO_X to nitrogen and water. Insufficient urea will impact on the level of NO_X reduction achieved by an SCR system.

Statistical modelling of telematics data for 185 retrofitted buses across several cities revealed that urea use is a highly significant predictor of NO_X emissions as measured in the 2022 remote sensing campaign. Figure 25 below shows this non-linear relationship with a 95% confidence interval in blue. High emissions are characterised by low urea use, and as urea use increases, emissions reduce substantially.

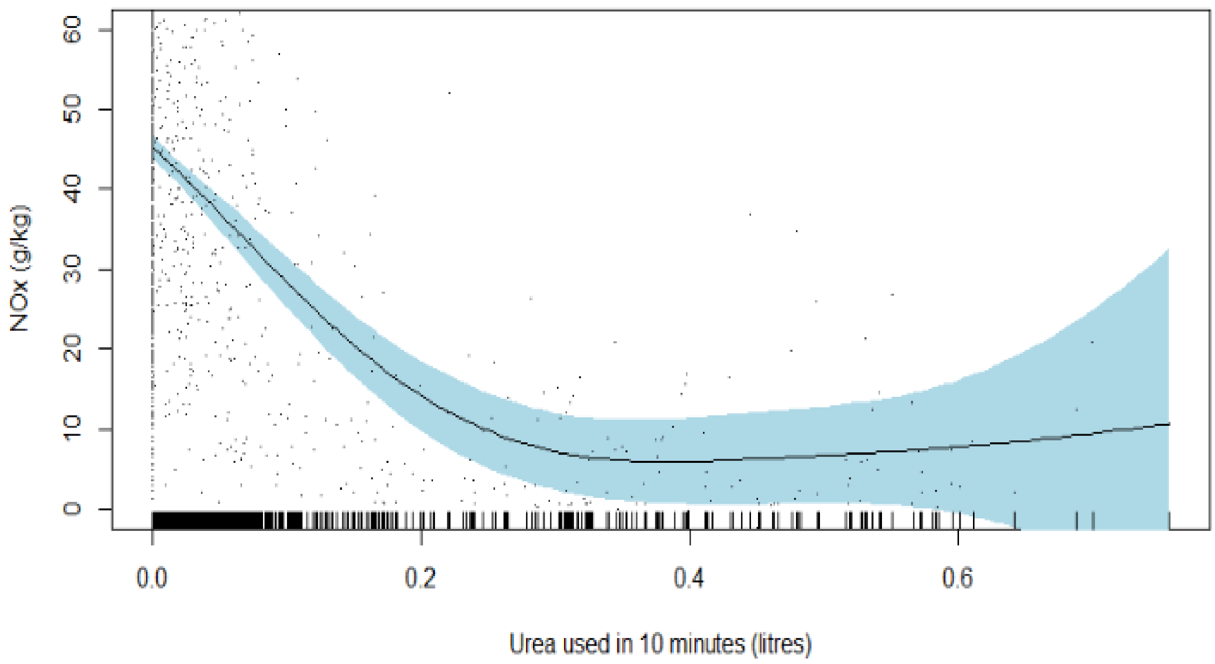


Figure 25 Relationship between urea usage and NO_X emissions.

The retrofit system is designed so that when SCR temperatures are low, urea is not injected to avoid ammonia slip and crystallisation. This analysis has sought to separate cases where urea use is low purely due to low SCR temperature from cases where the urea dosing system is not functioning as expected.

Telematics data provides an insight into how often issues relating to urea dosing occur (though the level of detail monitored and reported by telematics varies across suppliers). 750 days of telematics data was assessed for 198 different buses retrofitted with SCR systems from one supplier. This data included information on both urea consumption and pressure in the urea dosing system. It is estimated that urea dosing issues occurred on 48% of the days where data was available[11]. Using 460 days of telematics data from another supplier (which includes information on urea consumption but not pressure) urea dosing issues occurred on 18% of the available days of data.

Where urea levels are sufficient, proper dosing of urea is crucial for the optimal functioning of the SCR system. Issues with levels of urea or its dosing are caused by one or more problems with components within the urea dosing system. Further details on the dosing system can be found in Annex E.

4.3.2 Sensors

Analysis of approximately 750 days of telematics data from a single supplier found that on 15% of days no NO_X reduction information was recorded, likely indicating a broken NO_X sensor.

One of the buses ('Bus 1') that was tested at the vehicle testing centre reported through telematics low urea usage and NO_X reduction. Poor NO_X reduction was confirmed by running the CVRAS test procedure on a chassis dynamometer. The causes of this were investigated through root cause analysis. A diagnostic scan for fault codes showed two codes related to NO_X sensors and one to intermittent SCR temperatures. Analysis of NO_X sensors revealed that the engine out NO_X sensor was consistently reading lower than the tailpipe NO_X sensor and an out of bounds code was recorded for many segments throughout the testing. This indicated a faulty sensor. It was discussed that front NO_X sensors are commonly faulty, becoming contaminated due to their proximity to the engine.

NO_X sensors at the engine outlet will determine the ammonia mass required and thus the mass of urea to be dosed. Sensors at the tailpipe can be used to refine the dosing but are not essential for reactive NO_X control. This dynamic control ensures that the right amount of urea is injected to achieve effective NO_X reduction while minimising ammonia slip. **The effective operation of these sensors is therefore critical to retrofit performance; faulty sensors typically lead to under dosing.** NO_X sensors are sensitive instruments and can malfunction or degrade on exposure to high temperatures or contamination. A replacement engine NO_X sensor on Bus 1 was fitted for a further CVRAS test and fault codes cleared. A 77% NO_X reduction was seen for the second CVRAS test compared to the first.

[11] These are the percentages of days where one or more of the following are true: 1) There is very low (i.e. zero or close to zero) total urea consumption throughout the day; 2) The average difference between the rail and air pressure in the dosing system is below 200kPa throughout the day (which will affect the quality of the urea dosing spray); 3) The urea consumption is low even though the bus spends a large fraction of time at high temperature.

4.3.3 AdBlue tank

SCR retrofit systems for buses should use AdBlue that is specified by ISO standard 22241-1. This specifies that the aqueous urea solution contains a 32.5% urea content. AdBlue samples from the buses tested at the vehicle testing centre and for in-service PEMS recorded urea content percentages from 32.4% to 32.8%. No issues have been identified through the human factors research regarding the refilling of AdBlue tanks; depots report the filling of tanks as part of well-established routines. However, the awareness of maintenance staff of the need to regularly replace filters on AdBlue tanks is low. Filters on tanks remove particles, dirt and crystallised urea to help preserve the SCR system and maintain pressure. One depot had developed an efficient way through trial and error to flush crystallised AdBlue (although quick fixes can have later problematic consequences).

During testing at the test centre, Bus 1 reported low rail pressure (around 90kPa; a well performing system would have a pressure above 350kPa). Rail pressure indicates the ability of the system to provide suitable injection. The cause of low rail pressure was investigated and the line between the AdBlue pump and AdBlue tank disconnected with a temporary tank installed to establish whether the pump or tank (or both) were faulty. Pressure and flow were restored. A filter inside the tank was suspected to be blocked and the cause of the low rail pressure. This is likely to have affected other components downstream. At this point a further CVRAS test took place. NO_X was reduced by 79% from the baseline test.

As SCR systems are already present in most Euro V buses, AdBlue tanks and filters are often retained. Engineers at the testing centre confirmed that on many buses parts were re-used to save costs and time. The reuse of these components may quicken degradation of the SCR system. Reuse can also complicate maintenance responsibilities – the ownership of a fault with the AdBlue tank on a bus tested at the vehicle testing centre could not be agreed. The extent of reuse of other components in the urea dosing system is unclear. For buses originally fitted with Exhaust Gas Recirculation (EGR) instead of SCR systems, a new tank and urea injection system is required as part of the retrofit.

The replacement of components during proactive and reactive maintenance has been commented on by bus operators who report the need to source components through third parties rather than directly from retrofit suppliers as this route is faster and at lower cost. The implications of these findings on SCR retrofit performance are unclear.

4.3.4 The dosing manifold

In physical testing further maintenance was performed on Bus 1 as it was felt that NO_X emissions could be reduced further still. The compressor air filter was replaced as this was blocked and can affect air pressure. The urea pump was replaced as the filter blockage may have resulted in excessive wear to the pump, and the mixing manifold contained some evidence of blockage so was replaced to ensure full system pressure. The SCR injector was also deemed partially blocked so replaced. The injector tip on the retrofit system of a second bus that underwent root cause analysis (‘Bus 2’) was also found to be partially blocked with urea crystals.

On a subsequent road test of Bus 1, SCR temperatures of 300°C were observed in under 10 minutes and NO_X reduction was greater than 90% compared to the baseline. After several more CVRAS tests, average NO_X was 1.5g/km (a range of 0.45 to 2.4g/km). A 34km real-world test cycle was also undertaken. NO_X emissions were 3g/km. This improvement does appear to have negatively impacted ammonia and particle numbers in at least some tests, but particle number average may be a more useful metric after excluding outlier runs relating to regeneration.

4.3.5 SCR catalyst

To function effectively, an SCR system requires a suitably specified and functioning SCR catalyst. Differences in chemicals used to coat the catalyst substrate, and the nature of the substrate itself (including precious metal content), may have an impact on the level of NO_X conversion. Similarly, any changes to the catalyst formation (such as the content of precious metals or catalyst dimensions) used in SCR systems after certification could impact conversion. No evidence has been obtained on these factors.

From conversations with retrofit suppliers, JAQU have been informed that the average lifetime of a SCR catalyst is five to seven years, with degradation of the SCR taking place over time. This is a known limitation of the system.

4.3.6 Retrofit control system

Strategies used by retrofit suppliers influence urea dosing. These strategies require investigation to determine whether changes could improve SCR efficiency. For example, early findings from the testing at the vehicle testing centre suggest that NO_X sensor release strategies may take longer than necessary. If NO_X sensors are not switched on, then urea dosing is limited because NO_X sensors are used in the control of urea dosing. This will increase periods of SCR operation where NO_X emissions are not reported, and higher emissions are likely.

Increased tailpipe NO_X emissions were also reported across the duration of a CVRAS test on Bus 1 which excluded a warm-up phase, in comparison to an equivalent test that ran with a warm-up phase. Whilst SCR temperatures in both tests were comparable after around 4 minutes, the urea rail pressure was reduced for the cold test which reduced the urea dosing quantity and NO_X reduction throughout. The supplier confirmed that the dosing strategy implemented does not include pressure compensation, therefore lower urea dosing quantity was expected for the cold test. Greater detail is required on the overall urea dosing strategy, including how rail pressure set points are defined and whether dosing control logics could include a pressure compensation. This may also impact on emissions of ammonia.

Other testing carried out on Bus 1 included simulating 30 minutes of a bus route in Sheffield on a chassis dynamometer. This route was driven over two tests; the first was started after five minutes of idling, whilst the second started approximately 30 minutes after the completion of the first test. Despite the same boundary conditions, the first test delivered approximately double the NO_X of the second. This was investigated and found to be due to the fact that the urea dosing was initiated almost immediately in the second test, however for the first test it didn't occur until approximately 5 minutes into the test, by which point 68% of the total NO_X had already been formed.

