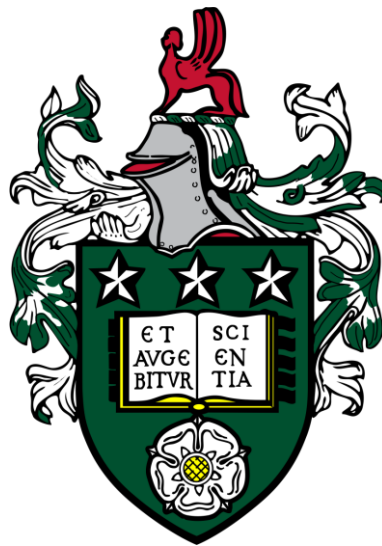

Real-driving Emission Performance and Potential Reduction from Vans



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Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

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Intellectual Property and Publication Statements

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The work in chapter 2 has been published as follows:

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The candidate developed the main idea for this paper under the guidance of James Tate, Eleonora Morganti and Simon Shepherd. The candidate validated the model, performed the data analysis, and wrote the manuscript. The manuscript was improved by comments from all the co-authors.

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Zhuoqian Yang, James E. Tate, Eleonora Morganti, Ian Phillips, Simon P. Shepherd. The CO₂ and NO_x emission reduction potential of the van sector: the impact of accelerating the electric vehicle transition in Great Britain.

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Abstract

Vans are a major contributor to NO_x emissions and CO₂ emissions in the road transport sector in Great Britain, however little attention is given to vans compared with passenger cars. The work aims to provide an accurate estimation of real-world NO_x and CO₂ emissions of the van fleet, explore how the external factors would affect the NO_x emission performance of vans, develop a reliable evidence-based knowledge of the van fleet composition and use, and project the future van emission pathways under different scenarios.

Firstly, the real-world emission performance of vans is assessed by the instantaneous vehicle emission model PHEM and remote sensing measurements. The validated emission model PHEM is used to simulate the real-world CO₂ and NO_x emissions from standard vans and refrigerated vans. Then the Gumbel distribution is introduced to remote sensing measurements to have a robust description of fleet-wide NO_x emissions from vans and identify candidate high-emitting vehicles. Secondly, the uncertainty associated with real-world NO_x emission estimation is evaluated. Simulation results by PHEM and remote sensing measurements are used to analyse the impact of ambient conditions (e.g., road grade, ambient temperature), driving conditions (e.g., speed and acceleration) on tailpipe emissions of vans. The impact of various NO_x control-systems is also considered. At last, the future emission trend in the van sector in Great Britain is estimated. Several scenarios are designed to identify the key factors influencing emission reduction speed.

This thesis validates PHEM's ability to provide representative real-world CO₂ and NO_x emissions from vans, introduces the Gumbel distribution to remote sensing measurements to provide a more relevant description of fleet NO_x emissions and identify candidate high emitters, and suggests that a fast transition to battery electric vehicles in the early 2020s will show significant benefit with regard to the CO₂ emission mitigation in the van sector.

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Abbreviations & Acronyms

AFV	Alternative Fuel Vehicle
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineer
AURN	Automatic Urban and Rural Network
AWEL	the Department for Waste, Water, Energy and Air
BE	Belgium
BEV	Battery Electric Vehicles
CAT	CENTRE FOR ALTERNATIVE TECHNOLOGY
CAZ	Clean Air Zone
CCC	Climate Change Committee
CH	Switzerland
CNH Industrial	Iveco
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COPERT	COmputer Programme to calculate Emissions from Road Transport
CVS	Constant Volume Sampling
DAIMLER	Mercedes-Benz
Defra	Department for environment, food and rural affairs
DfBEIS	Department for Business, Energy and Industrial Strategy
DfT	Department for Transport
ECCo	Electric Car Consumer Model
EDAR	Emissions Detection and Reporting
EEA	European Environment Agency
EGR	Exhaust gas recirculation
EU	European Union
FCA GROUP	Fiat
FEAT	Fuel Efficiency Automobile Test

FOEN	Federal Office for the Environment
GHG	Greenhouse Gas
HBEFA	Handbook Emission Factors for Road Transport
H ₂	Hydrogen Fuel
HEAT	Hager Environmental & Atmospheric Technologies
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
ICCT	International Council On Clean Transportation
ICE	Internal Combustion Engine
IIASA	International Institute for Applied Systems Analysis
IPCC	Panel on Climate Change
LDC	London Drive Cycle
LDV	Light Duty Vehicle
LGV	Light Goods Vehicle
LCV	Light Commercial Vehicle
LNT	Lean NO _x Trap
N ₂	Nitrogen
NAEI	National Atmospheric Emissions Inventory
NEDC	New European Driving Cycle
NH ₃	Ammonia
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxides
O ₃	Ozone
OZEV	Office for Zero Emission Vehicles
PEMS	Portable Emissions Measurement Systems
PHEM	Passenger car and Heavy duty vehicle Emission Model
PHEV	Plug-in Electric Vehicle
PM	Particulate Matter

PN	Particle Number
PSA GROUP	Citroen, Opel, Peugeot, Vauxhall
RDE	Real Driving Emission
SCR	Selective Catalytic Reduction
SE	Sweden
SMMT	Society of Motor Manufacturers and Traders
THC	Total Hydrocarbon
TRU	Transport Refrigeration Unit
UK	United Kingdom
ULEV	Ultra Low Emission Vehicle
VSP	Vehicle Specific Power
VW GROUP	Man, Volkswagen
WHO	World Health Organization
WLTP / WLTC	Worldwide harmonized Light vehicles Test Procedure /Cycle

Chapter 1 Introduction

1.1 Motivation

Nitrogen oxides (NO_x) are a key environmental and social issue. They have been associated with a range of adverse health effects, such as premature deaths, respiratory conditions and cardiovascular problems ([Hoek et al., 2013](#); [Khreis et al., 2017](#)). In addition, it damages the ecosystem ([EEA, 2017](#)). Road transport is a major source of NO_x, responsible for 32.9% of emissions in 2019 in the UK ([NAEI, 2021b](#)). Furthermore, in urban areas it is estimated that about 80% of the NO_x concentrations at roadsides are contributed by the road transport sector, among which diesel vans account for 22% ([Defra and DfT, 2017](#)).

With the increasing concern over the negative effect of NO_x on public health and the environment, the EU has set strict regulations on emissions that should be emitted by vehicles, known as Euro standards. Since 1992, new light passenger and commercial vehicles¹ have had to meet corresponding exhaust emission limits, before they can be put on sale. However, the discrepancy between test-approval limits and real-driving emissions has raised concerns. The real-world NO_x emissions were found to far exceed the type-approval limits ([Carslaw, D. et al., 2011](#); [Luján et al., 2018](#); [O'Driscoll et al., 2016](#)). While most previous studies have mainly focused on the real-driving emissions of passenger cars, vans have also contributed a significant amount of emissions to the environment and have largely been ignored.

Many of the changes that would mitigate NO_x emissions (e.g., improving fuel efficiency and transferring to alternative fuel vehicles) would also help to reduce

¹ Light commercial vehicles (sometimes called 'light goods vehicles' in the UK) are vehicles designed and constructed primarily for the carriage of goods with a maximum mass not exceeding 3,5 tonnes. By the definition of EU (REGULATION (EU) 2018/858) and Department for Transport's (DfT's) vehicle licensing statistics (<https://www.gov.uk/government/publications/vehicles-statistics-guidance/vehicle-licensing-statistics-notes-and-definitions>), light commercial vehicles consist vans and a very small share of pick-up trucks and chassis-cabs. However in DfT's road traffic statistics report (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/916749/road-traffic-estimates-in-great-britain-2019.pdf) and DfT's 2019-2020 van survey (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1065072/van-statistics-2019-to-2020.pdf), light commercial vehicles refer to vans only. In this research the term 'van' is regarded the same as light commercial vehicle and light goods vehicle.

carbon dioxide (CO₂), the main greenhouse gas (GHG) in the world. It is unequivocal that GHG emissions from human activities have warmed the climate, and have caused substantial damages and irreversible losses to nature and people ([IPCC, 2022](#)). To mitigate road transport's contribution to GHG emissions and accelerate the transition to a 'net-zero' society, the UK government has decided in 2020 to end the sale of new petrol and diesel cars and vans by 2030. Research to date ([CCC, 2019](#); [DfT, 2021a](#); [DfT and OZEV, 2021](#)) focusing on the decarbonization trajectory of light duty vehicles (passenger cars and vans) have been largely limited to passenger cars, as it accounts for 82.4% of light duty vehicles (LDVs) in 2019 in Great Britain ([DfT, 2022b](#)), whereas CO₂ mitigation pathway for vans is unclear.

Effective actions to reduce the negative impacts of NO_x and CO₂ emissions from vans require a good understanding of its causes. A detailed assessment of real-world emission factors of vans, how external factors are affecting the emission performance, projections of future emission reduction pace based on van fleet characteristics are needed.

1.2 Related work

This chapter provides an overview of the background relevant to the research project as well as a review of the existing academic literature. It starts with the background relating to NO_x and CO₂ emissions from the road transport in the UK. Then the vehicle emission regulation and the emission monitoring methods are introduced, as well as the gap between real-world emissions and type-approval limits. Finally, the introduction narrows down to emissions from vans, van fleet characteristics, vans' NO_x control technology and the main external factors affecting the van emission performance.

1.2.1 Impact of tailpipe emissions

1.2.1.1 NO_x emission and its effects

Nitrogen dioxide (NO₂), along with nitric oxide (NO), are referred to as NO_x, which are mainly produced during the combustion of fossil fuels. NO will quickly react with certain oxidants (such as oxygen, ozone and Volatile Organic Compounds) in the atmosphere to produce secondary NO₂ ([WHO, 2010](#)). NO₂ is a toxic gas harmful to health. Short-term exposures to NO₂ can irritate and inflame airways in the respiratory system, increase susceptibility to allergens, and aggravate the symptoms of those already suffering from lung or heart function reduction ([Defra, 2021b](#)). Long-term exposures to NO₂ has been associated with premature death and years of life lost ([Hoek et al., 2013](#); [EEA, 2020](#)). Besides, NO₂ together with

other NO_x will react with substances in the air to form additional pollutants, such as particulate matter and ozone (O₃) ([Nriagu, 2019](#)), both of which are attributed to adverse health effects when inhaled. NO_x also has several negative impacts on ecosystems ([EEA, 2020](#)) (e.g., eutrophication, acidification). Deposition of nitrogen can change the chemical make-up of minerals, soils and aquatic systems and damage sensitive ecosystems such as lakes and forests ([Defra, 2021b](#)).

The total UK NO_x emissions were 839 kilo tonnes in 2019 ([NAEI, 2021b](#)), and almost one third of NO_x emissions came from the road transport sector. Figure 1-1-a shows that vans were responsible for 36.1% of NO_x emissions in the road transport sector in 2019. Though the total NO_x emissions from the road transport sector have decreased by 77.8% between 1990 and 2019, total NO_x emitted by vans has only saw a slight reduction of 6.7% (see Figure 1-1-b). Moreover, it is estimated that about 80% of the NO_x concentrations at roadsides are contributed by the road transport ([Defra and DfT, 2017](#)), among which diesel vans account for 22%.

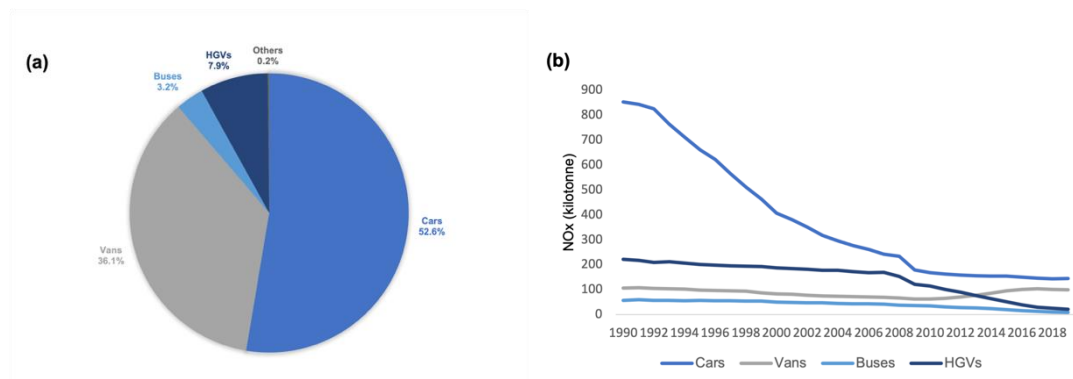


Figure 1-1 (a) Source apportionment of NO_x by transport mode in the UK in 2019 [left]; (b) NO_x emitted by transport mode during 1990-2019 [right] ([NAEI, 2021b](#))

1.2.1.2 Greenhouse gases and climate change

GHG emissions include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and fluorinated gases ([DfBEIS, 2021a](#)). GHG emissions are believed to drive global warming ([IPCC, 2014](#)), they act like the glass in the greenhouse, trapping the earth's outgoing longwave infrared radiation, which heats the lower atmosphere. To limit the global warming to well below 2°C and pursue efforts to

keep it to 1.5°C relative to pre-industrial temperatures, the UK as well as the EU aim to achieve carbon-neutral by 2050².

In 2019 in the UK, the total GHG emissions were 43.8% lower than they were in 1990 ([DfBEIS, 2021a](#)), however, the road transport sector has seen little change between 1990 and 2019. It contributes nearly a quarter of total domestic GHG emissions³, and passenger cars and vans together account for 78.5% of the road transport GHG emissions in 2019. Though there is a great improvement in fuel efficiency of new light-duty vehicles (passenger cars and vans), the emission reduction has been largely offset by their increasing use ([DfT, 2020b](#)). Among the main source of road transport emissions, vans have seen the largest increase in traffic and are the only transport mode whose absolute GHG emissions are still growing (see Figure 1-2) between 1990 and 2019.

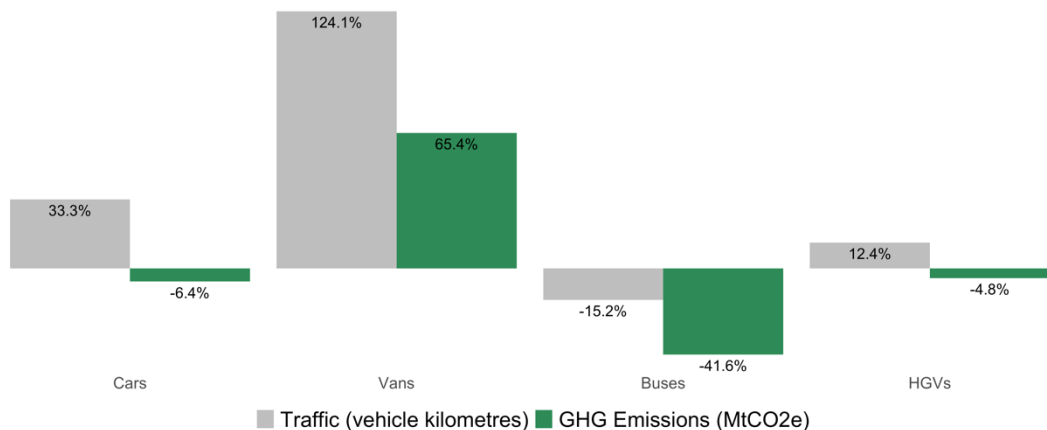


Figure 1-2 Change in road transport traffic (vehicle miles) and GHG emissions, 1990-2019 ([DfBEIS, 2021a](#); [DfT, 2021c](#))

1.2.2 Vehicle emission regulations

1.2.2.1 Euro emission standard

- Laboratory test

LDVs are major contributors to roadside NO_x emissions ([Defra and DfT, 2017](#)). In order to reduce the impact of tailpipe emissions on public health and the environment, the EU has set limits for the maximum amount of NO_x as well as other pollutants (carbon monoxide (CO), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), particulate matter (PM), particle number (PN)) that can

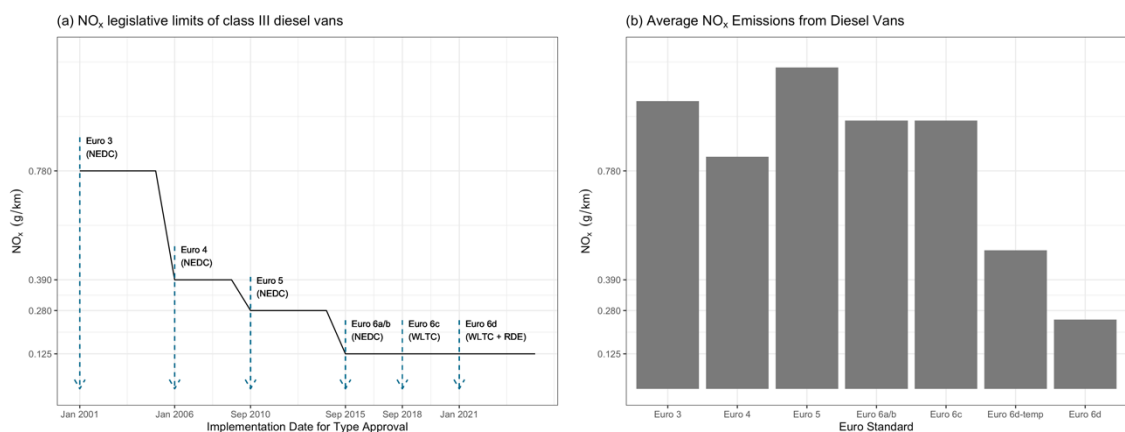
² https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en

³ CO₂ is the most prominent tailpipe GHG emissions in the road transport sector (94%), the research presented in this thesis assumes GHGs include CO₂ only.

be emitted from LDVs, known as Euro standards. New LDV models are therefore tested in a laboratory on a chassis dynamometer with emissions (expressed in g/km) measured over a driving cycle before they can be driven on roads.

Vehicles were once tested on the New European Driving Cycle (NEDC). The NEDC's uniformed speed profile is unrealistic and therefore leads to a big discrepancy between on-road and type-approval NO_x emissions from vehicles ([Weiss et al., 2011](#); [Chen and Borken-Kleefeld, 2014](#); [DfT, 2016](#)). From September 2017 (Euro 6c onwards), a new test cycle called the Worldwide Harmonised Light Vehicle Test Cycle (WLTC) has gradually replaced the previously used NEDC. The WLTC covers a wider range of driving situations and represents a more realistic driving behaviour. The introduction of the WLTC is expected to reduce the divergence between type-approval and real-world driving emissions ([Stewart et al., 2015](#); [Ko et al., 2017](#); [Pavlovic, J. et al., 2018](#)).

Figure 1-3-a shows the main NO_x legislative limits for diesel vans over the last 20 years. The x-axis is the implementation date of each Euro standard for type-approval class III vans⁴, and the y-axis is its corresponding NO_x emission limit. Even though the emission regulation becomes more and more stringent, the real-world NO_x emissions are not improving as expected, especially Euro 5 ([ICCT, 2019a](#); [Chen et al., 2020](#)). Only after the implementation of Euro 6a/b, the most strict NO_x regulation (emission standard declines from 0.28 g/km (Euro 5) to 0.125 g/km (Euro 6a/b), a reduction of 55%⁵), a big improvement has been seen ([ICCT, 2019a](#)) for the on-road NO_x emission performance of diesel vans (see Figure 1-3-b).



⁴ Vans can be further classified into three sub-categories by reference mass, where class I are vans not exceeding 1305kg, class II are those between 1305kg and 1760kg, and class III are those exceeding 1760kg.

⁵ Regulation (EC) 715/2007

Figure 1-3 (a) NO_x legislative limits (g/km) for class III diesel vans; (b) average NO_x emissions (g/km) from diesel vans (adopted from [NAEI \(2021a\)](#))

- On-road test

Although the WLTC is a better reflection of normal on-road conditions compared with the NEDC, it is still a chassis dynamometer test cycle and cannot cover all the on-road driving variations. To supplement the lab test, a new real driving emission (RDE) test procedure was introduced in September 2017 for cars and one year later for vans, as the final part of testing a LDV⁶. This RDE test uses portable emission measurement systems (PEMS) to measure exhaust pollutants of NO_x and PN (Particle Number) on public roads in real traffic ([Giakoumis, 2017](#); [ICCT, 2017](#)). It includes three speed phases (urban, rural and motorway), with random acceleration and deceleration patterns⁶.

The RDE test is introduced in two stages. In stage 1 (Euro 6c emission standard) the RDE procedure would only be used for monitoring purposes, to allow the automakers, technical services, and type-approval authorities to become familiar with the new test procedure. In stage 2 (from Euro 6d-temp onwards) new LDV models have to pass both lab tests and RDE tests before they can be put on sale. Corresponding requirements would be set for RDE tests in the form of conformity factors (see equation 1-1).

$$NTE_{pollutant} = EURO_6 * CF_{pollutant} \quad (Eq. 1 - 1)$$

Where $NTE_{pollutant}$ is the not-to-exceed limit of a certain pollutant at any possible RDE test at type approvals, $EURO_6$ is the applicable Euro 6 emission limit, $CF_{pollutant}$ is the conformity factor. The temporary conformity factor is 2.1 (Euro 6d-temp emission standard) for new types approvals and then drops to 1.5 (Euro 6d emission standard) for new type approvals.

On-road emission tests by [Suarez-Bertoa et al. \(2019\)](#) have already shown improvements in NO_x emission performance by diesel cars alongside the Euro standard: tested Euro 6c and Euro 6d-temp diesel cars have met the emission limits applicable to Euro 6d-temp during RDE tests. The RDE test would be applied to all new vans by 2022. It is expected that the RDE test could further close the gap between real-world and test cycle emissions and ensure that vehicles meet the emission standards on roads.

1.2.2.2 CO₂ emission regulation

Road transport is the most significant contributor to the UK's domestic GHG emissions, responsible for 24.3% in 2019 ([DfBEIS, 2021b](#)). To reduce CO₂

⁶ Commission Regulation (EU) 2017/1151

emissions in the road transport sector, the EU introduced emission performance standards for passenger cars and vans respectively in 2009 and 2011, setting a mandatory fleet-wide target of 175 g CO₂/km by 2017 and 147 g CO₂/km by 2020 for vans⁷. In 2019, stricter fleet-wide CO₂ emission targets⁸ have been set for vans, with a 15% reduction from 2025 on and a 31% reduction from 2030 on (based on the new WLTC from 2021 onwards).

With the implementation of the stricter regulation, the fleet-wide CO₂ emissions of new LDVs has been reduced by technological improvements in fuel efficiency ([National Research Council, 2015](#)) and raising the share of electric vehicles (EVs). The laboratory tests have shown that the average CO₂ emissions of the new passenger cars decreased by 11.8% in 2020 in the EU compared with the previous year⁹, while the average CO₂ emissions of new vans were 155.7 g/km in 2020, only a slight decrease by 1.5%. The take-up of alternative fuelled vans has also been slow, where hybrid electric vehicles¹⁰ (HEVs), plug-in hybrid electric vehicles¹¹ (PHEVs) and battery electric vehicles (BEVs) only represented 2.2% of the newly registered vans in 2020 in the EU, Iceland, Norway and the UK.

1.2.3 Emission measurement methods

Diverse methods have been developed to monitor the real-world emissions from LDVs ([Ropkins et al., 2009](#); [Franco, V et al., 2013](#)). This section introduces and compares the most widely used emission measurement techniques: chassis dynamometer tests, portable emission measurement systems (PEMS), and remote sensing.

1.2.3.1 Chassis dynamometer test

Chassis dynamometer tests are conducted in laboratories. A chassis dynamometer platform consists of several major systems that control and monitor different aspects of the test. One large roller is placed underneath the test

⁷ REGULATION (EU) No 510/2011 <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2011R0510:20120313:en:PDF>

⁸ https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en (after the UK leaves the EU the regulation would be at least as ambitious as this one)

⁹ https://ec.europa.eu/clima/news-your-voice/news/average-co2-emissions-new-passenger-cars-registered-europe-decreased-12-2020-and-share-electric-cars-2021-06-29_en

¹⁰ A hybrid electric vehicle uses an internal combustion engine plus an electric motor.

¹¹ A plug-in hybrid electric vehicle is a hybrid electric vehicle that can be connected to a mains electricity supply to replenish the electric supply.

vehicle's front wheels that are used to replicate the road and simulate the driving resistance (e.g., aerodynamic drag and rolling resistance) to the vehicle, while a human or robot operates the vehicle according to a predefined driving cycle. During the tests the exhaust pollutant is diluted continuously with filtered ambient air using a Constant Volume Sampling (CVS) system and the exhaust emission concentration is measured second-by-second using a gas analyser ([Alves et al., 2015](#); [Burke et al., 2018](#)).

Chassis dynamometer laboratory tests have been employed worldwide to measure pollutant and GHG emissions of vehicles for type-approvals. It allows for the largest degree of control over test conditions (e.g., speed profile, ambient temperature, driving resistance). However, the main disadvantage of the chassis dynamometer also comes from the limited input parameters variability, which leads to not representing the real-world driving and environmental conditions ([Franco, V et al., 2013](#)). In addition, both the initial capital investment and operation cost of chassis dynamometer tests are very high.

1.2.3.2 Portable emissions measurement systems

Portable emission measurement systems (PEMS) are an on-board measurement to monitor the vehicle emissions under real-world operations. The main component of PEMS is a set of exhaust gas analysers directly connected to the tailpipe. CO, CO₂, THC and NO_x exhaust gas concentrations are measured with a time resolution of one second ([Weiss et al., 2012](#); [O'Driscoll et al., 2016](#)). An exhaust flow meter is included to measure the mass flow and exhaust temperature. Global Positioning System (GPS) data logged to track vehicle speed and location, with meteorological parameters also recorded (ambient temperature and humidity). In addition, a data logger is often connected to the engine control units (ECUs) or the controller area network (CAN) ([Beusen et al., 2009](#)), providing all the relevant vehicle and engine parameters.

PEMS have been used in the RDE test procedure of type approval of vehicles in Europe to verify the NO_x and PN emissions in the normally-operating conditions in the real-world¹². The main advantage of PEMS is that it can capture the emission performance of vehicles under the real-world conditions ([Ghaffarpasand et al., 2020](#)). The main limitation is that the test results are less repeatable due to the day-to-day variation in driving and environmental conditions ([Franco, V et al., 2013](#)). PEMS testing is also time-consuming and expensive even for small samples of vehicles.

1.2.3.3 Remote sensing

¹² COMMISSION REGULATION (EU) 2016/427

A remote sensing system is positioned at the roadside ([Bishop, G. A. and Stedman, 1996](#); [Huang et al., 2018](#)) or above the roadway ([Ropkins et al., 2017](#); [Ghaffarpasand et al., 2020](#)). It measures the concentration of pollutants in the exhaust plume of a passing vehicle via spectroscopy. Speed and acceleration when the vehicle passes by the measurement location, vehicle information (fuel type, Euro standard, make, model, etc.) are also recorded together with the snapshot of vehicle emissions.

Compared with chassis dynamometer tests and PEMS tests that collect second-by-second emission data of a limited number of vehicles, remote sensing technology is able to sample a large number of vehicles in a short period of time. As only one snapshot of the emissions from a vehicle is recorded, some form of data aggregation is needed to derive useful insights. Remote sensing is considered well-placed to monitor the overall fleet real-driving emission behaviour and trends by Euro standard, registration year, or make and model for example ([ICCT, 2018](#); [Ghaffarpasand et al., 2020](#)). Remote sensing has also been used to identify candidate high-emitters of CO, HC and NO ([Huang et al., 2018](#); [Rushton et al., 2021](#)). The main limitation is that there is a requirement for the minimum sample size of remote sensing records for aggregation analysis ([Chen et al., 2019](#)). And how to robustly characterize the fleet emission behaviour ([Carslaw, D. et al., 2011](#); [Rushton et al., 2021](#)) and effectively identify the threshold for candidate high-emitters ([Pujadas et al., 2017](#); [Huang et al., 2019](#)) remains debated. In addition, of the successful delivery of remote sensing measurements and survey campaigns in cities is subject to the constraints of suitable sampling sites, favourable weather, traffic and vehicle operating condition ([ICCT, 2018](#)).

1.2.3.4 Fuel consumption and emission modelling

Due to the cost or the feasibility of the test conditions, vehicle emission measurement campaigns are not always an option. In this case, emission models are a powerful approach to predict vehicle emissions and evaluate environmental policies ([Zamboni et al., 2013](#); [Wang and Rakha, 2016](#)). For emission projection at national or regional levels, macroscopic emission models (e.g., MOBILE, COPERT, HBEFA, ARTEMIS) based on average speed or traffic situations are used. For emission estimation at local traffic levels, microscopic emission models (e.g., PHEM, MOVES) based on instantaneous engine speed and torque are used ([Smit et al., 2008](#)).

The accuracy of emission models is largely dependent on the representativeness of emission factors ([Franco, V et al., 2013](#)). Different emission measurement technology can derive emission factors at different resolution. Chassis

dynamometer and engine dynamometer test data can provide vehicle emissions as a function of instantaneous engine power and engine speed. For example, instantaneous emission model PHEM ([Hausberger and Rexeis, 2017](#)) uses chassis dynamometer measurements to underpin the simulation of engine and emission map, and it's able to predict second-by-second vehicle fuel consumption and exhaust emissions (g/s). On the other hand, it's difficult for PEMS and remote sensing to accurately allocate measured instantaneous emissions to vehicle or engine status ([Franco, V et al., 2013](#)), as a result these emission measurement technologies are more suitable to derive average emission factors based on speed.