4.3.7 Upstream devices

4.3.7.1 Diesel particulate filter

Testing and inspections at the vehicle test centre identified that Bus 2 had high NO_X emissions (9.6g/km) and low NO_X reduction. Engine out smoke tests were completed, with the mean result exceeding the CVRAS limit. High particulate emissions were recorded during the initial CVRAS test, with soot present in the SCR system. Telematics data showed that the retrofit had recently been affected by a thermal event which caused NO_X reduction to decline very rapidly. This may have been related to a problem with the Diesel Particulate Filter (DPF) as failure of the DPF can send both soot and ash downstream to the SCR catalyst leading to blocking of the active sites and deactivation. This failure could have come from sustained low temperature operation and/or poor maintenance where oil collects on the soot which ignites leading to high localised temperatures and melting of the ceramic substrate.

The retrofit engineer who attended Bus 2 noted that DPFs are removable and can be cleaned through a process of baking to 600°C. However, through conversations with retrofit suppliers, it was noted that responsibility for the maintenance of the DPF can differ between the maintenance packages purchased by bus operators, with different cleaning processes used which may impact DPF performance and longevity.

4.3.6.2 Diesel oxidation catalyst

Diesel oxidation catalysts which optimise NO conversion to NO_2 to enable passive regeneration of soot on the DPF and facilitate a fast SCR reaction, can also be affected by faults with the engine operation or thermally damaged from the ignition of accumulated soot. This will lead to less efficient SCR reactions and lower NO_X reduction.

4.3.8 Conclusions on the retrofit system

Precise dosing of the right quantity of urea and good mixing of urea into exhaust gases is required for optimum NO_X reduction. This relies of the functioning of several key components within the retrofit system. Filters, on a number of components delivering urea to the exhaust gases, can become blocked if not serviced regularly. NO_X sensors also require frequent servicing. The reuse of components from old SCR systems may quicken the degradation of the system. DPFs are also prone to blockage with soot if soot oxidation and removal (regeneration) does not happen in normal use (if regeneration is used).

The CVRAS technical requirements include specific emissions durability limits (age and distance driven), which aim to ensure emissions performance is upheld for the useful life of the retrofit system. More evidence is needed on how retrofitted SCR systems degrade and whether they are still capable of meeting CVRAS emissions requirements after several years in service.

The control strategies implemented by retrofit suppliers, such as urea dosing control and NO_X sensor protection, are influential in robust NO_X reduction. Information in this area is currently limited, so further investigation may be needed. The telematics data on rail and air pressure were useful in identifying the sub systems where faulty components in Bus 1 may be. The work revealed that **it was possible to reduce NO_X emissions very substantially when these components were replaced. Identifying and diagnosing faults required time and expertise from the retrofit supplier. Yet once identified, the fixes were not complex.** Whilst good NO_X reduction was achieved, it may be more difficult to replicate this process in a bus depot on many buses showing poor NO_X reduction. The longevity of these repairs is also unknown.

4.4 Base vehicle

4.4.1 Condition of the base vehicle

In statistical modelling of the 2023 remote sensing dataset, age of the base vehicle did not have a strong correlation with NO_X emissions.

During the physical testing, Bus 2 failed a smoke test by a very large margin on arrival at the vehicle test centre. The engine of Bus 2 was in 'derate' status – the power or speed had been limited to avoid substantial damage. This implied that there were underlying issues with the base vehicle (and upstream devices) that should be investigated and that these were likely to be negatively impacting the SCR retrofit system. These issues were not reported when the bus was assessed against the exclusion criteria used to select a sample of buses for testing.

The condition of buses prior to installation is a point of concern for retrofit suppliers. Before installation, pre-fitment inspections should ensure that vehicles are ready for fitment. Inspections include a smoke test of tailpipe exhaust gases to determine engine condition. There can be a lack of clarity on the findings from these inspections with potential impacts on the warranty of the installed system. Installations can occur on buses in unfit conditions, on the agreement that issues are addressed before warranties become valid. More details on this issue are provided in Section 4.6.

4.4.2 SCR system integration with the base vehicle

Limited evidence has been obtained on how retrofit installations vary between buses and any associated impacts on NO_X reduction. Retrofit systems are designed to be fitted within the available chassis space of a bus with the system itself customised to match the bus model. The extent of customisation of features such as the size of the SCR catalyst is unclear although this is intimately related to the engine size and exhaust flow so should be a fundamental part of the system specification.

Installations are generally overseen by an employee of a retrofit supplier but with subcontractors carrying out most of the work.

The human factors research highlighted some suggestions that installations undertaken by subcontractors may not be as reliable as those installed by retrofit suppliers directly. Retrofit systems are tested upon installation though not always under the conditions that are experienced in the routes that buses will serve.

A bus's base engine control unit is not adjusted when a retrofit system is installed. Due to limitations in accessing this, there are reduced opportunities to exploit combustion-based thermal management strategies to promote SCR capability, as are often implemented on OEM developed Euro VI applications. Some engineers in bus depots have reported negative interferences with the engine control unit by retrofit systems potentially due to installation errors.

4.4.3 Conclusion on the base vehicle

The effective operation of an SCR system can be influenced by the condition of the DPF and DOC (which the DPF relies on) and the base engine of a bus, particularly in certain sub-optimal conditions. It is suspected that the quality of installation of the SCR system is also influential although greater evidence would be required to understand how variations in installation can impact performance.

4.5 Summary of technical factors

Figure 26 summarises the evidence described in the sections above. It shows the key technical factors that can impact SCR performance and their associated causal factors. It is often a combination of factors that lead to poor SCR performance, particularly those that drive low exhaust temperatures and poor urea dosing.

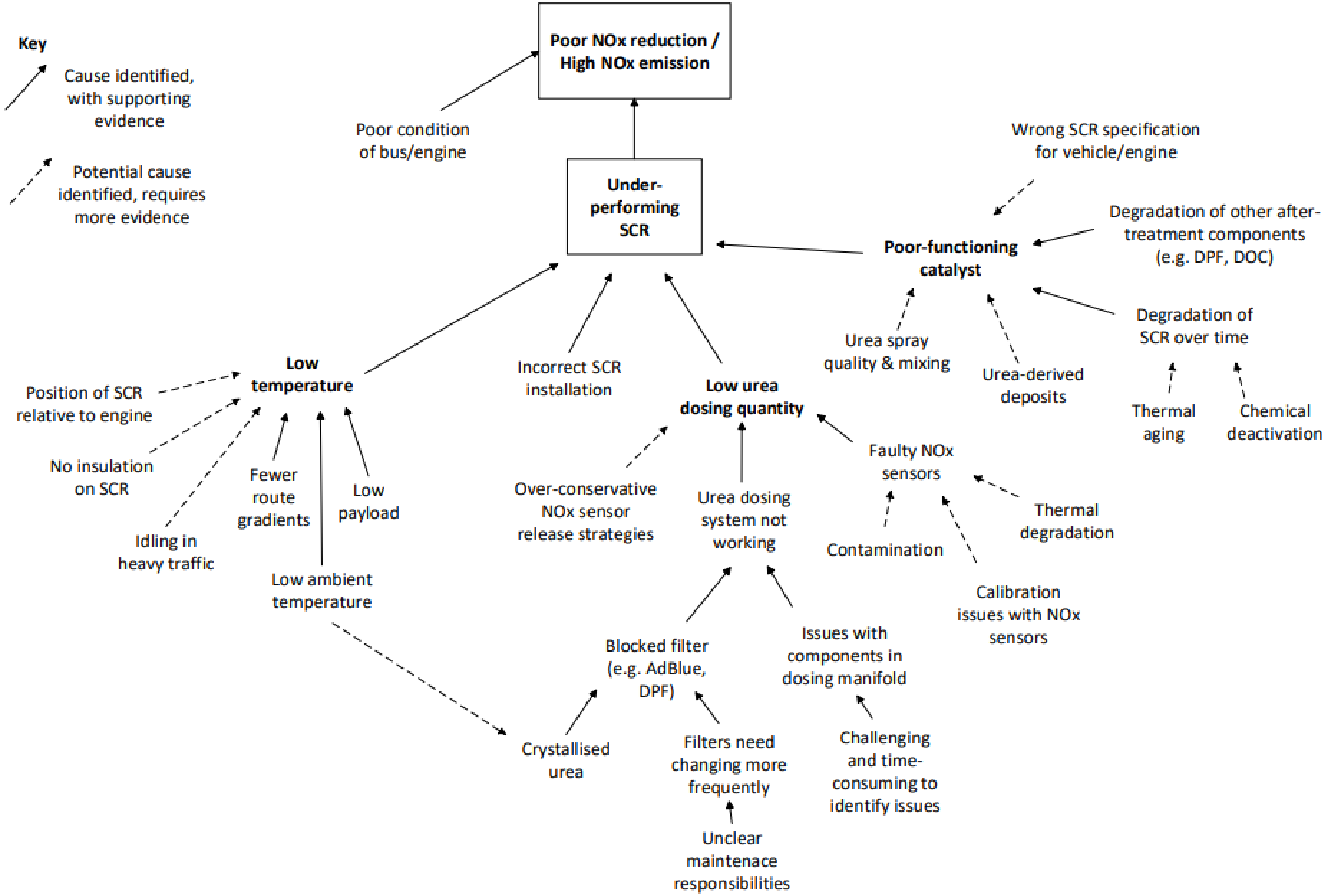


Figure 26 A summary of the technical factors impacting SCR performance

4.6 Human Influences

Qualitative evidence collected through stakeholder interviews and from observations at bus depots, identified a range of emerging human factors and wider contextual findings that may help to explain variations in SCR retrofit performance. Findings are integrated into Section 4 above where they specifically relate to technical factors. However, there are a range of other findings that underpin the wider evidence base. These are detailed here.

4.6.1 Wider Context

The decision by bus operators to retrofit buses is strongly influenced by the need to remain commercially viable in Clean Air Zones where buses must meet Euro VI emissions standards to travel without charge. Operators face continued pressure to maintain services and revenue; there is often little capacity to take buses out of service. Retrofit funding includes some maintenance contingency funding, but this generally does not make up the increased cost of servicing and maintaining retrofit systems through their lifetimes, particularly where maintenance issues are more frequent than expected. The cost of AdBlue has increased significantly in recent years.

Labour market conditions are currently extremely tight for bus drivers and experienced engineers. Senior engineers report that industry-wide training has become more theoretical and less experiential, leading to less confident and experienced newly qualified staff. Retrofit suppliers face challenges in retaining experienced staff. These constraints and financial pressures exacerbate the range of human factors influencing performance of retrofit technology.

There is also a view in the industry that retrofit systems are an “imperfect stopgap” - a bridge to full electrification or other cleaner power sources. **This limits the market for suppliers and reduces incentives for long-term investment in maintaining retrofit systems and for young engineers to specialise in the technology.**

4.6.2 Maintenance and warranties

Maintenance training for depot staff is generally included in contracts with retrofit suppliers but this training reportedly varies significantly in quality. Training may not include information about how to use and interpret diagnostic software unless operators know specifically to request this. Even if available to the depot maintenance team, the outputs from diagnostic software may not cover most faults meaning that only some can be addressed in-house, and others will require input from the retrofit supplier to resolve.