1.2.4 Vans in the UK

1.2.4.1 Background

Light goods vehicles (LGVs), or vans are a type of 4-wheel vehicle constructed for transporting goods and must have a gross weight of 3.5 tonnes or less ([DfT, 2022a](#)). Van numbers and fleet share has grown significantly over the last 25 years in Great Britain¹³, increasing 92.9% to 4.1 million licensed vans in 2019 ([DfT, 2022b](#)), and accounting for 10.7% of total licensed vehicles. Vans can be further classified into three sub-categories (class I, class II, and class III) by reference mass. Large class III vans take up over 60% vans on the road ([DfT, 2022b](#)), and there has been a growth in the share of large class III vans being registered recently ([SMMT, 2019](#)).

Van activity (vehicle kilometres travelled) has also met a significant growth, increasing by 106.2% over the last twenty-five years (compared with 29.8% for cars and 12.8% for heavy goods vehicles) ([DfT, 2020c](#)). Total van traffic has reached a record high of 55.5 billion vehicle miles in 2019 and making up 16% of all motor vehicle traffic ([DfT, 2020c](#)). The van survey conducted by [DfT \(2020d\)](#) in 2019-2020 estimated that vans primarily used for 'carrying equipment, tools and materials' account for 61% of total van mileage, followed by 'delivery/collection of goods' (24%).

Thanks to the improvement of emission performance over recent years, with manufacturers responding to the introduction of the Euro 6a/b/c then d-temp and d legislation, total NO_x emitted by vans is not following the trend of van fleet share and use. However, the share of NO_x contributed by vans in the road transport sector have increased 279.1% between 1994 and 2019, and [NAEI \(2021b\)](#) estimated that vans contributed 36.1% of overall road transport NO_x emissions in

¹³ The vehicle stock statistics by DfT don't include data of the UK before 2014, as a result data in Great Britain is used.

2019. Vans are responsible for a disproportionately large share of NO_x emissions in the road transport sector mainly for two reasons. Firstly, the van market in the UK is dominated by compression-ignition diesel engines, in 2019 diesel vans accounted for 96.3% of the licensed vans in Great Britain ([DfT, 2022b](#)). A fleet dominated by diesel vehicles will certainly contribute more total NO_x emissions ([O'Driscoll et al., 2018](#)). Secondly, vans in the real-world emit much more than the emission limit. Though limited research has studied the real-world emissions from diesel vans ([ICCT, 2019a](#); [Chen et al., 2020](#)), it is assumed that diesel vans might be following a similar trend as diesel cars, where the real-world emissions exceed the emission limits several times for Euro 3-Euro 6a/b.

To help decarbonise the entire vehicle fleet by 2050, the UK government has brought forward the end to the sale of new petrol and diesel cars and vans to 2030 (from 2040), with all new cars and vans be fully zero emission from the tailpipe from 2035¹⁴. Figure 1-4 shows the uptake speed of BEVs, PHEVs and HEVs of the newly registered cars and vans. In 2020 the new registration of BEV cars nearly tripled (+183.7%) compared to the previous year, and accounted for 6.6% of the newly registered cars. BEV vans has also seen an increase (64.0%) in 2020 and made up 1.9% of new registrations in 2020 ([DfT, 2022b](#)), but the growth is less significant than BEV cars. In addition, in the van sector, the registration of PHEVs and HEVs is very rare.

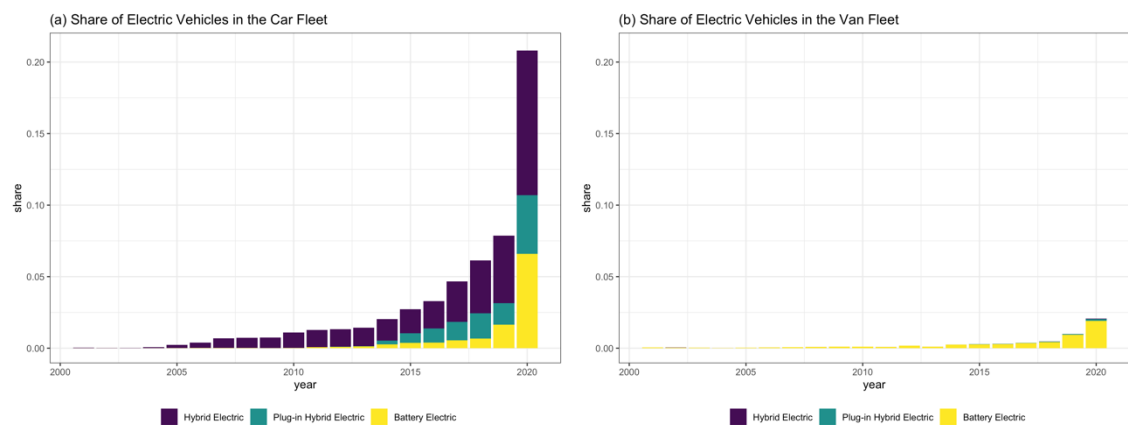


Figure 1-4 AFV take-up speed of (a) cars [left]; (b) vans [right]

Apart from a fast electrification transition, vehicles can also reduce CO₂ emissions by 'avoiding travel' (reduce the amount of mobility required) ([Sikarwar et al., 2021](#)) and 'shifting travel' (transfer from car use to sustainable mode of transport) ([Cuenot et al., 2012](#); [Brand et al., 2021](#)). However, the van traffic

¹⁴ <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution>

demand is more likely to remain stable or even continue growing and account for up to 21% of traffic mileage by 2050 ([DfT, 2018a](#)), considering the growth of population and online-shopping. The urban traffic could be slightly decreased because of the introduction of innovative vehicles such as e-cargo bikes ([Energy Saving Trust, 2020](#)) and collaboration between operators on the same route ([Clarke et al., 2018](#)).

1.2.4.2 NO_x abatement technologies

Euro 6 type-approval limit (Euro 6a/b) for NO_x has decreased 55% compared with Euro 5. Moreover, the introduction of the more dynamic WLTP test cycle (Euro 6c onwards) and the RDE test procedure (Euro 6d-temp onwards) are also posing challenges to manufacturers. To meet the more and more stringent emission standards, manufacturers are adopting various NO_x control technologies: exhaust gas recirculation (EGR), lean NO_x trap (LNT), and selective catalytic reduction (SCR).

- EGR

EGRs have been used widely in both gasoline and diesel cars from Euro 3 to Euro 6 ([Yang, L. et al., 2015](#)), and can also be used in conjunction with LNTs or SCRs. It reroutes some of the exhaust gas back into the engine's combustion chamber and dilutes the air/fuel mixture. A lower oxygen content leads to a cooler combustion process, which reduces the production of engine-out NO_x. The main limitation is that EGR systems are more suitable to reduce NO_x emissions during low load operation, because when the engine is driven under a high load (e.g., at high speed, or on a steep road), the EGR is switched off temporarily to maintain the performance of the engine ([Zheng et al., 2004](#)).

- LNT

A LNT combines a stainless steel catalytic converter with an adsorber. Under lean-burn conditions, NO_x is captured and stored onto a catalyst rather than being emitted from the tailpipe. When the trap is saturated, the system is regenerated by short periods of fuel-rich operation, during which NO_x is converted into harmless nitrogen (N₂) and water. Due to the physical size of the LNT, it's mainly applied on vehicles with engine displacements under 2 litres. When the vehicle is driven under high engine load, there is a possibility that the regeneration process is overwhelmed, leading to high NO_x emissions ([Yang, L. et al., 2015](#)).

- SCR

SCR is a highly effective NO_x exhaust after-treatment abatement technology that has been used in HDVs since the introduction of Euro IV, and now it has been deployed in LDVs to achieve a better NO_x control ([Franco, Vicente et al., 2014](#)).

A urea-based additive called diesel exhaust fluid is sprayed into the exhaust stream and it vaporizes to yield CO₂ and ammonia (NH₃). A chemical reaction between NH₃ and NO_x is set off in the exhaust gas to produce N₂ and water. SCR systems are suitable for LDVs with engine size above 2 litres. An effective NO_x reduction process in the SCR system requires an exhaust temperature of at least 180°C ([Yang, L. et al., 2015](#); [Ntziachristos et al., 2016](#)). As a result SCRs are found to perform better than other technologies in an extra-high speed phase (extra high load), which enables the SCR meet certain operational temperature ([Moody and Tate, 2017](#)). However in an extra-urban phase (stop-start driving conditions), vehicles equipped with SCRs are found to have high NO_x emissions ([Koebel et al., 2002](#); [Johnson, T., 2014](#); [Moody and Tate, 2017](#)).

1.2.4.3 External factors affecting NO_x and CO₂ emissions

One of the main contributors to the divergence between the type-approval and real-driving emissions is that the driving and operational conditions that might have an influence on the real-world emission performance cannot be fully covered by lab tests ([Zachiotis and Giakoumis, 2019](#)). This section introduces three important influencing factors: auxiliary electrical devices, ambient temperatures, and road grades.

- Auxiliary electrical devices

Electric power imposed on the engine when conducting the NEDC test procedure is 350W¹⁵, however in reality drivers tend to use more electrical devices (e.g., electric seat, steering wheel heating, navigation system) ([Zachiotis and Giakoumis, 2019](#)). It is estimated that the use of auxiliary systems will increase the CO₂ emissions by 6% for small passenger cars and 3.5% for vans on average ([ICCT, 2015](#)).

One typical example of the use of auxiliary systems in the van sector is refrigerated vans for grocery home deliveries. They are typically 3.5-tonne gross weight vehicles equipped with temperature-controlled units called Transport Refrigeration Units (TRUs). Vehicles with an extra weight of TRUs would consume more fuel and emit more NO_x, let alone the vehicles' diesel engines are also powering the refrigeration units, which further elevates the emissions. The UK online grocery industry is among the most developed in the world ([Hood et al., 2020](#)) and demand for grocery home deliveries has surged since the outbreak of COVID-19, which lead to an increasing use of the refrigerated vans.

- Ambient temperature

¹⁵ (EU) 2019/313

The test temperature for the WLTP type-approval chassis dynamometer test is set at 23°C for tailpipe pollutant (for CO₂ corrected to 14°C). The average ambient temperature in the UK when the real-world driving is conducted, will usually be lower than 23°C. Previous studies ([Sjödin et al., 2017](#); [Grange et al., 2019](#); [ICCT, 2019a](#)) have identified the temperature dependence of NO_x emissions on diesel cars, where lower ambient temperatures result in higher NO_x emissions. As the ambient temperature decreases, the NO_x aftertreatment systems such as EGR, LNT and SCR might be ineffectively functioning ([Kwon et al., 2017](#); [Ko et al., 2017](#)). In addition, these studies have also indicated that the ‘low temperature NO_x emission penalty’ is stronger for pre-Euro 6a/b vehicles (Euro 3-5) than for Euro 6a/b. [ICCT \(2019a\)](#) has also shown that for Euro 6a/b, NO_x emissions are only elevated when the ambient temperature is below 10°C, but for the temperature bin of 10°C-20°C and 20°C-30°C, NO_x emissions are almost the same.

- Road grade

Road grade is defined as the ratio of the altitude of the path to the horizontal of the path. It has been identified as the major parameter that affects the emission performance of the test diesel van by [Zachiotis and Giakoumis \(2019\)](#). A steeper road grade would elevate the engine load because of the gradient resistance imposed, which unavoidably increases the NO_x emissions. RDE tests for diesel 5 cars shows that a 5% road grade would rise the NO_x emissions by 4.06 times compared with a 0.5% road grade ([Costagliola et al., 2018](#)). It is estimated that for a Euro 6 class III diesel van, even a 2% elevation in road grade can increase the NO emissions by 26.6% and fuel consumption by 27.4% ([Zachiotis and Giakoumis, 2019](#)).

1.3 Research gaps

Knowledge of the real-world vehicle emissions is important to assess the effectiveness of current control measures and substantiate future policy decisions. Despite the fact that vans contribute a significant amount of NO_x and CO₂ emissions to the road transport sector in the UK, little is known about the real-world emission performance of vans. Based on the literature review, this thesis identifies three gaps:

- **Gap G1: Real-world NO_x and CO₂ emission factors of vans.**

The studies on tailpipe NO_x and CO₂ emissions from LDVs have been mainly focused on passenger cars, and only a limited amount of research has studied the real-world emission performance of vans. Apart from Euro standards derived from chassis dynamometer tests, representative van NO_x and CO₂ emission

factors in the real-world are needed, as an accurate estimation of emission factors is essential to predict total emissions and evaluate environmental policies.

- **Gap G2: Uncertainty in exhaust emissions from vans.**

One of the main reason causing the discrepancy between real-world NO_x emission performance of vehicles and Euro standard type-approval limits is the day-to-day variation in driving and environmental conditions (auxiliaries, cargo weight, road gradient, etc.). Though many studies have evaluated how the external factors (extra load, ambient temperature, road grade, speed profile, etc.) would affect the real-world emission performance of passenger cars, having a full assessment of the variability around real-world van emissions is still necessary to better mitigate van related pollutions.

- **Gap G3: Vans future emission trend.**

Vans have an important role to play in meeting future emission reduction targets. Research on how to decarbonize the road transport sector has been largely limited to passenger cars and heavy goods vehicles, while vans are often generalised with passenger cars in the LDVs sector. A robust and detailed analysis of the future van emission trend based on van fleet's unique characteristics and driving pattern is needed, to see whether the emission reduction speed is fast enough to reach 2050 net-zero target in the van sector.

1.4 Objectives and implementation

The primary aim of this research is to develop a reliable evidence-based knowledge of the van fleet composition, use and emission contribution (NO_x and CO₂). To address the overall aim, the objectives and their corresponding methods are:

- **Objective O1: Develop an accurate estimation of real-world van CO₂ and NO_x emission factors.**

Emission model simulations and remote sensing can be used to have a detailed assessment and comparison of the average NO_x and CO₂ emission factors of standard vans. Firstly, the instantaneous emission model PHEM will be validated under both normal and heavy-loaded conditions. Then PHEM will be used to estimate the CO₂ and NO_x emissions of standard vans as well as the elevation of emissions from refrigerated vans. The first part is demonstrated in **Chapter 2**. Secondly, the Gumbel distribution will be introduced to remote sensing measurements to better account for the share and emission contribution from “high-emitting” vehicles and have a robust description of the fleet NO_x emission behaviour. The second part is demonstrated in **Chapter 3**.

- **Objective O2: Assessing the uncertainty associated with real-world NO_x emission estimation.**

Emission models are a powerful tool to study the impact of changing driving and environmental conditions on vehicle emission performance, especially when the test conditions are not available in the real-world. Objective O2 is firstly accomplished by using the validated emission model PHEM to evaluate the impact of ambient temperature, cargo weight and driving condition on refrigerated van emissions. The first part is demonstrated in **Chapter 2**. Then the remote sensing results derived from the Gumbel distribution will also be used to assess the impact of changing driving (speed and acceleration) and environmental (road grade and ambient temperature) conditions on van emission performance. To ensure the sample size is big enough to conduct statistical analysis, the two-sample Kolmogorov-Smirnov test (K-S test) will be applied on remote sensing dataset to investigate whether the NO_x emission data from different measurement sites share a statistically similar distribution and can be merged into a bigger dataset. The second part is demonstrated in **Chapter 3**.

- **Objective O3: Predicting the future van emission trend.**

Objective O3 will be addressed by identifying the key enablers and barriers affecting the effectiveness of CO₂ and NO_x emission reduction pace of the van fleet, and several future scenarios will be built on them. The future emission trajectories in the van sector will be projected under different scenarios to see whether tailpipe net-zero in the van sector can be reached by 2050. This objective will be addressed in **Chapter 4**.

1.5 Thesis outline

Since this thesis is submitted in the alternative format by publications, the subsequent three chapters present the three papers composed during the PhD study period before a final concluding chapter. **Chapter 2** validates the instantaneous emission model PHEM and develops real-world CO₂ and NO_x emission factors for standard vans and refrigerated vans. **Chapter 3** characterizes van NO_x emission performance and identifies the cut-off point for candidate high-emitters of diesel vans by applying the Gumbel distribution on remote sensing measurements. **Chapter 4** investigates the CO₂ and NO_x emission trend in the van sector in Great Britain from 2020 to 2040 under the 2030 ICE phase-out. **Chapter 5** summarises the principal findings of the thesis, highlights the contributions, reflects on the limitations, and suggests the outlook for future studies.

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Chapter 2 Real-World CO₂ and NO_x Emissions from Refrigerated Vans

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Abstract

Refrigerated vans used for home deliveries are attracting attention as online grocery shopping in the UK is expanding rapidly and contributes to the increasing greenhouse gas (CO₂) and nitrogen oxides (NO_x) emissions. These vans are typically 3.5-tonne gross weight vehicles equipped with temperature-controlled units called Transport Refrigeration Units (TRUs), which are usually powered off the vehicles' engine. It is obvious that vehicles with added weight of TRUs consume more fuel and emit more NO_x, let alone the vehicles' diesel engines are also powering the refrigeration units, which further elevates the emissions.

This research uses an instantaneous vehicle emission model PHEM (Passenger car and Heavy duty vehicle Emission Model, version 13.0.3.21) to simulate the real-world emissions from refrigerated vans. A validation of PHEM is included using data from laboratory (chassis dynamometer) tests over a realistic driving profile (the London Drive Cycle), to assess its ability to quantify the impact of changing vehicle weights and carrying loads. The impact of the TRU weight, greater frontal area increasing aerodynamic drag and refrigeration load on van emissions is then estimated by PHEM. The influence of ambient temperature, cargo weight and driving condition on CO₂ and NO_x emission from refrigerated van are also assessed.

Overall CO₂ emissions of vans with TRUs are found to be 15% higher than standard vehicles, with NO_x emissions estimated to be elevated by 18%. This confirms the need to take into account the impact of additional engine load when predicting van emissions in this and other sectors such as ambulances which are relatively heavy, high powered vehicles. Moreover, findings of the impact of TRUs on fuel consumptions can be used to optimize fuel-saving strategies for refrigerated vans and test cases for alternative low- or zero-emission technologies, to support progress to a sustainable net-zero society.

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Keywords

real-world emissions; light commercial vehicles; transportation refrigeration units (TRUs); PHEM; Carbon Dioxide (CO₂); Nitrogen Oxides (NO_x)

2.1 Introduction

Estimation of road transport emissions in the UK shows that light commercial vehicles (LCVs), or vans have seen the fastest growth in both CO₂ and NO_x emissions, accounting for 17% of CO₂ emissions and 35% of NO_x emissions in 2017 ([NAEI, 2019](#)), while van numbers only make up around 10% of total licensed vehicles ([DfT, 2018b](#)). One of the main factors contributing to the increasing van emissions is the rapid rise in the heavy class III² van demand ([SMMT, 2019](#)). Heavy vans are deployed for a wide range of services such as construction, refrigerated food delivery and ambulances. These vans are always with additional engine load, which is more polluting than standard, un-modified vehicles. Among all the modified vans with high-power demands, refrigerated vans are considered the most important due to their growing fleet share as online grocery continues to gain market over the recent years ([Braithwaite, 2017](#)).

Refrigerated vans are typically 3.5-tonne gross weight vehicle equipped with temperature-controlled units called Transport Refrigeration Units (TRUs), which are usually powered off the vehicles' diesel engine. It is obvious that vehicles with added weight of TRUs consume more fuel and emit more NO_x, let alone the vehicles' diesel engines are also powering the refrigeration units, which further elevate the emissions. [Braithwaite \(2017\)](#) suggested that there were 15,000 refrigerated vans used for grocery home delivery in the UK in 2016 and the annual distance travelled by refrigerated vans is at least twice the average ([DfT, 2019](#)). The COVID-19 outbreak has also accelerated online grocery shopping and home delivery orders were found to grow by 38% from 2.1 million to 2.9 million per week³ in the UK.

Despite the fact that vans have contributed a significant proportion to total UK's CO₂ and NO_x emissions, the majority of existing studies focus on the passenger

² Vans in the UK are defined as 4-wheel vehicles constructed for transporting goods and having a gross weight of 3500kg or less. They can be further classified into three sub-categories by reference mass, where class I are vans less than 1305kg, class II are those between 1305kg and 1760kg, and class III are those above 1760kg.

³ <https://www.gov.uk/government/speeches/environment-secretarys-statement-on-coronavirus-covid-19-26-april-2020>

car emissions ([Carslaw, D.C. et al., 2013](#); [Chen and Borken-Kleefeld, 2016](#); [Pavlovic, Jelica et al., 2016](#)). Considering many studies have already demonstrated the gap between laboratory and real-driving emissions for passenger cars ([Carslaw, D. et al., 2011](#); [O'Driscoll et al., 2018](#); [Tietge et al., 2019](#)), it is expected there is a significant divergence for vans as well. Besides, all the European emission standard for vans follow passenger cars⁴ by one year. Time delays between emission legislation and its effective implementation may well lead to a larger discrepancy between van emissions generated from lab test cycle and real-world driving. In order to better understand and control the negative impact of CO₂ and NO_x emissions on public health and the environment, it is considered both timely and significant to examine on-road emissions from vans.

To assess the environmental impact of vehicle exhaust pollutants, numerous emission models have been developed. Macroscopic emission models based on average speed or traffic situations (e.g., MOBILE, COPERT, HBEFA, ARTEMIS) ([Smit et al., 2008](#)) are suitable for emission estimation for national or regional inventories, but they might be unreliable when applied to local traffic situations ([Ahn and Rakha, 2008](#)). Microscopic emission models (e.g., PHEM, MOVES) ([Boulter et al., 2007](#)) better capture vehicle emission behaviour given that they require detailed input data such as second-by-second speed profile, altitude and signals, as well as the design and operation strategy of engine and powertrain ([Küng et al., 2019](#)). Microscopic models are typically used in specific user test cases and scenario testing, such as estimating the vehicle emissions of heavy goods vehicles (HGVs) in port areas ([Zamboni et al., 2013](#)), optimizing transit buses' cruising speeds range for fuel economy ([Wang and Rakha, 2016](#)), or assessing the impact of the additional engine loads of road grade on fuel consumption and exhaust emission ([Wyatt, 2017](#)). This paper uses PHEM (Passenger Car and Heavy Duty Emission Model) to estimate the emissions from refrigerated vans as it has one of the largest vehicle emission database ([Zamboni et al., 2013](#)) compared to other instantaneous emission models, and it is capable of accounting for the impact of increased weight, frontal area and refrigeration load on its emissions.

The main focus of this paper is CO₂ and NO_x emissions from refrigerated vans as CO₂ is directly linked to global warming and NO_x is detrimental to public health

⁴ The latest Euro 6d temp and Euro 6d requires light-duty vehicles to meet corresponding 'not to exceed' limits in Real Driving Emissions testing (RDE) procedure before they could be placed on the market. The RDE test has gradually taken effect since 2017 and will apply to all new passenger cars by the beginning of 2021 and all new vans by the beginning of 2022 (Commission Regulation (EU) 2017/1151).

and the environment. Independent chassis dynamometer tests over a realistic on-road driving profile (the London Drive Cycle ([Moody and Tate, 2017](#))) are used to validate PHEM's ability to simulate transient tail-pipe emissions and quantify the impact of changing vehicle weights and carrying loads. The emission performance of vans with additional loading of TRUs is then assessed by PHEM. The influence of ambient temperature, cargo weight and driving condition on CO₂ and NO_x emission from refrigerated van are also evaluated.

2.2 Method

2.2.1 PHEM characteristics and application to vans

PHEM is an instantaneous vehicle emission model able to simulate second-by-second fuel consumption and most relevant tail-pipe pollutant emissions based on transient engine maps ([Hausberger and Rexeis, 2017](#)). PHEM was first developed by the Institute for Internal Combustion Engines and Thermodynamics at the Graz University of Technology (TUG, AU) in late 90's and has been continually updated to include new technologies and advance the accuracy of prediction.

As input, PHEM requires a defined driving cycle (speed curve and road longitudinal gradient over time) at 1 Hz so it can calculate engine power demand from the driving resistance and losses. It requires vehicle specifications (tyre diameter, final drive and transmission ratio as well as a driver gear shift model) to simulate engine speed, with default parameters available. The engine power and engine speed are linked to an engine emission map specific to the test vehicle type, which underpins the simulation of vehicle fuel consumption and exhaust emissions (g/sec).

To represent average European vehicles, PHEM provide a set of predefined "default vehicles", which is based on chassis dynamometer measurements from HBEFA version 4.1 database. The database covers the most common vehicle categories (passenger cars, vans, heavy duty vehicles) from Euro 0 to Euro 6 (including Euro 6a/b, Euro 6c, Euro 6d-Temp and Euro 6d) with gasoline-, diesel- and alternatively-fuelled engine. For vehicles with selective catalytic reduction (SCR) systems such as diesel Euro 6 vans, PHEM would also activate the exhaust gas after-treatment model to achieve a more accurate prediction of NO_x emissions. In the next section, average emission data in PHEM are compared with test results of single vehicles to validate PHEM's capability to simulate second-by-second fuel consumption (CO₂) and tail-pipe emissions in defined driving cycles.

2.2.2 Laboratory validation

2.2.2.1 Driving conditions and test vehicles

Chassis dynamometer tests were conducted by Millbrook Proving Ground Ltd⁵ on behalf of Transport for London (TfL) over a drive cycle called the London Drive Cycle (LDC). The tests were performed with a warm start, compliant with the requirements of current type approval regulations⁶. During the tests the exhaust pollutant was diluted continuously with ambient air using the Constant Volume Sampling (CVS) system ([Costagliola et al., 2018](#)) and the emissions were measured second-by-second using a gas analyser.

The LDC contains 9 sub-cycles, representing 3 different road types (urban, suburban and motorway) under 3 different traffic conditions (AM peak, inter peak and free-flow)⁷ ([Moody and Tate, 2017](#)). London is assumed to be flat and the drive-cycle doesn't consider fluctuations in road gradient. The speed profile of the LDC is illustrated in Figure 2-1. Measurement data from Millbrook Vehicle Emission Laboratory tested over the LDC is considered to be authentic and representative of real-world driving behaviour and vehicle emissions of the UK city traffic streets.

⁵ <https://www.millbrook.co.uk/services/vehicle-emissions-testing-facility-powertrain/>

⁶ The Millbrook Vehicle Emission Laboratory is in accordance with the requirements of Directive 2007/46 EC Article 41, Section 3 and has been designated as a Category A Technical Service for Individual Vehicle Approvals (IVA)

⁷ AM peak is defined as: weekday morning (AM) with the highest measured volume of traffic (roughly between 7am and 9pm); inter peak is defined as: roughly between 9am and 4pm on weekdays, with traffic 10-40% lower than the AM peak; free-flow is defined as: traffic condition where individual users are virtually unaffected by the presence of others in the traffic stream.

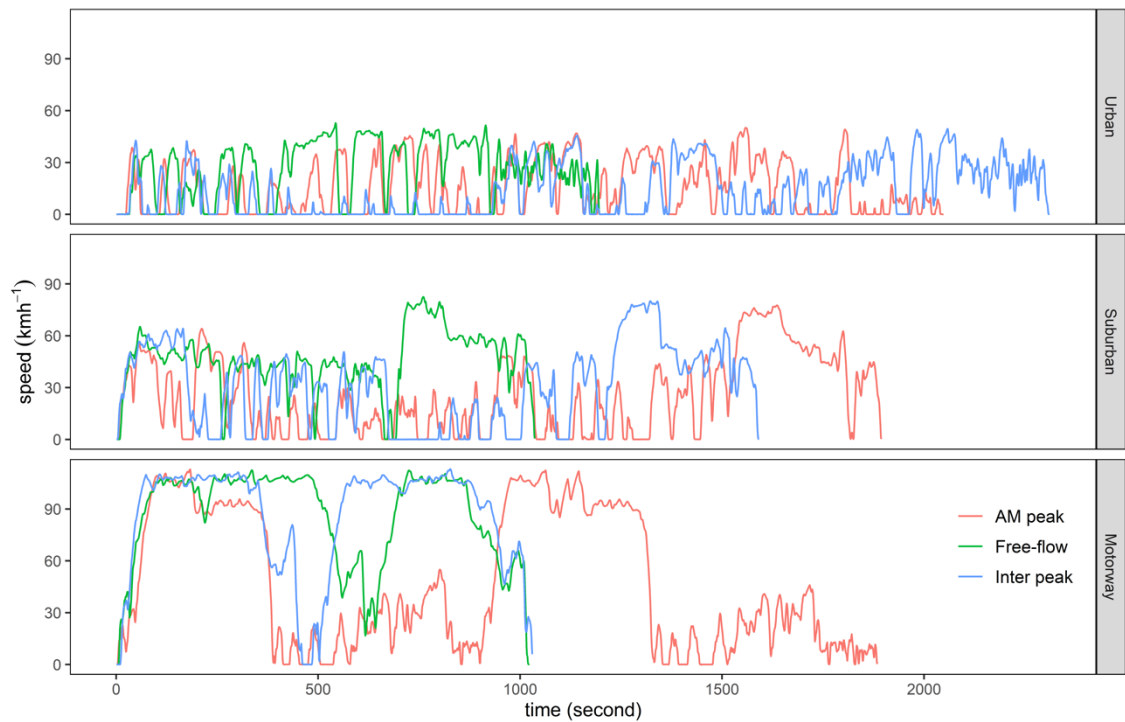


Figure 2-1 The London Drive Cycle speed profile

Two vehicles with different NO_x after-treatment systems were tested on chassis dynamometer over the LDC in this study. Vehicle A was a Euro 5 class III diesel LCV tested over the entire 140 km of the LDC, to verify PHEM's capability to simulate a standard van's fuel consumption and tail-pipe emission performance. Vehicle B was a Euro 6 small HGV tested over the suburban sub-cycle (free-flow and AM peak) in both un-laden (B1) and full-laden (B2) conditions. This allows PHEM's performance in quantifying the impact of changing vehicle weights and carrying loads to be evaluated. As vehicle B was a small HGV of 3450kg vehicle mass, we assume it had similar behaviours like a heavy van and is suitable for van validation. Detailed vehicle characteristics and drive cycle statistics are presented in Table 2-1.