Warranty contracts for repairs vary significantly between bus operators with those that are more cash-constrained reporting an inability to afford full warranty agreements. There are significant variations in the lengths of agreements and which elements of the retrofit system they cover. Bus operators must negotiate contracts on a case-by-case basis, and some are unaware of the full breakdown of options that are available. The uptake and use of warranties also varies by the level of knowledge within a bus depot of retrofit systems and capacity for repairs; there is an evident proactive-reactive spectrum which is driven by finances, age of the fleet and size of the area covered by a depot. There is significant variation across depots in levels of ongoing, proactive maintenance.

Where warranties do exist, retrofit suppliers can have a shortage of capacity to send staff to diagnose and repair faults, so agreements can be hard to enforce. There have been disputes between operators, retrofit suppliers and in some cases, engine manufacturers, over which party is liable for faults and whether the cost of a repair is covered by an operator's warranty. Buses may be a dwindling market for retrofit suppliers versus other interests with higher growth potential, meaning that priorities may shift elsewhere. Many of the engineers used by the retrofit suppliers are subcontractors who may have less experience of SCR technology.

Hence where possible, depot maintenance teams have adapted to reduce how often they need to call on retrofit suppliers. Operators report the need to source replacement parts through third parties rather than directly from the retrofit supplier, as third parties can provide parts more quickly and at a lower cost. Staff in depots describe building experience and familiarity with retrofit systems to try to reduce how much time faults take to diagnose and repair. In many cases, the 'tricks' depots have learned themselves rather than through training are an important part of this. There is scope for greater knowledge sharing between depots so that the value of this experience is not lost if retrofitted buses are sent elsewhere when depots receive upgraded vehicles. This is important given the consistent reporting by bus operators of retrofit systems as being complex and challenging to maintain.

4.6.3 Use of telematics

Telematics are a practical tool to monitor performance of retrofit systems. They can give a good enough indication of performance to enable the identification of poorly performing vehicles. A bus tested at a vehicle testing centre was observed to have a low rail pressure from telematics data, which indicated a problem with the urea dosing system that required investigation. **This demonstrated the potential to use telematics to remotely identify sub-systems that require attention to control emissions.**

However, a consistent finding is the sense that telematics are a wasted opportunity as they are not being used effectively. Bus operators do not always know that this service is available to include in agreements with retrofit suppliers, and these telematics services are sometimes not proactively offered. Those who are signed-up to a service receive data directly from retrofit suppliers onto dashboards after the data has been processed. Operators report this data can be hard to interpret and use to diagnose specific faults. This limited use also extends to sharing data with local authorities; there is no mechanism to do this, and so local authorities may be unaware of the performance of retrofitted buses running on their roads which reduces the incentive for urgent repairs of faulty retrofit systems.

4.6.4 Summary of human influences

The landscape within which retrofitted buses are operating is complex. There are multiple actors facing competing challenges and with differing motivations. There is no single point of intervention which would improve SCR performance, although the difficulty in maintaining retrofit systems has been a recurring theme. There is a clear shortfall in the capacity and technical knowledge to do so, but also evidence of operators implementing 'workarounds' to compensate for factors such as a lack of support from retrofit suppliers.

Economic challenges and higher than expected costs heighten some of the issues within this system. There may be a lack of incentives and motivations by all parties to achieve good levels of performance. **The complexity of the human factors at play in response to the influences of the wider system limit the scope for achieving better retrofit performance**.

5. Wider considerations

The evidence assessed to this point has been predominantly about NO_X; how SCR retrofit technology is impacting the reduction of NO_X between the engine and tailpipe, and reasons why in some cases reduction isn't to the level expected. Whilst making this assessment, other observations have emerged on topics that sit beyond the immediate scope of this programme of work and report, but which have the potential to influence conclusions on the effectiveness of SCR retrofit technology at improving air quality. As such, although these topics have not been investigated, early observations are stated here and their scope for wider impact factored into the conclusions of this report.

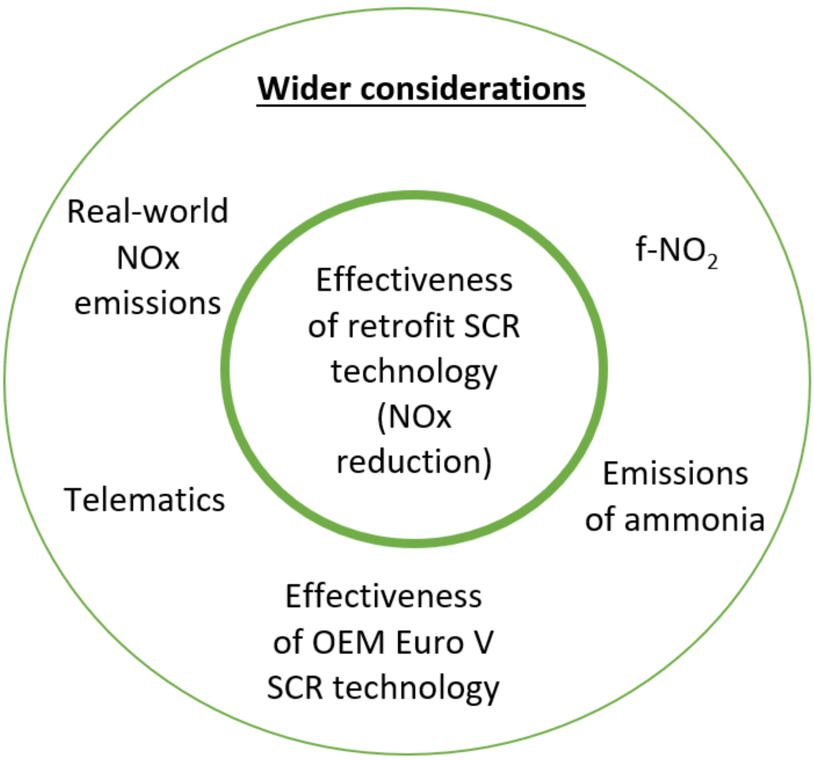


Figure 27 Diagram highlighting the wider considerations beyond the immediate scope of this report.

5.1 Real-world NO_X emissions

The CVRAS requires that SCR retrofits must meet a daily in-service monitoring requirement of 80% NO_X reduction between the engine and tailpipe. Evidence in this report suggests that 80% NO_X reduction can lead to tailpipe emissions that are approaching those of Euro VI buses. A NO_X reduction metric is a practical means of assessing ongoing performance of retrofit technology to ensure that the performance upon which it was accredited remains true once operational in the real-world. The work described in this report sets out to assess why this reduction requirement was not always being achieved.

Whilst this metric is practically useful, Section 2.3 of this report describes its limitations, principally that it only applies to periods where the NO_X sensors are recording, and not to an entire journey. In real-world operation therefore, there is no guarantee that emissions at the tailpipe are within acceptable limits. Use of a daily NO_X reduction metric also does not capture differences throughout the drive cycle. This may be particularly important as urban parts of a bus route, which are associated with a more stop-start driving style and cooler engine operating conditions, are also likely to be locations where a reduction in NO_X emissions is most needed. So, whilst this report focuses on what the technology was certified to deliver, **an important consideration must also be the impact of NO_X reduction on absolute NO_X emissions at the tailpipe**. It is these emissions, and their subsequent dispersion in the air, that have a real-world effect on roadside NO_2 concentrations to which people are exposed.

NO_X emissions at the tailpipe are not just a result of the performance of the SCR technology but also the size and condition of the vehicle engine. Evidence has emerged of wider issues with bus engines that cause high engine-out emissions. These issues can diminish the impact of SCR systems and lead to high tailpipe-out emissions, regardless of the performance of the SCR system. Whilst this complicates the attribution of absolute NO_X at the tailpipe to specific sources, it highlights the need to consider absolute emissions as these may be masked by a metric that looks solely at NO_X reduction.

The actual impact of SCR retrofit technology on absolute emissions and roadside NO_2 is not entirely clear. Several studies (such as Barratt et al.[12]) have investigated this although it is widely acknowledged that the sustained performance of SCR retrofit technology, especially in urban areas, requires further investigation.

5.2 f-NO_2

NO_X emitted from the tailpipe of a bus is composed of nitric oxide (NO) and NO_2 (known as primary NO_2) with the fractional ratio of NO_2/NO_X known as f-NO_2. At the roadside, most NO_2 comes from secondary reactions of NO in the air with ozone (O_3). Primary NO_2 from the tailpipes of road vehicles also contributes to ambient concentrations of NO_2.

The in-service reduction requirement in the CVRAS applies only to the reduction of NO_X. Whilst total emissions of NO_X are a very important consideration, there is historical evidence to suggest that the ratio of NO to NO_2 at the tailpipe varies widely in urban

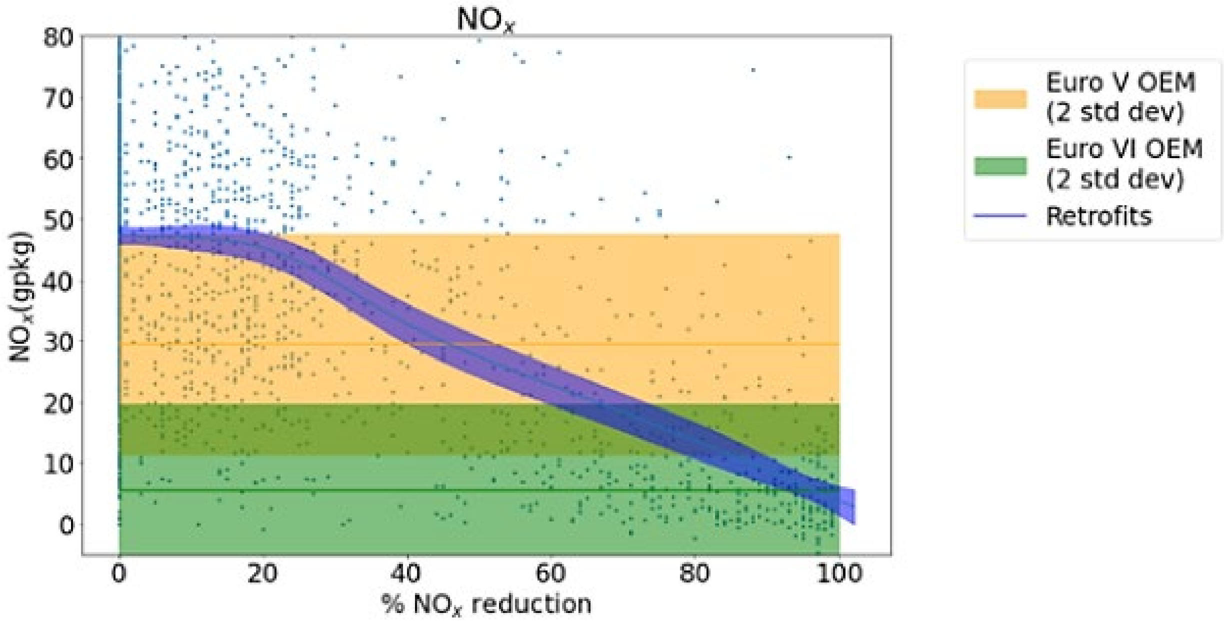
[12] Impacts of the bus retrofit programme on NO_2 concentrations along Putney High Street, Kings College London, 2014.

environments and that a high fraction of f-NO_2 can make a significant contribution to roadside NO_2 levels.