Table 2-1 Technical specification drive cycle characteristics of each tested vehicles

Vehicle	A	B1	B2
Vehicle Category	N1 class III LCV	N2 HGV	N2 HGV
Vehicle Class	Euro 5 diesel	Euro 6 diesel	Euro 6 diesel
Engine Power (kw)	90	120	120
Vehicle Mass (kg)	2150	3450	3450
Vehicle Loading (kg)	375	0	4050

NO _x after-treatment system	Exhaust gas recirculation (EGR)	Selective catalytic reduction (SCR)	Selective catalytic reduction (SCR)
Road Type	Urban, Suburban, Motorway	Suburban	Suburban
Time Period	Free-flow, AM Peak, Inter Peak	Free-flow, AM Peak	Free-flow, AM Peak
Duration (s)	14019	2930	2930
Distance (km)	140	27	27
Average Speed (km/h)	35.92	32.65	32.65
Maximum Acceleration (m/s ²)	2.67	2.67	2.67

Vehicle specifications such as rated engine power, vehicle mass and vehicle loading were adjusted in PHEM's average vehicle folder to match the tested vehicles in Table 2-1, where vehicle A belongs to LCV N1-III and vehicle B belongs to HGV rigid truck (7.5-12ton). The LDC speed profile were also fed into PHEM to match scenarios tested in the laboratory. When comparing laboratory measurement and simulation results, the time shifts and instrument sensitivity need to be considered. In chassis dynamometer tests, tail-pipe emissions have been delayed and engine-out peaks smoothed through the exhaust analyser systems (CVS), while PHEM aims to predict the instantaneous tail-pipe emissions. In order to make laboratory measurements comparable with instantaneous simulation results, emission data from PHEM has been processed using a simple (equally weighted) moving-average method. By creating a series of averages over 2 seconds, a moving-average method is able to smooth out fluctuation in PHEM emission data and better track trend determination ([Hansun, 2013](#)). The time consistency between observed and modelled values has also been checked before validation.

2.2.2.2 Standard van validation

Figure 2-2 presents PHEM's capability to predict vehicle A's tailpipe emissions from three illustrative sample 300 second periods of the speed profile chosen to be contrasting the LDC, which include driving in: an urban setting during the AM peak (low speed, stop-start), a suburban district during inter peak (moderate speed) and a free-flow, higher speed motorway driving conditions. The observed

and modelled CO₂ values (second panel) are in close agreement in all driving conditions, while the observed NO_x values (bottom panel) for the specific test vehicle are slightly higher than the modelled value in high speed driving (Motorway, Free-flow section).

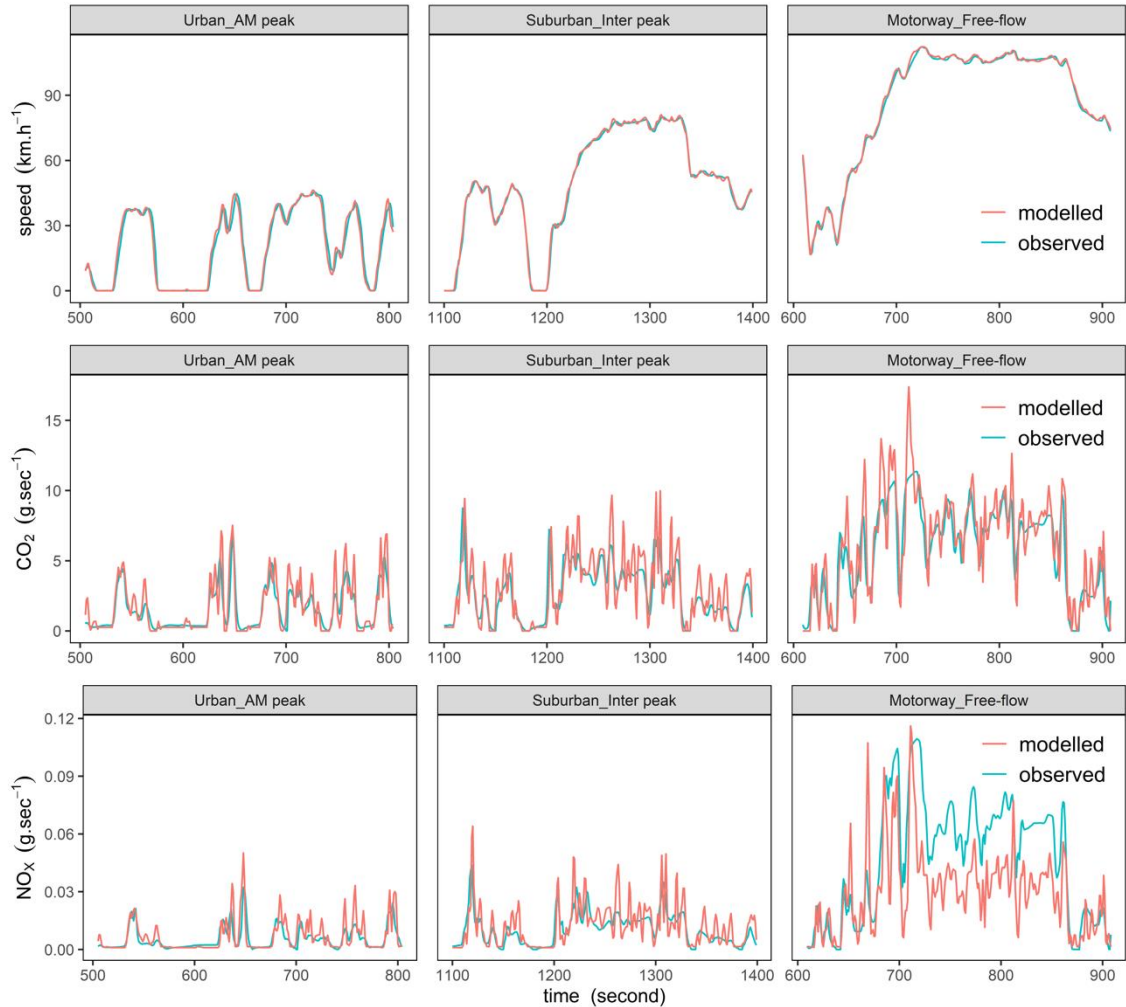


Figure 2-2 Illustrative time-series plot of different sections of the London Drive Cycle driven by vehicle A (a) speed (top); (b) CO₂ (middle); and (c) NO_x (bottom)

In order to study the reason behind the disagreement of observed and modelled NO_x emissions in free-flow driving conditions, we explored the impact of speed on both CO₂ and NO_x emissions and the results are illustrated in Figure 2-3. The second-by-second observed CO₂ and NO_x emissions are plotted against modelled CO₂ and NO_x emissions, and the emission values are grouped by driving mode of that corresponding second. The driving mode definitions proposed by ([Moody and Tate, 2017](#)) are used and expanded:

- Idle | vehicle speed < 0.5m/s and acceleration in the range $\pm 0.1\text{m/s}^2$;

- Cruise with normal speed | $0.5\text{m/s} < \text{vehicle speed} < 22\text{m/s}$ and acceleration in the range $\pm 0.1\text{m/s}^2$;
- Cruise with high speed | $\text{vehicle speed} > 22\text{m/s}$ and acceleration in the range $\pm 0.1\text{m/s}^2$;
- Acceleration with normal speed | $\text{vehicle speed} < 22\text{m/s}$ and acceleration $> 0.1\text{m/s}^2$;
- Acceleration with high speed | $\text{vehicle speed} > 22\text{m/s}$ and acceleration $> 0.1\text{m/s}^2$;
- Deceleration | $\text{acceleration} < -0.1\text{m/s}^2$.

Figure 2-3 illustrate that both CO₂ and NO_x emissions shows strong dependency on driving mode. High speed (top 15% speed range in the LDC) dominates the high emission rates, due to the elevated engine power demands needed to overcome the greater aerodynamic and rolling resistances. The left plot for CO₂ emissions shows that the second-by-second observed and modelled CO₂ data is highly consistent and the coefficients of determination (R^2) between observed and modelled CO₂ is 0.84, which demonstrates PHEM's ability to deliver a reliable, transient estimation of real-world CO₂ emissions for different speed ranges. The right plot for NO_x emissions are also in close agreement with the R^2 value of 0.67, and the main deviation between observed and modelled NO_x values is at higher emission rates ($> 0.03\text{g/sec}$) when a more aggressive driving style (top 15% speed in cruising and accelerating driving mode) is taken. Vehicle A with a EGR after-treatment system has the most effective NO_x control performance during low engine load operation ([Zheng et al., 2004](#)). When the vehicle is driven at high speed (high engine load), it's quite challenging to predict exhaust emissions as after-treatment system performance are more variable. Moreover, PHEM engine power and emission maps are based on an average (normalised) of several vehicles of that category, and there are differences between specific vehicles and fleet averages. In this case, the tested LVC is a heavy diesel van and its engine and emission map may perform slightly worse than the average sized van of its type in PHEM.

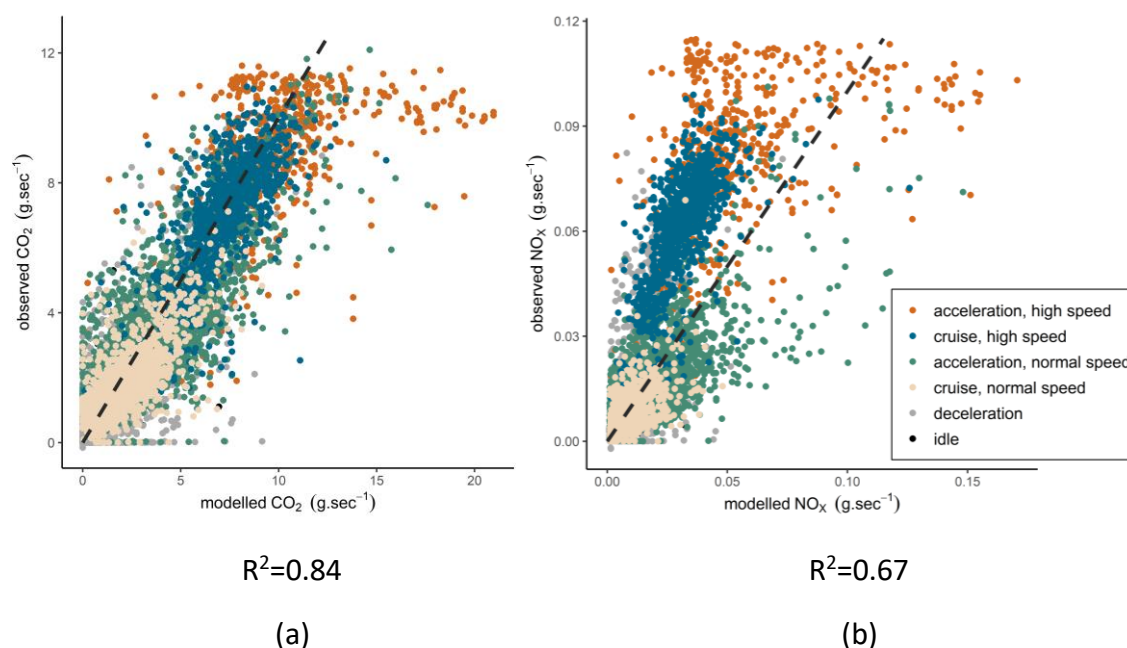


Figure 2-3 comparing observed and modelled emission rates for vehicle A by driving mode (a) CO₂ (left); (b) NO_x (right). Black line denotes a 1:1 relationship between the modelled and observed emission rates ($R^2=1$)

2.2.2.3 Loaded van validation

To assess PHEM's performance of quantifying the impact of varying load (weight), vehicle B was tested over the suburban sub-cycle (free-flow and AM peak) in both un-laden (vehicle B1) and full-laden (vehicle B2) conditions. A summary of the observed and modelled average CO₂ and NO_x emission rates is presented in Table 2-2. It's worth noticing that the observed NO_x emissions were highest when the un-laden vehicle was driven in AM peak with low speed, stop-and-go conditions. This is suggested to be due to low engine load (un-laden and urban driving) operations, resulting in cooler exhaust temperatures and the SCR system not meeting its operational temperature to achieve effective conversions and catalytic reductions ([Koebel et al., 2002](#); [Johnson, T., 2014](#); [Moody and Tate, 2017](#)). The observed and modelled CO₂ emission rates (g/km) are in close agreement in both un-laden and full-laden conditions, while the modelled NO_x emission rates (g/km) are roughly half those from the laboratory tests. Though PHEM failed to reliably predict the NO_x emission rates of this specific vehicle, it does capture the trend that the NO_x emissions rates in un-laden conditions are considerably higher than in full-laden conditions for each sub-cycle.

Table 2-2 summary of observed and modelled CO₂ and NO_x emission rates from un-laden and full-laden Euro 6 N2 HGV

Pollutant	Time period	Un-laden (g/km)		Full-laden (g/km)	
		Observed	Modelled	Observed	Modelled

CO ₂	Free-flow	291.11	280.66	410.49	400.61
	AM peak	355.63	379.02	530.22	539.10
NO _x	Free-flow	0.27	0.33	0.17	0.11
	AM peak	1.08	0.41	0.46	0.16

Figure 2-4 presents the scatterplot of observed and modelled CO₂ values for un-laden and full-laden conditions over the chosen test cycle. The frequency of data points in a hexagonal bin is illustrated on a colour-scale, so both the range in values and where the core of the data lies are visualised. The scatterplots for CO₂ indicate that PHEM is reliably predicting the dynamics and magnitude of CO₂ emissions under both un-laden and full-laden conditions. The R² between 2930 simulation values and laboratory results are 0.84 and 0.71 for un-laden and full-laden conditions respectively, demonstrating PHEM's ability to quantifying the impact of carrying loads on CO₂ emissions.

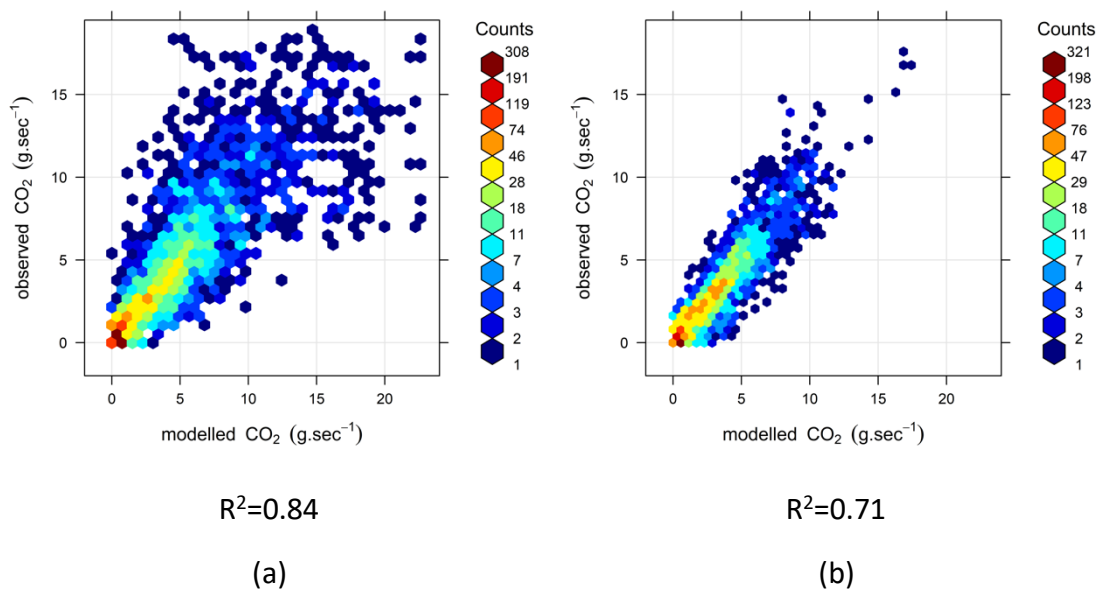


Figure 2-4 Scatter plots of comparing modelled (PHEM) and observed CO₂ values for suburban sections in free-flow and AM peak (a) 0% payload (left); (b) 100% payload (right)

The results in former sections suggest that PHEM accurately estimates the instantaneous CO₂ emissions from both standard van and loaded small HGV (and potentially vans). Though PHEM didn't compute the instantaneous NO_x emission rates very precisely for a specific loaded HGV, it is suggested the test vehicles' engine and emission map deviates from the average vehicle in the fleet

that PHEM is attempting to represent. The model does capture the trend and dynamics of the measurements. These validation results suggest PHEM is a suitable modelling tool and capable of simulating the real-world emissions from refrigerated vans including the relative impact of TRUs.

2.3 Impact of TRUs on vans

2.3.1 Additional load of TRUs

The additional load of TRUs on the vehicle engine can be divided into three parts, added weight of the TRUs (insulation material included), increased frontal area of the condenser mounted in front of a van, the refrigeration load (additional electrical load on the engine to power belt-drive compressor). The added weight and frontal area of TRUs can be directly added to vehicle specification in PHEM, and the refrigeration load depends on many external parameters besides TRU's cooling capacity: the ambient temperature and refrigerated compartment temperature; the actual van size and engine type; the load of chilled and frozen food; insulation properties of the isothermal box; door opening times during operating; test cycle and driver's behaviour.

To capture the accurate power demand of refrigeration units under real-operating conditions, we calculate the refrigeration load based on [ASHRAE \(2018\)](#) thermal load calculation procedures, which divides the refrigeration load into five parts (represented in Figure 2-5): (1) transmission load, which is the heat transferred into the refrigerated space through its surface; (2) product load, which is the heat removed from product to keep the refrigerated space in a setting temperature; (3) infiltration air load, which is the heat gain when door opens and air enters into the refrigerated space; (4) precooling load: which is the heat removed from the insulated box and inside air; (5) other load: including heat of internal sources, equipment related load and heat released by human.

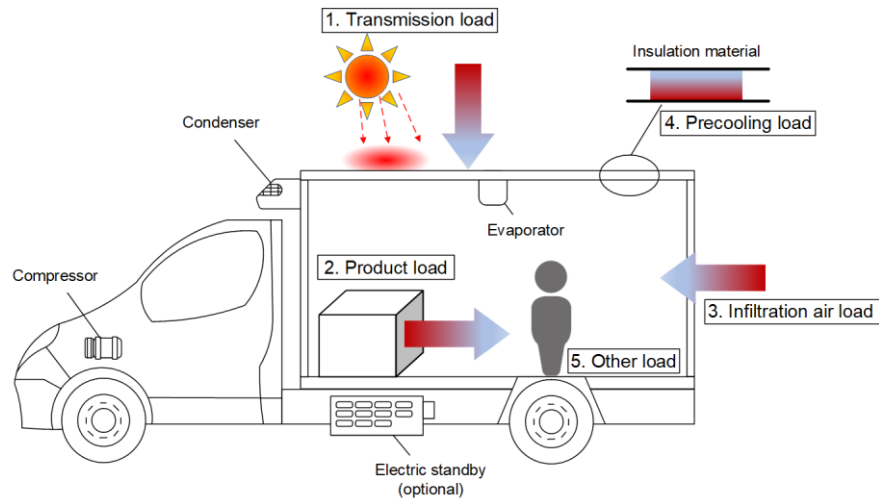
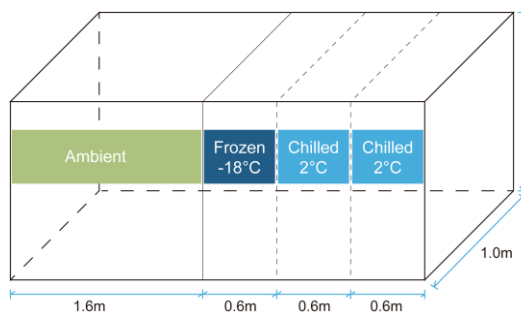


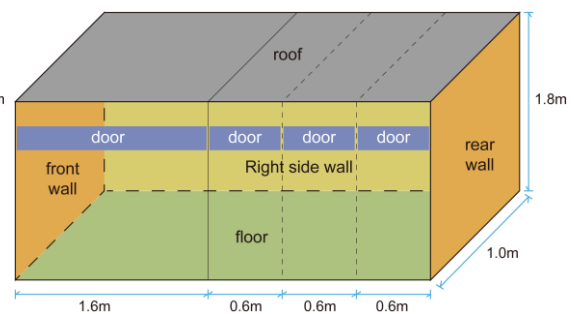
Figure 2-5 Main sources of heat in refrigerated van

This study uses an example to calculate the refrigeration load of the grocery delivery van and illustrate the temperature and cargo weight impact on the total refrigerated load of a refrigerated van. We consider a Euro 6a/b class III delivery van with the following specifications:

- The internal dimensions of the insulated box are 3.4m long, 1.0m wide and 1.8m high (see Figure 2-6-a); the box is made up with four compartments: one ambient compartment, one frozen compartment with the setting temperature of -18°C , two chilled compartments with the setting temperature of 2°C ; the dimensions for each compartment is stated in Figure 2-6-b.
- The roof, the walls, the doors and the floor are made up of 60mm polyurethane foam ([Ashida, 2006](#)), with thermal conductivity $0.0228\text{W}/(\text{m}\cdot\text{K})$ ([Tassou et al., 2009](#)). Between each compartment an insulated bulkhead is installed, and the bulkhead is also made up of 60mm polyurethane foam.
- The total delivery time is assumed to be 8 hours per day, delivering to 4 customers per hour (figures established on interview). For every customer, the driver will keep the frozen compartment door and one of the chilled compartments door open for 1 minute.



(a)



(b)

Figure 2-6 (a) internal dimensions and setting temperature of each compartments (left); (b) schematic diagram of the insulated box of a delivery van (right)

Only transmission load and infiltration load are considered for simplification here. The complete calculation procedure is documented in the supplementary material. In order to evaluate the impact of ambient temperature on total refrigeration load, this paper uses three illustrative temperature settings, from 40°C in the summer, 20°C in spring/autumn to 0°C in the winter. When comparing the total refrigeration load in different temperature (see Table 2-3), considerable reduction is found as the temperature decreases, which demonstrate the significant effect of ambient temperature on refrigeration load.

Table 2-3 total refrigeration load in different temperature

Temperature, °C	Transmission load, kW	Infiltration load, kW	Total refrigeration load, kW
40	0.31	2.63	2.93
20	0.18	1.75	1.93
0	0.06	0.73	0.78

2.3.2 Fuel consumption and exhaust emissions from refrigerated vans

Impact of TRUs on a Euro 6a/b class III van with average loading of 375kg (default setting in PHEM) was assessed by PHEM over the LDC. When considering the additional load of TRUs, an added 135kg TRU weight, 0.23 m² increased frontal area and 1.93 kW refrigeration load at an ambient temperature of 20°C were added to vehicle specifications in PHEM over the full 140km LDC. These were contrasted with emissions from the same base Euro 6a/b class III standard van with 375kg loading following the same driving trajectory and conditions. In both refrigerated van and standard van simulations, the SCR module is activated, as Euro 6a/b class III van are commonly equipped with SCR after-treatment system to mitigate NO_x emissions.

Simulation results shows that average CO₂ emission for a refrigerated van is 282 g/km, 15% higher than standard van, while average NO_x emission factor for a refrigerated van is 0.43 g/km, 18% higher than standard van. The real-world CO₂ emissions from refrigerated vans is nearly 2 times the government's target (147 g/km) and NO_x emissions more than 3 times the Euro 6ab limit (0.125 g/km).

The increased frontal area, added TRU weight and additional refrigeration load were added respectively in PHEM to assess their impact on CO₂ and NO_x emissions performance. Figure 2-7 illustrates these additional loads over the whole LDC at an ambient temperature of 20°C, and slope in each sub-cycle represents the average emission rate per second (g/sec) for different driving conditions. It's clear that the refrigeration load contributes to the largest share of additional CO₂ and NO_x emissions.

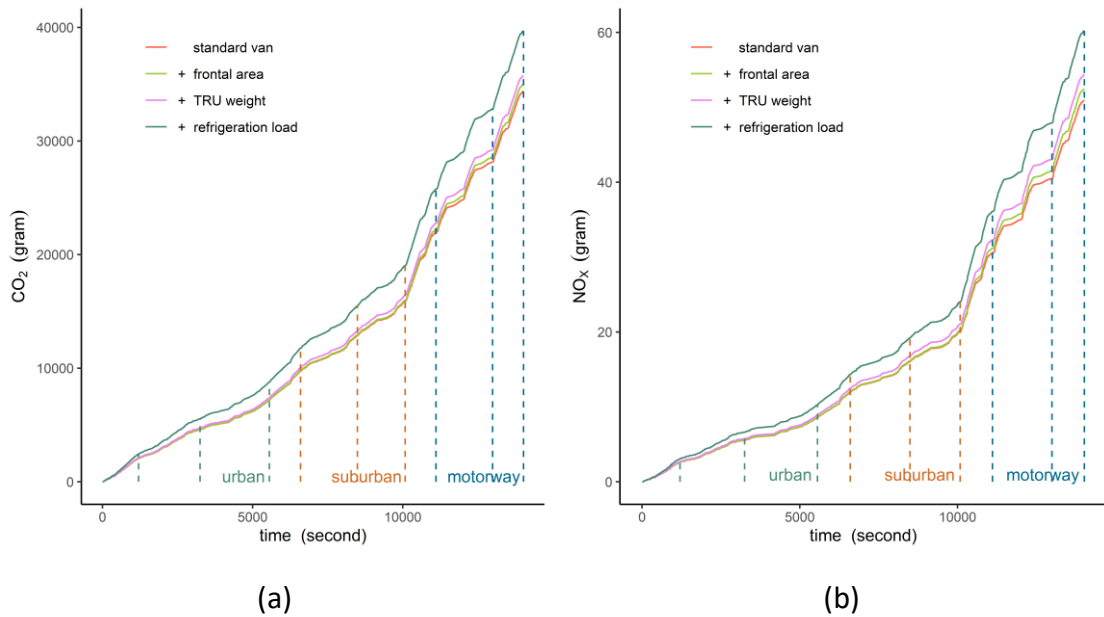


Figure 2-7 cumulative plot of (a) CO₂ emissions (left) and (b) NO_x emissions (right) at an ambient temperature of 20°C (different parts of TRU load)

The refrigeration loads in 3 ambient temperature scenarios specified in Table 2-3 were added to PHEM as auxiliary electrical engine loads, with the standard TRU increased frontal area and additional weight also applied. Table 2-4 summarizes the impact of ambient temperature on CO₂ and NO_x emissions from refrigerated vans, as well as the relative contribution of these three additional loads. A high ambient temperature of 40°C is found to impose a significant additional auxiliary power load for cooling, and associated increases in fuel consumption and NO_x emissions. In all ambient temperature scenarios, the refrigeration load is found to account for the majority of the additional emissions associated with equipping the vehicle with a TRU. The results demonstrate the need to minimise refrigeration load through storage compartment and door opening management/strategies, especially when ambient temperature is high, for the heat gain through the insulation box and from air infiltration when door is open and closed is considerable.

Moreover, the increase in emissions may be partly offset by a “low temperature NO_x emission penalty” found in diesel vehicles ([Grange et al., 2019](#)), where ambient temperature has an impact on diesel vehicle’s post-combustion control technology and high temperature resulting in lower NO_x emissions. Vehicles equipped with LNTs (lean NO_x traps) shows more temperature dependency than vehicles with SCRs.

Table 2-4 Impact on the CO₂ and NO_x emissions by various ambient temperature

Pollutant	Ambient temperature, °C	Emission rates, g/km	Share of different parts in additional emissions		
			Frontal area	TRU weight	Refrigeration load
CO ₂	40	297	8%	10%	82%
	20	282	11%	14%	74%
	0	265	21%	26%	53%
NO _x	40	0.45	12%	16%	72%
	20	0.43	16%	21%	62%
	0	0.40	27%	35%	38%

In Table 2-5 two sub-cycles (free-flow and AM peak time period in suburban areas) were chosen to contrast refrigerated van’s emission performance with different cargo loading under different driving conditions. Loading factors from un-laden (135kg TRU weight counted), average-laden (375kg cargo plus 135kg TRU weight) to full-laden (1265kg cargo plus 135kg TRU weight) were added in PHEM. Unlike the emission test results in the validation process in Table 2-2, NO_x emissions are higher in full-laden conditions than in un-laden conditions, which might be due to the fact that refrigerated vans already have additional TRU weight even in un-laden conditions, providing enough exhaust emission temperature for SCR to work efficiently. Both CO₂ and NO_x emissions are higher when vehicles were driven in AM peak traffic conditions. Further research, perhaps including chassis dynamometer test or portable emission measurement is suggested to be needed, to study the cause and impact of loading on refrigerated vans.