Exhaust after-treatment technologies increase f-NO_2[13]. Diesel oxidation catalysts (DOCs) which sit upstream of the SCR oxidise some NO to NO_2. This enables passive regeneration of soot in the diesel particular filter (DPF) and optimises SCR reactions. The configurations of catalysts within SCR systems may also influence NO to NO_2 ratios.

Figure 28 shows how NO_X and NO_2 measured by remote sensing is dependent on the NO_X reduction achieved by the SCR retrofit at the point the measurement was taken. When the SCR is performing poorly and the % NO_X reduction is low, while NO_X emissions are within one standard deviation of those from OEM Euro V buses, the NO_2 emissions are greater on average than those from the OEM Euro V buses.

[13] Trends in Primary Nitrogen Dioxide in the UK, Air Quality Expert Group, 2007; Analysis of the 2013 vehicle emission remote sensing campaigns data, King’s College London, 2015; New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK, D. Carslaw and G, Rhys-Tyler, 2013.



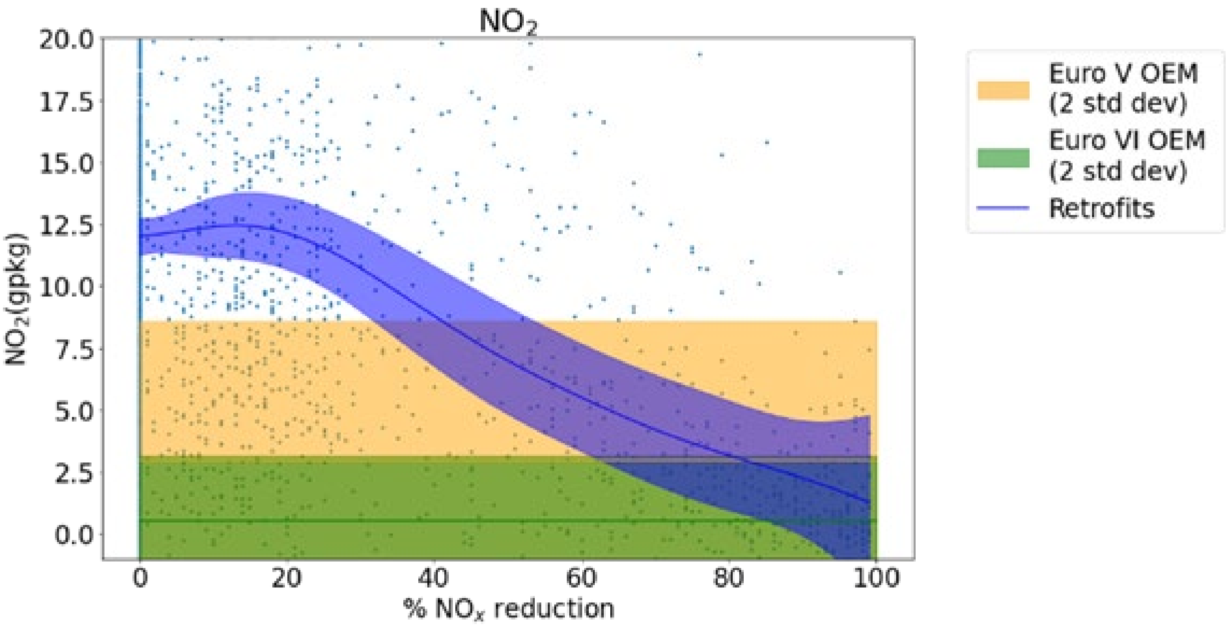


Figure 28 Variation in NO_X (top) and NO_2 (bottom) with retrofit SCR performance as measured by remote sensing. NO_X and NO_2 are expressed in grams per kilogram of fuel. The orange and green shaded regions show the distribution for OEM Euro V and Euro VI buses respectively. Each blue point is a measurement. The blue lines show a generalised additive model (GAM) fit to the data.

The analysis of telematics data showed that high SCR temperature and urea use are required for good NO_X reduction (see also Section 4.1). Figure 29 illustrates a sample of the current retrofitted fleet (185 buses) and f-NO_2 production; higher SCR temperature and lower urea use is generally related to higher f-NO_2. With some urea use and higher SCR temperatures, which are key for a correctly operational system, f-NO_2 is lower.

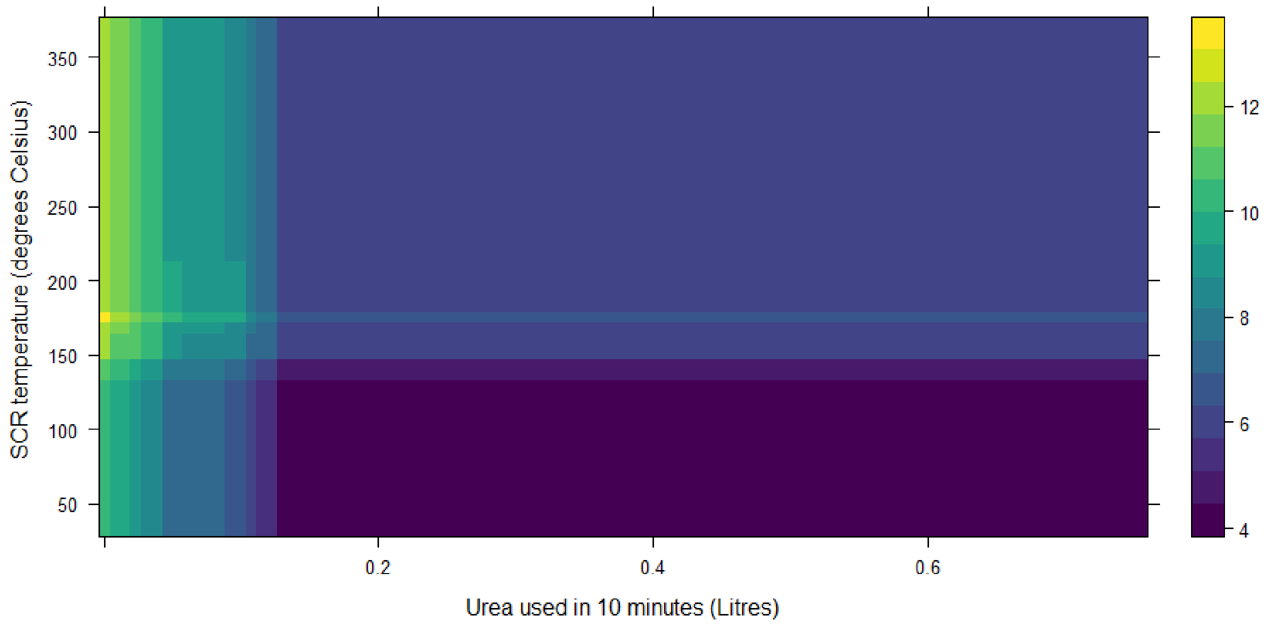


Figure 29 Statistical model showing the impact of temperature and urea usage on f-NO_2. Units are g/kg. The key bar on the right of graph shows lighter colours represent higher f-NO_2.

The application of SCR retrofit technologies to buses represents a relatively small proportion of the total UK vehicle fleet with after-treatment systems. A greater understanding is required as to how and why SCR may influence f-NO_2 in buses. This includes more detailed information on the specifications of after-treatment technologies, such as the chemicals in the catalyst substrates.

Recent measurements of ambient NO_2 suggest that **in some locations where retrofitted buses make up a substantial proportion of local road traffic, the conditions exist where roadside NO_2 concentrations could increase as a result of increased f-NO_2 emissions from buses with retrofitted SCR systems**. Further investigations are required to fully assess such impacts.

5.3 Emissions of ammonia

Ammonia (NH_3) is a critical element of the SCR system as it reduces NO_X in the presence of a catalyst. The optimum dosing of ammonia on to the exhaust gases is required; over-dosing results in ammonia passing through the SCR and out of the tailpipe (ammonia slip). Ammonia is a damaging pollutant for which the UK has an emissions reduction commitment. Although road transport is a very small contributor to total UK emissions (2% of the total UK ammonia emissions in 2021), vehicle emissions in general are an important urban source of ammonia. The CVRAS sets a maximum permitted limit for ammonia during the certification process.

Elevated ammonia emissions were observed during testing of a single bus at a vehicle test centre as part of this work, when efforts were made to improve the performance of the SCR in reducing NO_X emissions. Whilst there is considerable uncertainty on the importance of ammonia emissions from SCR retrofits, care must be taken to ensure that efforts to optimise NO_X reductions achieved by SCR retrofits do not unintentionally increase ammonia concentrations in urban environments where there are high levels of NO_X, as this could lead to increased fine particulate matter ($PM_{2.5}$[14]) formation. In the atmosphere, ammonia can form secondary inorganic aerosol (ammonium nitrate), which is an important component of $PM_{2.5}$. This formation occurs through the reaction of ammonia with nitric acid, which itself originates from NO_X emissions.

$PM_{2.5}$ is a pollutant of considerable importance due to its impact on health and because it is produced from a wide range of sources. Government has introduced legislation for two new targets for $PM_{2.5}$ under the Environment Act 2021 to improve public health by tackling the highest concentrations while ensuring all areas benefit from continuous improvement. Further work is required to understand the impact of SCR on ammonia emissions and whether there are any impacts on $PM_{2.5}$.

5.4 OEM Euro V SCR Technology

Many OEM Euro V buses implemented SCR technology for NO_X abatement to achieve Euro V emissions standards. Some have EGR in addition. OEM SCR systems were designed to pass the Euro emission standards of the time; for Euro V NO_X emission limits were higher than for Euro VI. OEM SCR systems benefit from full integration and calibration with the vehicle engine which facilitates optimum emissions control. When a bus is retrofitted, OEM SCR systems are removed and replaced by CVRAS accredited systems (designed to achieve Euro VI equivalent levels of emissions).

The average level of NO_X reduction between the engine and tailpipe for an OEM Euro V bus is not yet clear, however some level of NO_X reduction is expected. The 2022 and 2023 remote sensing campaigns identified that in some cases, tailpipe NO_X emissions from OEM Euro V vehicles were lower than those from retrofitted Euro V buses. However, on average emissions from retrofitted Euro V buses were slightly lower than OEM Euro V NO_X emissions (see Section 3.4.1). Further work could be undertaken to better understand the extent of improvement in NO_X emissions reductions between OEM Euro V and retrofitted Euro V vehicles.

5.5 Telematics

The monitoring and reporting of in-service NO_X reduction is done via on-board systems that log and report data. PEMS testing of a small number of buses showed some inaccuracies in reported NO_X conversions and concentrations at the tailpipe. Where NO_X sensors were faulty, emissions were underestimated, but small inaccuracies also occurred with NO_X sensors that were working correctly. Further work would be required on a greater number of buses to establish the true relationship between actual NO_X and that reported by telematics, and the prevalence of problems with NO_X sensors.

Data that is logged by NO_X sensors and other sensors requires processing by technology suppliers before being used elsewhere. There is a lack of clarity with regards to what this processing entails and how it relates to actual reported data. **More detailed knowledge of how telematics data is derived is required to ensure this is satisfactory for intended**

[14] Particles which pass through a size-selective inlet with a 50% efficiency cut-off at 2.5 μm aerodynamic diameter. These particles are small enough to be inhaled very deep into the lung.

use, and standardised so outputs can be understood with confidence. This diligence is vital given the prominence of telematics in monitoring SCR performance.