Table 2-5 the influence of grocery weight and driving condition on emission rates for a Euro 6 class III refrigerated van (20°C ambient temperature)

Pollutant	Time period	Un-laden (g/km)	Average-laden (g/km)	Full-laden (g/km)
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CO ₂	Free-flow	209	223	255
	AM peak	264	280	322
NO _x	Free-flow	0.27	0.30	0.39
	AM peak	0.33	0.37	0.49

Simulation results over the realistic London Drive Cycle suggest significant differences of CO₂ and NO_x emissions between standard vans and refrigerated vans. The influence of higher ambient temperatures, heavier loading factor and stop-start driving condition on emissions are also worth attention. Findings confirm the need to take into account the impact of additional engine load when predicting refrigerated van emissions.

Aside from higher emission factors for refrigerated vans, demand for grocery home deliveries has surged since the outbreak of COVID-19, and the rise is expected to be sustained as the pandemic has brought new customer to online grocery and many would retain the habit. Mintel⁸ estimates the market to be worth £17.9 billion by 2024, growing by 41% over the five year period, resulting in a significant growth and associated environmental impact of refrigerated vans.

2.4 Summary and conclusions

Analysis conducted in this study aims to understand the contribution of TRUs to CO₂ and NO_x emissions from vans. By simulating the CO₂ and NO_x emissions of vehicles measured on the chassis dynamometer, PHEM has been proven to be a model capable of estimating instantaneous emissions for vehicles carrying loads. Real-world CO₂ and NO_x emission factors for refrigerated vans have been developed using PHEM, and the analysis highlights the following findings:

- Vans with TRUs generate ≈15% more CO₂ emissions and ≈18% more NO_x emissions than standard vans.
- The impact of TRU weight, frontal area and electrical load on the engine by the TRU on emissions were independently assessed, illustrating that the refrigeration load is the most significant cause of excess emissions, contributing increase of 74% and 62% to CO₂ and NO_x emissions respectively.
- The burden of additional emissions of a TRU van becomes more significant in higher ambient temperature as the refrigeration load increases. Stop-start

⁸ <https://www.mintel.com/press-centre/retail-press-centre/mintel-forecasts-online-grocery-sales-will-grow-an-estimated-33-during-2020>

driving conditions and heavier cargo loading are also shown to elevate emissions.

Analysing the difference between standard van and refrigerated van by PHEM is important in three ways. Firstly, simulation results confirm the need to take into account the effect of additional load when predicting refrigerated van emissions and fuel consumption. Secondly, findings on the impact of temperature, grocery loading and driving conditions on refrigerated van emissions can be used to improve fuel-saving and eco-friendly strategies in grocery delivery. Moreover, PHEM is capable of evaluating the impact of real-world factors on emissions. Local policy makers can adjust the vehicle parameters so that they are specific to their own applications and situations.

Van traffic is forecast to continue growing significantly and make up between 14% and 21% of traffic mileage by 2050 ([DfT, 2018a](#)), in the meanwhile results in this study suggests that real-world emission factors of standard vans are higher than official statistics. It is both timely and significant to accurately assess the real-world van emissions as city authorities consider whether to include restrictions on vans in policies such as Low Emission and Clean Air Zones ([Defra, 2018](#); [DfT, 2020a](#)).

Recommendations for further research include laboratory (chassis dynamometer) test for refrigerated vans under different scenarios, to study the impact of changing ambient temperature, door opening times or weight of cargo. A special test (drive) cycle could also be designed to assess the influence of driving conditions and refrigeration unit designs/operation. Besides, further research could also focus on the environmental impact from all the other kinds of vans with extra loading, like ambulances which are always high powered and heavy loaded, and to include different measurement or estimation methods like laboratory (chassis dynamometer) testing, on-road (PEMS), remote sensing and simulations.

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Chapter 3 Detecting Candidate High NO_x Emitting Light Commercial Vehicles Using Vehicle Emission Remote Sensing

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Abstract

Vehicle emission remote sensing devices have been widely used for monitoring and assessing the real-world emission performance of vehicles. They are also well-suited to identify candidate high emitting vehicles as remote sensing surveys measure the on-road, real-driving emissions (RDE) of a high proportion of the operational vehicle fleet passing through a testing site. This study uses the Gumbel distribution to characterise the fuel-specific NO_x emission rates (grams.kg⁻¹) from diesel vans (formally referred to as light commercial vehicles or LCVs) and screen candidate high emitting vehicles. Van emission trends of four European countries (Belgium, Sweden, Switzerland and the UK) from Euro 3 to Euro 6a/b have been studied, and the impact of road grade on candidate Euro 6a/b high-emitters is also evaluated. The measurements of Euro 6a/b fleets from four countries are pooled together, and a consistent 4% of candidate high-emitters are found in both class II and class III Euro 6a/b vans, accounting for an estimated 24% and 21% total NO_x emissions respectively. The pooled four country data is differentiated by vehicle models and manufacture groups. Engine downsizing² of Euro 6a/b class II vans is suspected to worsen the emission performance when vehicles are driven under high engine load. The VW Group is found to be the manufacture with cleanest NO_x emission performance in the Euro 6a/b fleets. By distinguishing high-emitters from normally behaving vehicles, a more robust description of fleet behaviour can be provided and high-emitting vehicles targeted for further testing by plume chasing or in an inspection garage. If the vehicle is found to have a faulty, deteriorated or tampered emission after-treatment system, the periodic vehicle inspection safety and environmental performance certificate could be revoked.

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² Engine downsizing is a design strategy to improve fuel efficiency for lighter vehicles by reducing the frictional losses and relative weight of the engine (and total kerb-weight), with a turbocharger helping provide the levels of power demanded.

Keywords

remote sensing; vans; NO_x emissions; high-emitters identification

3.1 Introduction

Road transport is a major contributor to nitrogen oxides (NO_x) concentrations, which has negative effects on public health and the environment ([Pastorello and Melios, 2016](#)). Knowledge of the real-world vehicle emissions is important to assess the effectiveness of current control measures and substantiate future policy decisions. The discrepancy between real-world driving and type-approval emissions for passenger cars has been made clear, where real-world emissions can exceed emission limits several times for different Euro standards ([Weiss et al., 2011](#); [Chen and Borken-Kleefeld, 2014](#); [DfT, 2016](#)). However, only a limited amount of research ([ICCT, 2019a](#); [Chen et al., 2020](#)) has studied the real-world emission performance of vans, even though vans saw a 106.2% rise in traffic over the last 25 years (compared with 29.8% for cars and 12.8% for lorries) ([DfT, 2020c](#)), and was estimated to contribute 36.1% of NO_x emissions from the road traffic sector in 2019 in the UK ([NAEI, 2021b](#)).

Researchers have been developing different methods to monitor the real-world NO_x emissions from vehicles using laboratory (chassis dynamometer) tests ([Demuyne et al., 2012](#); [Moody and Tate, 2017](#)), on-board tests (portable emissions measurement systems — PEMS) ([O'Driscoll et al., 2016](#); [Luján et al., 2018](#)), plume chasing ([Wang, X. et al., 2011](#); [Lau et al., 2015](#)) and remote sensing instruments ([Carslaw, D. et al., 2011](#); [Chen and Borken-Kleefeld, 2016](#)). Unlike laboratory tests, PEMS or plume chasing that provide second by second emission rates (grams.sec⁻¹) over a whole driving cycle or journey for a limited number of test vehicles, remote sensing instruments un-intrusively takes a snap-shot sample of fuel-specific emission rates (grams.kg⁻¹) from a large number of vehicles in a single day ([Beaton et al., 1995](#); [Huang et al., 2018](#)). This makes remote sensing a powerful approach for monitoring fleet emission characteristics ([Carslaw, D. et al., 2011](#); [Carslaw, D. et al., 2013](#); [Chen and Borken-Kleefeld, 2016](#); [Grange et al., 2019](#)) and detecting candidate high-emitting vehicles ([Borken-Kleefeld, 2013](#); [Pujadas et al., 2017](#); [Huang et al., 2019](#)).

When analysing remote sensing measurements some form of data aggregation is needed as a single record is insufficient to derive meaningful, statistically significant insights. The most common way to aggregate remote sensing data is to calculate the mean emission rates classified by Euro standard and fuel type ([Carslaw, D. et al., 2011](#); [Chen and Borken-Kleefeld, 2014](#)), based on an

assumption that the distribution of vehicle emissions is symmetrical, such as following a normal distribution. However, previous remote sensing studies ([ICCT, 2018](#); [AWEL, 2019](#); [Chen et al., 2019](#)) have shown that vehicle NO_x emissions are not normally distributed, rather skewed-right, making mean emission statistics less appropriate to represent a group of remote sensing measurements. Moreover, early studies often use arbitrary predetermined cut points to identify high-emitters ([Pujadas et al., 2017](#); [Huang et al., 2019](#)), regardless of the fact that the normal emission performance may differ in a certain campaign site. Therefore further research is considered to be needed to develop a more robust method to describe the fleet behaviour and effectively distinguish high NO_x emitters from normally behaving vehicles.

This paper uses the Gumbel distribution (explained in section 3.2.3) to analyse the remote sensing measurements of diesel vans. Vehicles that follow the fitted Gumbel distribution (referred to as 'on-model' vehicles) are selected to represent the emission performance of the normally behaving vehicles in the operational fleet, while the smaller and more highly emitting population which do not follow the Gumbel distribution (referred to as 'off-model' vehicles) are regarded as candidate high-emitters ([Rushton et al., 2021](#)). Four European countries' (Belgium, Sweden, Switzerland and the UK) remote sensing campaigns during 2011-2019 have been selected from the CONOX project ([Borken-Kleefeld et al., 2018a](#)) database and an overall fleet emission trend of each country is studied. The impact of road grade on Euro 6a/b fleet in the Swiss fleet is evaluated as this dataset includes a number of measurement sites with relatively steep road gradients. Euro 6a/b fleet data from the four EU countries are then combined based on two sample Kolmogorov-Smirnov test, and a more differentiated degree of analysis by manufacture groups and models is conducted.

3.2 Materials and methods

3.2.1 The measurement principle

A vehicle emission remote sensing instrument is a monitoring system that has been widely used to estimate the real-world vehicle emissions ([Beaton et al., 1995](#); [Carslaw, D. et al., 2011](#)). As shown in Figure 3-1-a, a remote sensing system positioned at a roadside includes:

- A source & detector module which passes infrared and ultraviolet light beams through the exhaust plume of passing vehicles and together with a reflecting mirror measure the attenuation of light wavelengths. The absorption of light is directly proportional to the concentration of pollutant in the atmosphere,

which includes the pollutant in the plume of the vehicle crossed and in the background. After the background pollution is subtracted, only the ratio of certain pollutant to CO₂ is reported ([Bishop, G. A. and Stedman, 1996](#)), as the amount of plume seen is dependent on the height of the tailpipe. Fuel-specific NO_x emission rates (in g/kg fuel burned) can then be generated based on the fuel burnt in the engine ([Burgard et al., 2006](#); [Carslaw, D. et al., 2011](#)).

- A speed & acceleration detector which records the instantaneous speed and acceleration of the vehicle passing by.
- A camera to capture the vehicle's number plate so that technical characteristics (fuel type, Euro standard, make, model, etc.) of the vehicle can be retrieved from national vehicle registration databases.

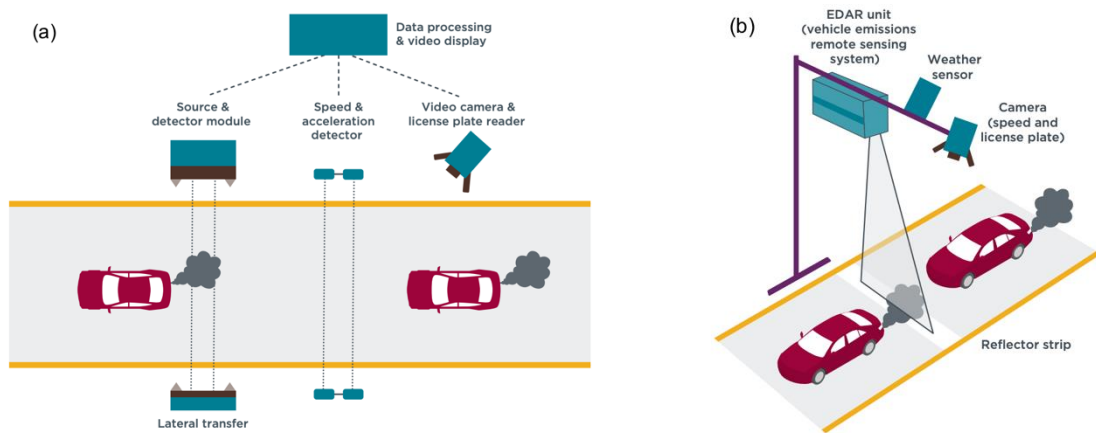


Figure 3-1 Schematics of a typical remote sensing deployment: (a) cross-road remote sensing system [left]; (b) top-down remote sensing system (EDAR) [right] ([Borken-Kleefeld and Dallmann, 2018](#))

An alternative configuration is the EDAR instrument which emits a sheet of laser-based infrared light in a top-down orientation, with a reflector strip mounted on the road surface scattering back the laser light (see Figure 3-1-b). This deployment means the measurements are less sensitive to the vehicle lane position, exhaust position and wind speed ([Ropkins et al., 2017](#)).

3.2.2 Data acquisition and preparation

Remote sensing campaigns have been conducted in Europe since the early 1990's. In 2016, the Swiss Federal Office for the Environment (FOEN) founded the CONOX (COMbining, COMparing and COLlaborating on NO_x real driving emission measurements) project, focusing on pooling, sharing, and analysing European remote sensing data collected in a range of European cities over the past 5 to 10 years ([Borken-Kleefeld et al., 2018b](#); [Sjödén et al., 2018](#); [Borken-](#)

[Kleefeld et al., 2018a](#)). The remote sensing data analysed in this paper are from the CONOX project and include several remote sensing sampling campaigns carried out during 2011-2019 across Belgium, Sweden, Switzerland and the UK. As diesel vans account for 94% of van market in Europe ([ICCT, 2019b](#)), this paper only considers the emission performance of vans powered by diesel. A detailed summary of fleet characteristics by country, Euro standard and class type³ is listed in Table A. 1 in the Appendix. The number of observations from Euro 3, 4, 5 and 6a/b diesel vans accessed and analysed is 106,662.