6. Scope for Improvement

There are several factors affecting the performance of bus retrofit technology. For some of these factors, there may be actions that can be taken to improve the performance of some retrofitted buses. Such actions could improve performance of SCR retrofits to some degree, so at the very least they are delivering NO_X emissions that are equivalent to Euro V OEM levels, and more so, delivering some benefit for local air quality by reducing NO_X emissions. It seems unlikely, given the age and condition of many vehicles and wider system constraints, that fleet-wide performance at Euro VI levels is realistic or would prove economically viable.

6.1 Improvements related to the retrofit system

6.1.1 Maintenance of components

Some improvements to the retrofit system are possible because of the human influences that intersect parts of the system**. There is scope for enhanced maintenance practices to reduce the occurrence of observed faults**, for example blockages on the filters of AdBlue tanks. There is scope for tweaks to other routine practices carried out within bus depots associated with the reporting and diagnosing of faults. Further research would be needed to trial modifications and quantify the scale of improvements that could be achieved.

Testing of Bus 1 provided a deep dive into issues related to the retrofit system and produced useful information regarding scope for improvement. Despite several concurrent faults it was possible with around 1.5 days of work for the retrofitted SCR system to reduce NO_X emissions (from a very high starting point) by more than 80%. Notwithstanding any issues around impacts on ammonia or particulate matter, the key to whether improvements last may be in the underlying engine and fuel system condition. Nothing encountered in the diagnosis and maintenance of this vehicle appeared unusual or arduous.

Ensuring that DPFs are not blocked with soot is important given the potential impact of this on engine efficiency and the efficiency of SCR reactions. However, this is not easy to achieve as the removal of soot is normally done via regeneration events that are controlled by the engine (fuel is injected or heat increased to burn off the soot). At low temperatures, these events may not happen, so DPFs must be removed, and the filters cleaned or replaced.

More effective maintenance could potentially lead to significant improvements in the poorest performing retrofit systems. Analysis of telematics data from one supplier found that **while NO_X reduction levels below 80% were more often due to low SCR temperature than due to problems with the urea dosing system, the very poorest performers tend to be those with urea dosing problems**. Buses with low SCR temperature but no identified urea dosing issues still achieved a moderate level of NO_X reduction (around 50% on average), but the average daily NO_X reduction for buses with urea dosing problems was only 18%. Identifying and addressing these issues more rapidly could therefore make a significant difference to overall performance.

6.1.2 Strategies and use of telematics

The strategies deployed by retrofit suppliers controlling parameters such as the operating threshold temperature of NO_X sensors and the initiation of urea dosing, could be adjusted to optimise NO_X reduction. One supplier provided information regarding NO_X sensor release that has indicated it is possible to activate NO_X sensors at lower temperatures using new controllers that take advantage of refined logic. Engaging with retrofit suppliers would be beneficial to identify approaches to meet requirements.

The routine provision of telematics data from retrofitted buses is important for monitoring in-service performance to ensure that SCR systems that are performing poorly are rectified swiftly. There is scope for far greater use of telematics data by bus operators and for this data to be presented in a manner that is easier to interpret. Metrics on low urea use and other indicators such as illogical/faulty NO_X sensor outputs, should be used to guide prioritised maintenance. It would be beneficial to test this on a wider sample of vehicles. Other telematics exploitation could be useful such as backpressure trends to detect DPF problems before they become serious.

6.2 Improvements related to temperature

Section 4.2 of this report describes the role that temperature plays in achieving effective NO_X reduction and maintaining the durability of the catalyst. Initial evidence **suggests that there may be scope for interventions to raise the temperature of the engine and SCR catalyst where needed,** for example by fitting insulation jackets around SCR systems or adding additional heating mechanisms.

It is not yet clear whether it would be feasible to implement these types of interventions to improve performance across the fleet. Where buses have been retrofitted to achieve the specific objective of achieving compliance with the limit value for NO_2, **the redeployment of retrofitted buses away from bus routes where the conditions for low temperatures prevail may be necessary.** However, whether this is economically or practically feasible has not been investigated and therefore requires exploration.

7. Limitations

This programme of work has relied on the support of several external stakeholders including retrofit suppliers and bus operators. Due to the limited timescales, not all stakeholders were able to provide the requested level of support to facilitate the evidence collection. This resulted in reduced testing at the vehicle test centre, both due to facility availability to complete testing on the chassis dynamometer and retrofit engineer availability to conduct root cause analysis; thus, limiting the amount of evidence gathered in the time available.

Secondly, due to operational needs, buses were only available for testing for limited time periods. This has resulted in a limited sample size of vehicles completing in-depth testing, with only two buses undertaking root cause analysis and one bus completing emulation testing. Subsequently, the technical findings presented in this report have been sourced from a limited sample size, and therefore caution must be taken when relating these findings to the wider retrofitted fleet. In-service PEMS testing was also completed on a limited sample size of four buses. Not all testing was completed in time to be included in this report and so limited results are presented. More information on the limitations of the selection of buses for in-service PEMS and testing at the vehicle test centre is provided within Annex C.

Thirdly, although exclusion criteria were shared with bus operators prior to bus selection to ensure buses with known faults were excluded from testing at the vehicle test centre, some buses selected still possessed faults. These faults may have limited findings as they reflected bus specific maintenance issues which could have impacted upon retrofit performance. Some faults, such as a leaking oil gasket on Bus 4, could not be repaired in time for testing, therefore limiting the testing outputs collected for the bus.

Requests for data, information, and clarification from third parties had to be prioritised meaning the derivation, completeness or meaning of all third-party data (especially telematics or historic testing data) could not always be verified. Efforts were focused on successfully verifying the most important results which underpinned key findings in the time available.

8. Conclusion

The evidence considered by the Bus Retrofit Expert Group (BREG) and presented in this report indicates that SCR retrofit technology can reduce NO_X emissions from Euro V buses to levels approaching those of Euro VI buses. However, multiple technical and human factors lead to variations in performance and widespread underperformance. Whilst performance is highly variable, on average NO_X emissions from retrofitted Euro V buses were 11% lower than those from non-retrofitted Euro V buses. The sample of retrofitted buses analysed are not consistently achieving the objective of 80% NO_X reduction to deliver emissions levels approaching those of Euro VI buses; NO_X reduction levels are considerably lower.

SCR retrofit systems are complex, so it is challenging to get them to perform well. Good performance requires an SCR temperature of at least 200°C, the correct dosing and good mixing of urea into exhaust gases, suitable exhaust and engine sensors, and suitably specified and functioning catalyst elements including the DOC and SCR catalyst.

Retrofit systems contain a set of component parts that must be working well and in harmony for efficient NO_X reduction. Component failures can quickly lead to sub-optimal dosing and total systems failures. Telematics can assist in remotely identifying sub-systems that require attention to control emissions however this data is not currently well used amongst bus operators. Fixing faults can be practically challenging to do, particularly with shortfalls in engineer capacity and technical expertise, with responsibility for maintenance often split between retrofit suppliers and bus operators.

Maintaining working temperature may be a fundamental limitation of some SCR retrofit technologies that in certain use cases cannot be overcome. The CVRAS testing cycle upon which the retrofit technologies were certified was not fully representative of real-world conditions as testing allowed a substantial warm up phase with emissions recorded over the part of the drive cycle when the engine is running hot. Technology may exist to raise SCR temperatures, however technical interventions may not be practical or cost-effective, particularly when applied across a large fleet.

The scope for improvement is greater where poor performance is caused by technical failures within the retrofit system that affect urea dosing. Enhanced maintenance and cooperation between retrofit suppliers and bus operators may improve fault diagnosis and repair. This includes maintenance of upstream devices such as DPFs, which can have a strong influence on the effectiveness of the SCR system. However, the levels of servicing required to sustain performance may be impractical in some circumstances given the complexity of the wider system within which retrofitted buses operate. Both bus operators and retrofit suppliers face challenges in maintaining commercial viability so pro-active maintenance to prevent serious faults may be uneconomic.

The evidence presented shows that real-world NO_X emissions from buses with retrofitted SCR systems are higher than expected. Evidence also indicates that the fraction of NO_X emitted as NO_2 is greater for retrofitted buses compared to non-retrofitted buses. Recent measurements of ambient NO_2 suggest that in some locations where retrofitted buses make up a substantial proportion of local road traffic, roadside NO_2 concentrations could increase because SCR technology increases the fraction of NO_X emitted as NO_2. There is a risk that in some situations, efforts to reduce NO_X emissions could cause emissions of ammonia to increase. Further evidence collection and air quality modelling is required to assess the full impacts of retrofitting on air quality.

9. Recommendations

The following recommendations are made based on the findings described in this report.

Recommendations to improve performance of the SCR retrofitted bus fleet:

1. Bus operators should be contacted and alerted to the importance of monitoring urea consumption in buses with retrofitted SCR systems. Operators should be advised that low urea usage is an indicator of very poor retrofit performance and so buses displaying this require urgent attention.

2. A robust centralised in-service monitoring regime should be developed to monitor and scrutinise telematics data from retrofitted buses across England. This data should be used to identify persistent poor performing buses and to inform appropriate action.

3. Telematics data should be made accessible to bus operators and easy to interpret, to assist in the identification of poor performing retrofit systems.

4. Bus operators should routinely and proactively monitor telematics data for all retrofitted buses in their fleets. This information should be used to improve early identification of faults in SCR systems and prioritise improvements to the poorest performing systems at the local level.

5. Best practice guidelines should be shared with bus operators and depot staff on the impact of enhanced maintenance on performance of retrofitted SCR systems.

6. Knowledge and experience of maintaining SCR systems should be shared between bus depots to ensure this is not lost if retrofitted buses are relocated when depots receive upgraded vehicles.

7. The CVRAS in its current format should not be used for new accreditations of bus retrofit technologies.

Recommendations for further work:

8. Assessments to support the development of enhanced maintenance strategies should be made, including analysis of the extent to which performance can be improved by enhanced maintenance.

9. An assessment should be made of the feasibility, scale and longevity of improvements that could be achieved from enhanced maintenance practices targeting specific components in the SCR system and upstream devices.

10. Engineering interventions to achieve and maintain higher SCR operating temperatures should be investigated.

11. Further work, including analysis of ambient NO_2 concentrations, should be undertaken to assess the impacts of SCR bus retrofit technology on f-NO_2 and roadside NO_2 concentrations.

12. Further work should be undertaken to assess the impacts of SCR bus retrofit technology on ammonia emissions and possible links to particulate matter.

13. A review should be made of the number and location of other non-bus vehicle types with retrofitted SCR technology to assess whether similar investigation into the performance of SCR in these vehicles is feasible and necessary.

10. Glossary

BREG	Bus Retrofit Expert Group
CBTF	Clean Bus Technology Fund
CVRAS	Clean Vehicle Retrofit Accreditation Scheme
CVTF	Clean Vehicle Technology Fund
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DVSA	Driver Vehicle Standards Agency
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
f-NO_2	Fraction of total NO_X that is nitrogen dioxide
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
OEM	Original Equipment Manufacture
PEMS	Portable Emissions Measurement System
$PM_{2.5}$	Fine Particulate Matter
SCR	Selective Catalytic Reduction
VCA	Vehicle Certification Agency

Annex A - Science Programme Design

Figure 30 shows the correlation between the evidence collection and statistical analysis projects within the programme of work, and the list of 38 factors potentially affecting retrofit performance. The programme of work was designed to investigate as many factors as possible, particularly those likely to have the strongest influence.

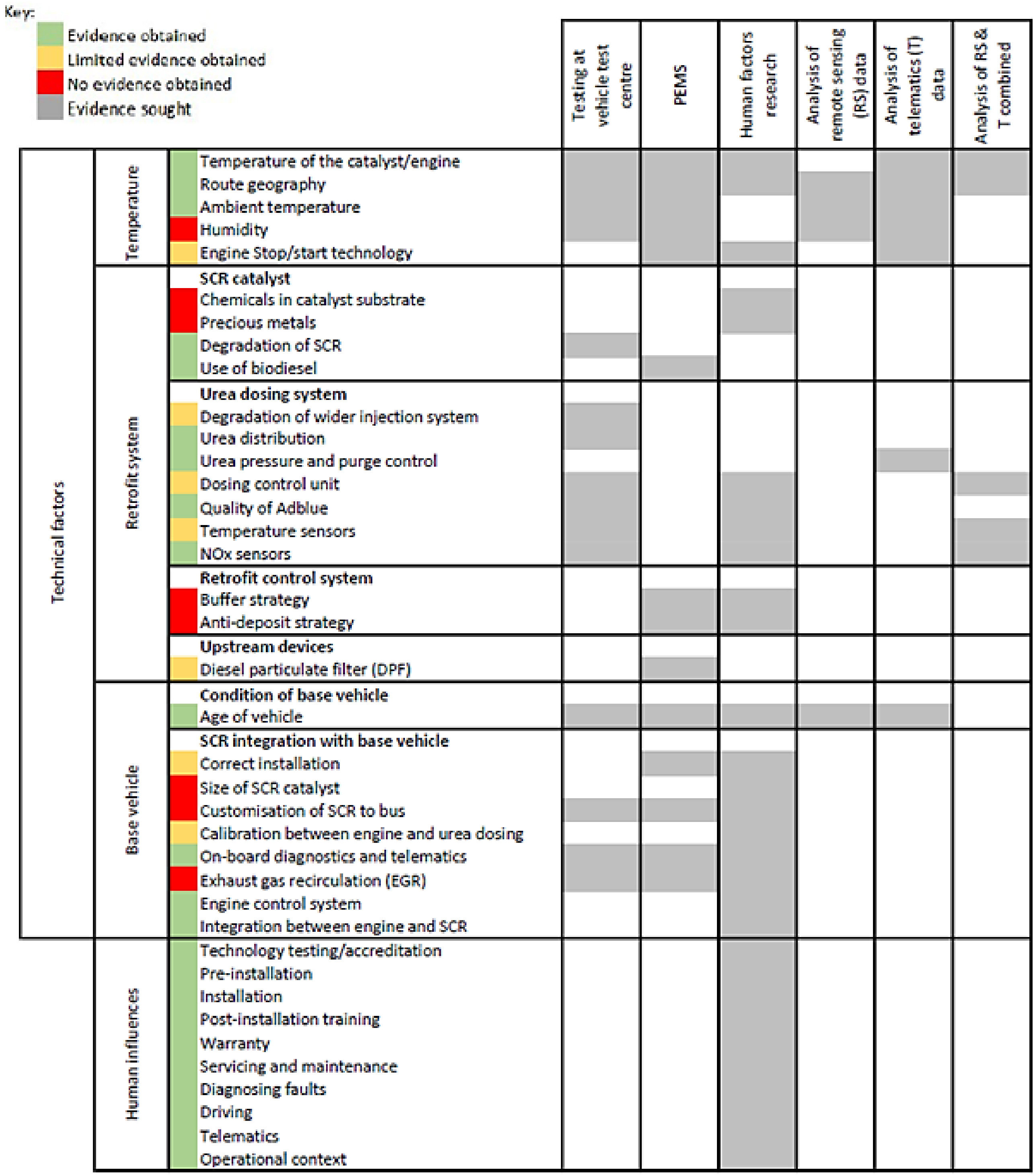


Figure 30 Potential factors influencing retrofit performance.

Annex B - Assessment of CVRAS

B.1 Impacts of cold start conditions

It became apparent that under the Revised 2017 Low CVP UK Bus Cycle, buses use the Outer London phase to warm up prior to testing. Testing is therefore always conducted on a warm vehicle and does not consider the impact of cold starts. It is widely known that emissions are significantly higher during a cold start. The impact of cold starts was considered by CVRAS within the daily average NO_X reduction target, with an 80% reduction deemed achievable across a full cycle (compared to the 95% reduction observed during the ‘hot’ part of the test).

Whilst it is common practice for bus operators to idle their vehicles prior to service beginning, this is usually only completed for a few minutes whilst vehicle checks are being completed. The Outer London phase runs for approximately twenty minutes, warming the vehicle and SCR technology to a higher temperature than would be expected under real-world conditions. This will result in better performance of the SCR technology and high percentage NO_X reduction during the test phase.

Three buses selected for testing completed a CVRAS assessment to benchmark their baseline performance. This included two hot tests and an additional cold start CVRAS test which was completed without a warmup cycle. The NO_X and NO_2 emissions outputs from these tests are displayed in Figure 31 and Figure 32 below. Tests 1a was completed prior to targeted maintenance on Bus 1, and tests 1b and 1c post-maintenance.

NO_X emissions outputs were 47% higher for Bus 1 during the cold start test compared to the hot tests across the three CVRAS tests completed. This trend however is not present for Bus 2 or Bus 4. Buses 1 and 2 recorded the highest NO_2 emissions during the cold start CVRAS tests. Whilst the testing sample is limited, the results reveal a potential link between vehicle temperature and emissions outputs. By testing from hot, the CVRAS testing procedure may underestimate emissions from retrofitted vehicles when compared to real-world in-service conditions.

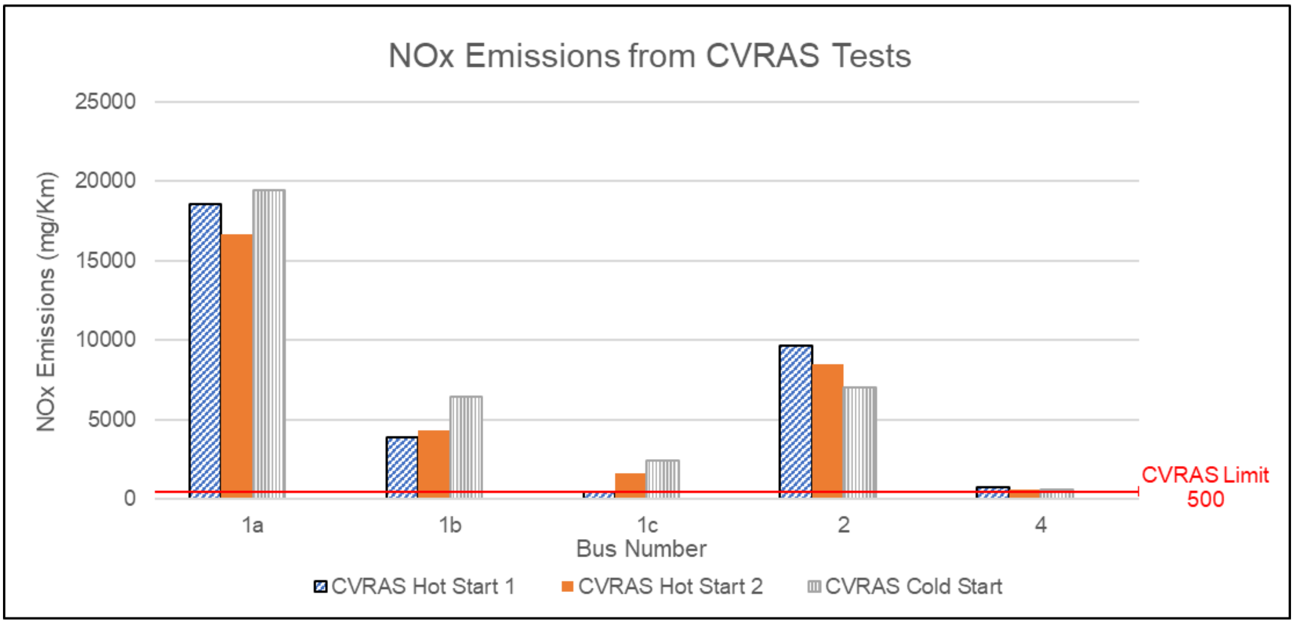


Figure 31 Total emissions of NO_X over the Low CVP UK Bus (LUB Revised) CVRAS test cycle conducted on Buses 1, 2 and 4 at the vehicle testing centre.

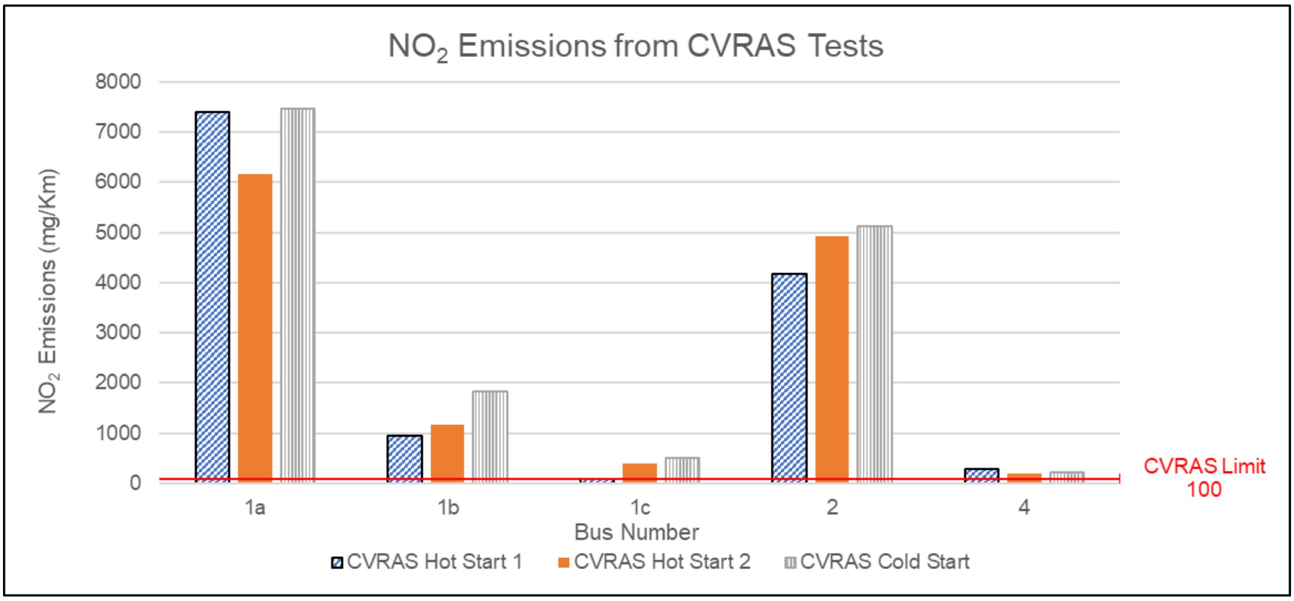


Figure 32 Total emissions of NO_2 from the Low CVP UK Bus (LUB Revised) CVRAS test cycle conducted on Buses 1, 2 and 4 at the vehicle testing centre.

B.2 Comparisons to real-world conditions

JAQU also explored how emissions of NO_X varied between the Revised 2017 Low CVP UK Bus Cycle and a real-world drive cycle. This was achieved though testing on a chassis dynamometer at a vehicle testing centre using a speed trace that replicated a real-world drive cycle (excluding gradient effects). The tests were completed on two buses (Buses 1 and 4) with SCR retrofit technology from different suppliers. Bus 1 was selected for testing after recording poor NO_X reduction, with Bus 4 demonstrating good NO_X reduction from telematics data.

As illustrated in Figure 33, emissions of both NO_X and NO_2 recorded during the real-world drive cycle for Bus 1 were higher than the emissions recorded during the CVRAS cycles. This trend is observed to a greater extent for Bus 4 in Figure 34. These findings suggest that the CVRAS testing cycles are likely to underestimate real-world NO_X emissions from SCR retrofit technologies[15].

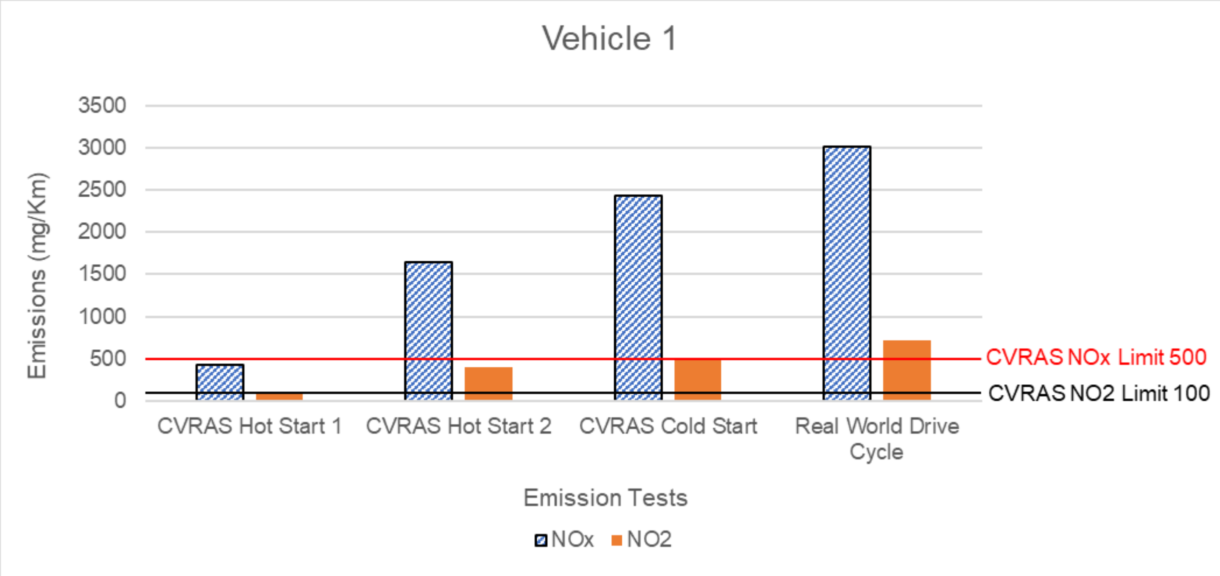


Figure 33 NO_X and NO_2 emission outputs for CVRAS tests and a real-world drive cycle completed by Bus 1.

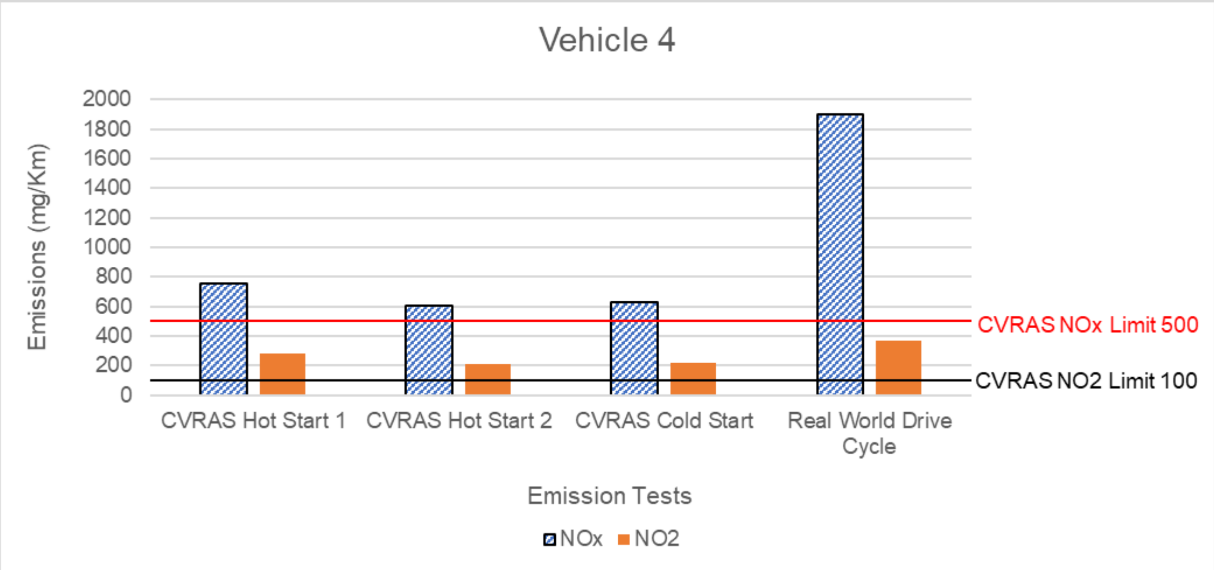


Figure 34 NO_X and NO_2 emission outputs for CVRAS tests and a real-world drive cycle completed by Bus 4.

[15] These findings are from a limited sample size of three vehicles. Further information on the limitations of the study is provided in Section 7.

Annex C - Buses selected for testing

Bus Number	Bus Operator	Retrofit Supplier	Performance Rating	Selection Rationale	Testing Complete
1	Operator 1	Supplier 1	Poor	Bus was identified as a poor performer by JAQU analysis of telematics along with demonstrating low rail pressure, low air pressure, and low urea use	CVRAS benchmark test (x4) Root cause analysis by retrofit supplier (x3) Emulation testing Real world drive cycle test
2	Operator 2	Supplier 2	Poor	Bus was identified as a poor performer by JAQU analysis of telematics detailing NOx conversion and AdBlue dosage	CVRAS benchmark test Root cause analysis by retrofit supplier
3	Operator 2	Supplier 2	Poor	Bus was identified as a poor performer by JAQU analysis of telematics detailing NOx conversion and AdBlue dosage	Vehicle was returned untested due to testing facility availability.
4	Operator 2	Supplier 2	Good	Bus was identified as a good performer by JAQU analysis of telematics and confirmed by Zemo (>90% NO_X reduction) on 17 August 2023.	CVRAS benchmark test Real world drive cycle test

Table 7 Buses selected for testing at the vehicle testing centre and selection rationale.

Bus Number	Bus Operator	Retrofit Supplier	Performance Rating	Selection Rationale	Testing Complete
5	Operator 1	Supplier 1	Good	Bus was identified as a good performer by JAQU analysis of telematics and confirmed by Zemo (71% NO_X reduction) on 15/08.	Sheffield Route 51 at 08:57am
6	Operator 1	Supplier 1	Good	Bus was identified as a good performer by JAQU analysis of telematics and confirmed by Zemo (81% NO_X reduction) on 15/08. JAQU were informed that the larger engine on the Volvo B9TL may influence retrofit performance therefore this bus model was selected for testing.	Sheffield Route 120 at 12:19pm Route 120 at 08:57am
7	Operator 1	Supplier 2	Good	Bus confirmed as a good performer by Zemo (average 86% NO_X reduction across 10 days between 12 September 2023 and 23 September 2023).	Bath Route 4 at 10:01am
8	Operator 1	NA	Euro VI OEM	EURO VI OEM bus was selected so a comparison could be drawn between the NO_X emission outputs from a retrofitted bus and an OEM bus.	Bath Route 4 at 09:08am

Table 8 Buses selected for in-service PEMS testing and selection rationale.

C.1 Limitations of bus selection

Access to full, detailed telematics data to inform the selection of buses for testing was not available for all retrofit suppliers considered, with the quality of data differing between suppliers in both format and time resolution. This lack of detailed telematics data was a key limitation and obstacle in the selection of buses as limited information was available on how these buses were performing in-service.

There are no current approved parameters for what is classed as ‘high’ or ‘low’ NO_X emissions from retrofitted buses. This means that the parameters used to select buses by emission characteristics, whilst developed using best judgement to devise a suitable sample size, are subject to scrutiny.

The sample size of eight buses (four buses completing differing levels of testing on the chassis-dynamometer and four buses completing in-service PEMS testing) may limit the conclusions that can be drawn from the results collected. The number of factors which could be investigated was limited and repeat testing was not always possible due to timescales available, potentially reducing the reliability of the results of each test. The limited sample size and project timelines also meant some bus types were excluded from testing and a limited number of engine types, retrofit technologies, locations and bus operator practices were investigated. In some cases, the choice of buses was further limited by the availability of drivers and the availability of certain buses due needs of bus operators to maintain services.

The small sample size also limited the sample to buses with conventional internal combustion engines although many of the findings are applicable to retrofitted hybrid buses.

Annex D - NO_X emissions during idling periods

To understand the underestimation of NO_X during periods of idling and associated low SCR temperatures, analysis of seven PEMS tests on four different buses commissioned by Zemo/EST as part of the ongoing CVRAS monitoring programme was undertaken.

Buses ran the same drive cycle on the test track at the Millbrook vehicle testing centre. This included an idling period of 10 minutes approximately two hours into the test. The analysis found that the telematics NO_X sensors were reporting for 88-95% of the test period. In all the data analysed, the telematics system continued to report data during the 10-minute idling period, indicating that the SCR remained hot and the NO_X sensors active.

Figure 35, Figure 36, and Figure 37 show this idling period along with a short time before and after for three of the tests on three different buses. All buses showed a significant spike in emissions after the idling period although some variation in NO_X emissions between buses was identified during the period.

A review of the PEMS NO_X emission data for buses retrofitted by one supplier, Supplier 2 showed a clear step change in emissions after approximately four minutes of idling. One example of this is in Figure 35. A review of the PEMS NO_X emission data for buses retrofitted by another supplier, Supplier 1, showed a considerable variation in the emissions during the 10-minute idling period between the ADL Enviro 400 bus and the Wrightbus Eclipse Gemini bus. The emissions from the ADL bus are generally low for the duration of the idling period as shown in Figure 36. However, for the Wrightbus, as shown in Figure 37, NO_X emissions fluctuate throughout the idling period and are higher overall. The cause of this difference is unknown.

This evidence on the impact of idling is not likely to be fully representative of that incurred by buses moving in heavy traffic in urban centres where idling periods are likely to be shorter but far more frequent. More evidence is required to assess the impacts of idling in real-world conditions in urban centres.

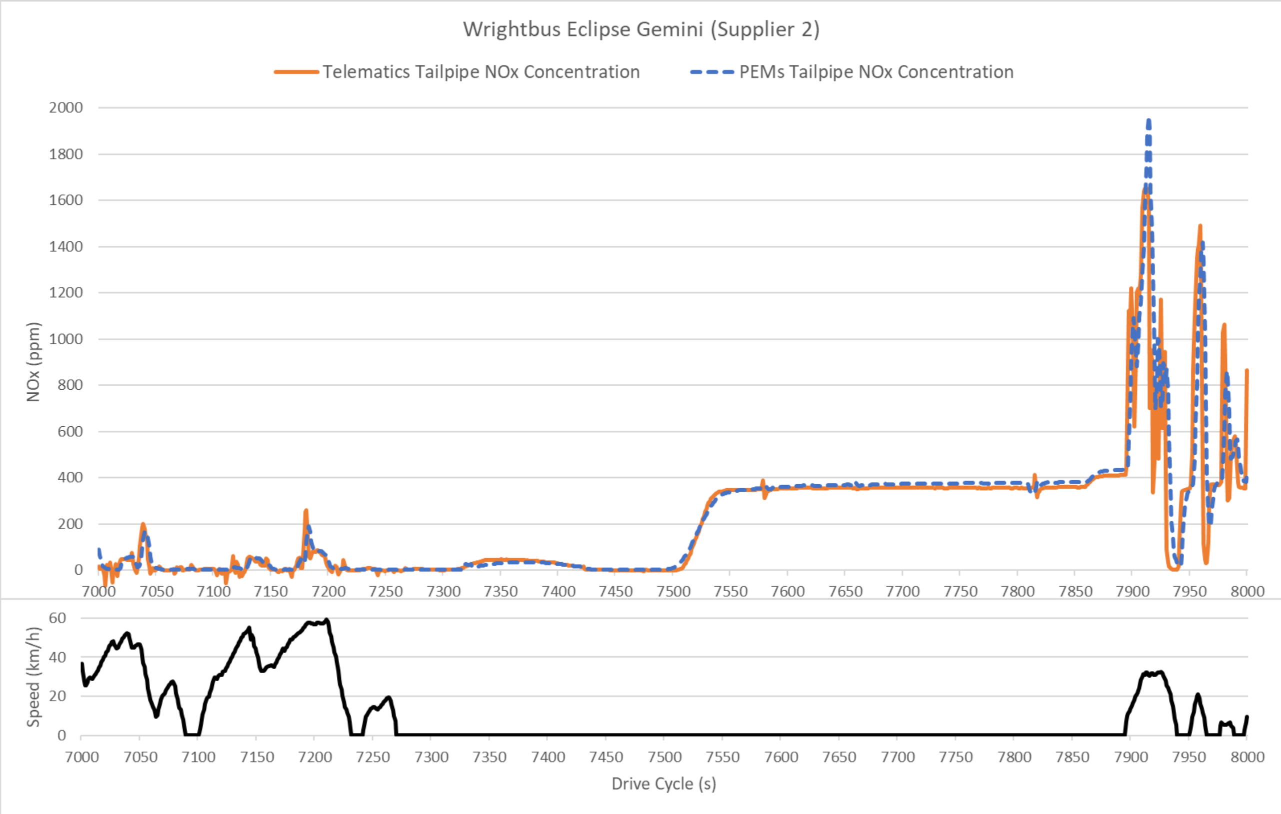


Figure 35 PEMS data from track testing of a retrofitted bus at Millbrook on the 9 November 2021.

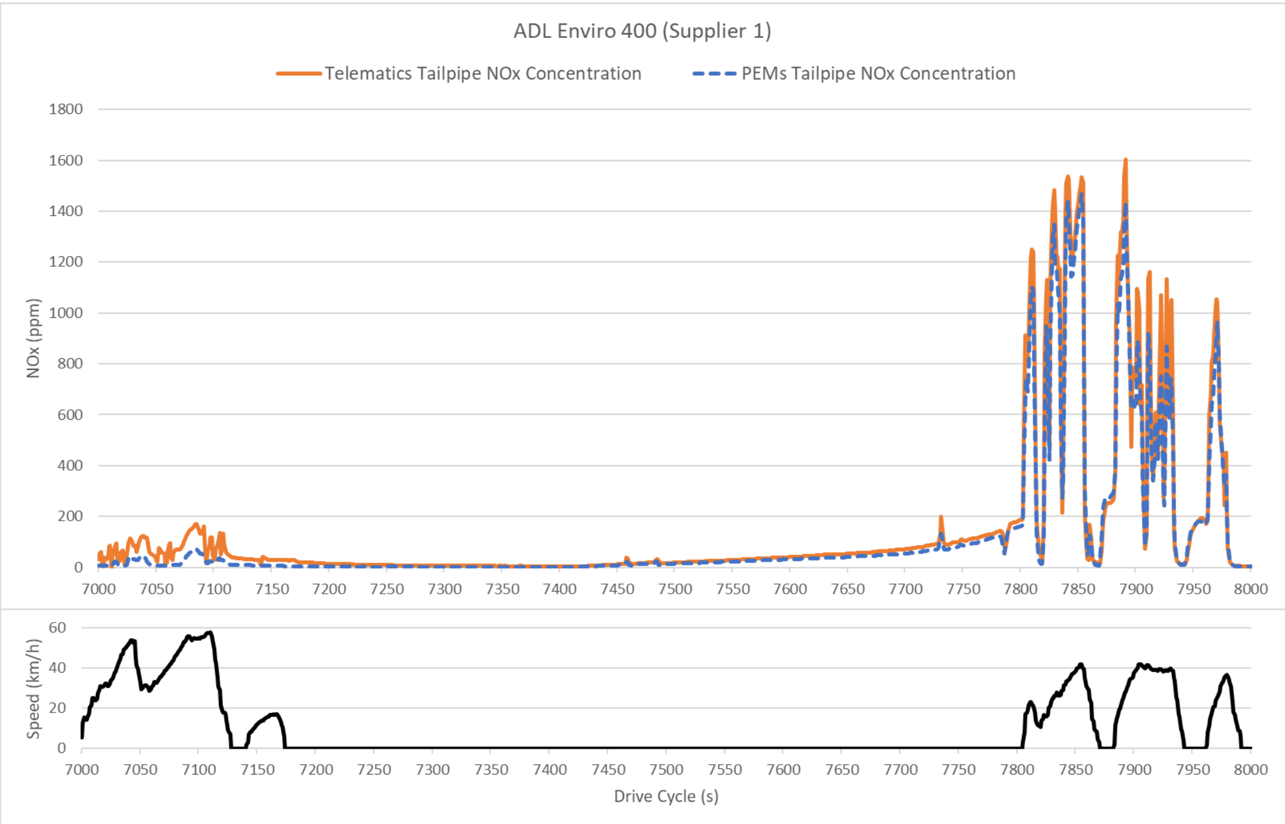


Figure 36 PEMS data from track testing of a retrofitted bus at Millbrook on 5 August 2021.

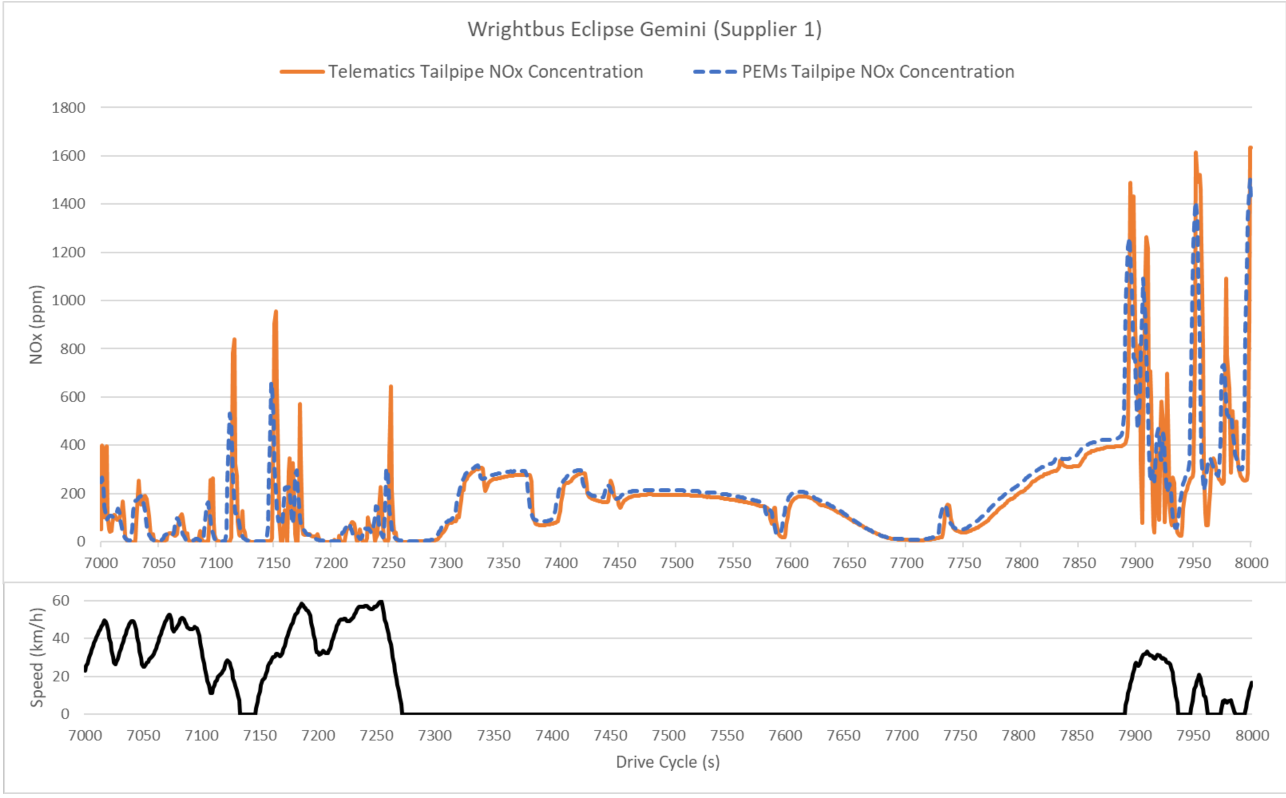


Figure 37 PEMS data from track testing of a retrofitted bus at Millbrook on 20 October 2021.

Annex E - Further details on the urea dosing system

Optimum dosing of urea onto the engine exhaust gases relies on the effectiveness of several key elements:

- Dosing rate: The rate at which urea is injected into the exhaust stream must be at least matched to the amount of NO_X present in the exhaust gases. The dosing rate is determined by the measured NO_X concentration, exhaust flow, exhaust temperature and the emissions control strategy of the retrofit system which is determined by the retrofit supplier.

- Spray pattern and atomisation: The urea solution should be atomised and evenly distributed within the exhaust gases to ensure thorough mixing with the NO_X. This helps promote efficient reaction between absorbed ammonia and the NO_X when passed over the surface of the SCR catalyst.

- Pressure control: The urea dosing system operates under pressure to ensure accurate and consistent delivery and overcome any backpressure in the system. The pressure is usually controlled by a pump within the dosing system.

- Ammonia slip avoidance: Overdosing of urea can lead to excessive ammonia emissions where unreacted ammonia passes through the catalyst and is released into the environment. This can happen if the dosing rate is too high compared with ammonia required for the real-time NO_X level plus storage capacity of the SCR catalyst, or if the system malfunctions. Precise dosing is required to avoid this.