Remote sensing data also include measurements of the testing conditions including ambient temperature, the road grade and the instantaneous speed and acceleration of each passing vehicle. The test conditions differ between countries as they are influenced by the characteristics of sample sites (road gradient, vicinity of junctions etc), driver behaviour and prevailing meteorological conditions. Based on the passing vehicles' speed/acceleration and campaign site's road grade, equation and parameters provided by [Davison et al. \(2020\)](#), a metric informing the instantaneous engine load called vehicle specific power ([Jiménez-Palacios, 1999](#)) is calculated. Vehicle Specific Power (VSP) value is a useful metric when analysing remote sensing measurements as it characterises the power demands on the engine and associated NO_x emissions ([Carslaw, D. et al., 2013](#)). It can identify vehicles under high load (where high emissions are expected) or at very low load (where fuel injection is disabled and plume sizes insufficient for valid remote sensing measurements) ([ICCT, 2018](#)). As shown in Table A. 1 in the Appendix, the average VSP value of each fleet is much higher than the type approval NEDC⁴ VSP value (around 4 kW/ton for vans). In other words, most of the vehicles (Euro 3, 4, 5 and 6a/b) being measured have higher engine load with either higher speed/acceleration or steeper road grade than the test cycle. It is hypothesized that these vehicles have been designed to have cleaner emission performance in NEDC-test-type conditions and less so in more dynamic and variable real-world driving ([Chen and Borken-Kleefeld, 2014](#); [Triantafyllopoulos et al., 2019](#)).

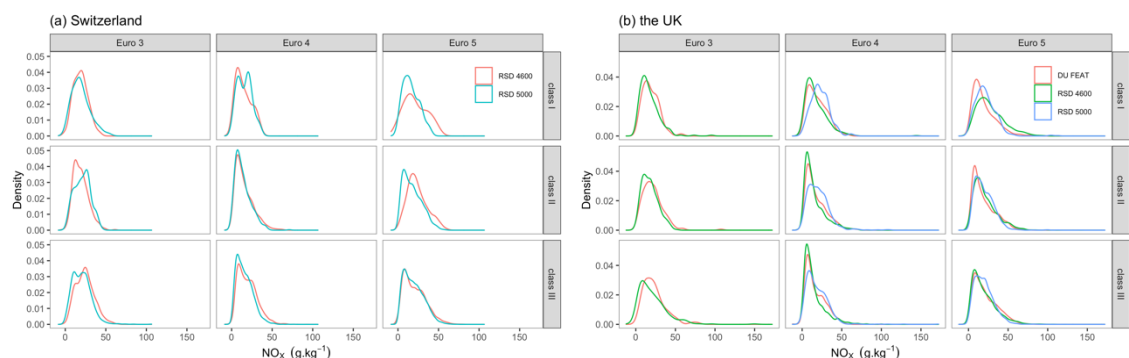
Four remote sensing instruments, or generations of instrument, were used to conduct the remote sensing campaigns being analysed, namely the RSD series (RSD 4600 and RSD 5000) developed by Opus⁵, FEAT developed by University

³ Van can be further classified into three sub-categories by reference mass, where class I are vans less than 1305kg, class II are those between 1305kg and 1760kg, and class III are those above 1760kg.

⁴ The New European Driving Cycle (NEDC) is a driving cycle used in European type-approval test. Average VSP value of NEDC cycle is also uniformly developed using the same equation and parameters, based on driving cycle's speed profile.

⁵ <https://www.opusrse.com/rsd-technology/>

of Denver⁶, and EDAR developed by HEAT⁷. The RSD series and FEAT are cross-road remote sensing systems (shown in Figure 3-1-a) while EDAR is top-down remote sensing system (shown in Figure 3-1-b). The RSD 5000, FEAT and EDAR instruments have the capability to measure NO and NO₂, to report estimated total NO_x emission rates (grams.kg⁻¹) ([Carslaw, D. and Rhys-Tyler, 2013](#); [Chen and Borken-Kleefeld, 2014](#); [HBEFA, 2019](#)). 35.0% Switzerland samples and 22.8% UK samples were recorded by the RSD 4600 instrument which doesn't have a NO₂ measurement capability. In order to include the sizeable samples of measurements made by RSD 4600 in this study, a fixed ratio of NO₂:NO_x needs to be proposed, then used to calculate an estimated NO_x (NO+NO₂) emission rate (grams.kg⁻¹) from the measured NO data. Between the FEAT and RSD 5000 instruments that share the same measurement principle with RSD 4600, the FEAT device is considered to have a more robust NO₂ sensing capability ([Carslaw, D et al., 2019](#)), and its measurement of NO has been proven to have a strong correlation with the RSD 4600 device ([Rushton et al., 2018](#)). Therefore it has been assumed that the fraction of primary NO₂ in NO_x (f_{NO2}) is directly derived from the average ratio of NO₂ to NO_x emissions measured by FEAT in remote sensing campaigns in the UK (detailed data for f_{NO2} by Euro standard and class type are listed in Table A. 2 in the Appendix) and applied to the RSD 4600 measurements. Density plots of the fuel-specific NO_x emissions (grams.kg⁻¹) from both with and without NO₂ measurement capability instruments are presented in Figure 3-2 (Euro 6a/b is not included because all Euro 6a/b samples were measured by devices with NO₂ measurement capability). The different instruments are found to provide comparable NO_x emissions within the same Euro standard and class type, which suggests it is appropriate to combine records measured by different instruments into a single dataset.



⁶ <http://www.feabiochem.du.edu/>

⁷ <https://www.heatremotesensing.com/edar>

Figure 3-2 Density plot of NO_x emission rates (g/kg) for class I to class III vans by Euro standard and instrument in (a) Switzerland [left]; (b) the UK [right]

3.2.3 The Gumbel distribution and maximum R^2 value method

Figure 3-2 also demonstrates that the distribution of NO_x emissions measured in Switzerland and the UK has a skewed-right character and includes a proportion of extreme high emitting records. [Bishop, G. A. et al. \(2016\)](#) and [Huang et al. \(2018\)](#) estimate that a small number of high-emitting vehicles could contribute a significant amount of total emissions, indicating that the emissions of the normally behaving vehicles would be elevated if simply using the mean emission statistics of a fleet. An accurate description of the remote sensing data distribution is essential in understanding the vehicle fleet behaviour. It does not only describe the average performance of the normally-behaving vehicles, but also identify candidate high-emitting vehicles.

The Gumbel distribution (Type-I Generalised Extreme Value distribution) ([Gumbel, 1935](#)) is a right-skewed distribution function commonly used and widely adopted to model populations with a small number of extreme values that would not be captured by a normal distribution ([Sherif et al., 2014](#); [Ouarda et al., 2015](#); [Bhagat, 2017](#); [Loucks and Beek, 2017](#)). [Rushton et al. \(2021\)](#) proposes using the Gumbel distribution to characterise passenger cars' remote sensing data. As diesel vans have similar emission characteristics to diesel passenger cars ([Chen et al., 2020](#)), the Gumbel distribution has also been applied to vans in this paper. The probability density function (*pdf*) $f(x)$ and cumulative density function (*cdf*) $F(x)$ of a Gumbel distribution are given as:

$$f(x) = \frac{1}{b} e^{-\left(\frac{x-a}{b} + e^{-\frac{x-a}{b}}\right)} \quad \text{Eq. 3-1}$$

$$F(x) = 1 - e^{-e^{-\frac{x-a}{b}}} \quad \text{Eq. 3-2}$$

Where a is the location parameter and represents the highest observation frequency in a dataset; and b is the scale parameter and represents the spread of the dataset.

When describing remote sensing measurements, the Gumbel distribution is considered superior to other commonly used skewed-right distributions (Weibull, Gamma, log-normal) as:

- The parameters in the Gumbel distribution are easy to interpret. The location parameter a describes the emission rates that have been recorded with the

most frequency and scale parameter b determines the statistical dispersion of the probability distribution; and

- The Gumbel distribution can be applied to negative values. In remote sensing campaigns, small negative values are sometimes recorded because of measurement noise and inaccurate determination of the background concentration (e.g., a clean vehicle with very low emissions of NO_x emissions follows with a short headway a high NO_x emitting vehicle) ([Huang et al., 2018](#); [Smit et al., 2021](#)). With negative emission rates clearly not being physically possible, it is standard practice in remote sensing analysis that these negative measurements are included and not rounded to zero ([Bishop, Gary A et al., 2006](#); [McClintock, 2011](#); [Gruening et al., 2019](#)), as this would artificially uplift the negative values to zero and would inflate the average values of the whole fleet.

It is hypothesised that the majority of the fleet follow the Gumbel distribution except some extreme values, and these outliers are interpreted as candidate high emitting vehicles ([Rushton et al., 2021](#)). To test this hypothesis in diesel vans, the distribution is cut successively by percentile, from 99% (vehicles with the highest 1% NO_x emissions is removed from the whole fleet) to 1% (vehicles in the top 99% NO_x emissions range is removed), and the Gumbel distribution is re-applied to each sub-fleets. Then a goodness of fit test is used to calculate R^2 value of observed and theoretical quantiles for each sub-fleet after cutting. The sub-fleet with the maximum R^2 value is regarded as the ‘on-model’ vehicle subset, and its corresponding Gumbel location parameter a is used to represent the typical emission rate of the normally behaving vehicles in the whole fleet, while scale parameter b determines the dispersion of the data. The percentage of vehicles that do not follow Gumbel distribution are regarded as ‘off-model’ percentage, and these vehicles are considered as candidate high emitting vehicles. The detailed algorithm is given in Table 3-1.

Table 3-1 Algorithm for identifying the ‘off-model’ vehicles

Step 1: Apply the Gumbel distribution to the whole fleet F_{100}
Step 2: Calculate R^2 value of the observed and theoretical quantiles for fleet F_{100}
Step 3: Cut the fleet at each integer percentile starting from 99, apply the Gumbel distribution to F_i , $i = 99, 98, \dots, 1$
Step 4: Calculate R^2 value of observed and theoretical quantiles for fleet $F_i (F_{99}, F_{98}, \dots, F_1)$
Step 5: Repeat step 3-4 until there is no vehicle left in the fleet
Step 6: Create a scatter plot of the cutting percentiles vs. the R^2 values

Step 7: Sub-fleet with the maximum R^2 value is regarded as the 'on-model' vehicle subset, and the fit parameters for the 'on-model' vehicles are the best description of the normally behaving vehicles in the whole fleet; the rest of the vehicles that do not follow Gumbel distribution are regarded as 'off-model' vehicles.

This method requires the original fleet to have a relatively large sample size, because vehicles being regarded as 'off-model' vehicles usually only make up a very small percentage of the whole fleet ([Rushton et al., 2021](#)), if the sample size is too small, no useful insight would be derived from the 'off-model' vehicles. To ensure the statistical validity, the application of Gumbel distribution to class I vans is not discussed in this paper as the Class I vans only take account of 4.6% of the total measurements.

3.2.4 A merged dataset

Remote sensing data is often further segmented by VSP value ([Carslaw, D. et al., 2013](#)), road grade ([Costagliola et al., 2018](#)), ambient temperature ([Grange et al., 2019](#)) and make/model ([ICCT, 2019a](#)) to study different factors' impact on vehicle emissions. As each single country has only a relatively limited number of samples, data from different countries needs to be combined together to conduct analysis at a higher level of granularity. Here, the consistency of the NO_x emission performance across fleets is checked before pooling data from different countries. The two-sample Kolmogorov-Smirnov test (K-S test) is applied to investigate whether the NO_x emission data from the four countries share a statistically similar distribution. The two-sample K-S test is a nonparametric hypothesis test that compares empirical distributions of two samples and evaluates the largest absolute difference between the two cumulative density functions ([Massey Jr, 1951](#)) ([Lopes et al., 2007](#)). The test statistic D^* is given as:

$$D^* = \max(|\hat{F}_1(x) - \hat{F}_2(x)|) \quad \text{Eq. 3-3}$$

Where $\hat{F}_1(x)$ is the empirical cumulative density function of NO_x of sample 1, and $\hat{F}_2(x)$ is the empirical cumulative density function of NO_x of sample 2.

For sufficiently large sample size, the critical value D_α at a 95% significance level is given as:

$$D_\alpha = 1.36 \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \quad \text{Eq. 3-4}$$

Where: The 1.36 value is obtained from the Kolmogorov-Smirnov table ([Massey Jr, 1951](#)). n_1 and n_2 are the sizes of sample 1 and sample 2 respectively.

The null hypothesis is: both samples come from a population with the same distribution. The null hypothesis is retained at significance level α if $D^* < D_\alpha$. However, when the sample size is too large (e.g., $n \geq 900$), the null hypothesis would be constantly rejected because its corresponding critical value D_α would be very small. In other words even extremely small difference between the estimate and the null hypothesis can be statistically significant ($p - values < 0.05$) ([Lin et al., 2013](#)). To illustrate this ‘large-sample, small p -values’ problem, Monte Carlo simulation was introduced into K-S test when testing whether two sample come from the same distribution. The detailed procedure is described in Table 3-2.

Table 3-2 Algorithm for illustrating ‘large-sample, small p -values’ problem in K-S test

-
1. Select two fleets, randomly sample n data points ($n = n_1 = n_2 = 100$) from each fleet, apply K-S test to generate the maximum difference $D_{100(1)}^*$ between these 2 fleets
 2. Repeat step 1 for 1000 times, D_{100}^* can be obtained as $\{D_{100(1)}^*, D_{100(2)}^*, \dots, D_{100(1000)}^*\}$
 3. Identify the theoretical distribution of $D_{(100)}^*$ $\{D_{100(1)}^*, D_{100(2)}^*, \dots, D_{100(1000)}^*\}$, estimate the typical value of D_{100}^* based on the distribution
 4. Compare the typical value of D_{100}^* with its corresponding critical value D_α
 5. Increase the last sample size n by 100, ($n_1 = n_2 = n = 200, 300, \dots, 1200$), repeat step 1-5 until the sample size n gets to 1200
-

Data from the Belgium and Switzerland Euro 6a/b class III fleets were taken as an example to demonstrate the relationship between sample size and test results. Figure 3-3-a shows the median value of D^* (the black line in each boxplot) is higher than its corresponding D_α value (the red line) when $n \geq 900$, and Figure 3-3-b shows p -value is constantly below 0.05 when $n \geq 900$. In other words, the null hypothesis would be constantly rejected when the sample size n is larger than or equal to 900.

Figure 3-3-a shows the median D^* value is stable when the sample size $n \geq 500$. To avoid the ‘big sample’ issue, a Monte Carlo simulation at a sample size of 500 was applied on K-S test when testing if two fleets are likely from the same distribution and can be combined to one. As D^* follows a lognormal distribution ([Wang, C. et al., 2011](#)), the mode value of D^* is compared with its corresponding

D_{α} . Once confirmed that data from the two countries follow the same distribution, the two data subsets are combined and compared with the next country's data.

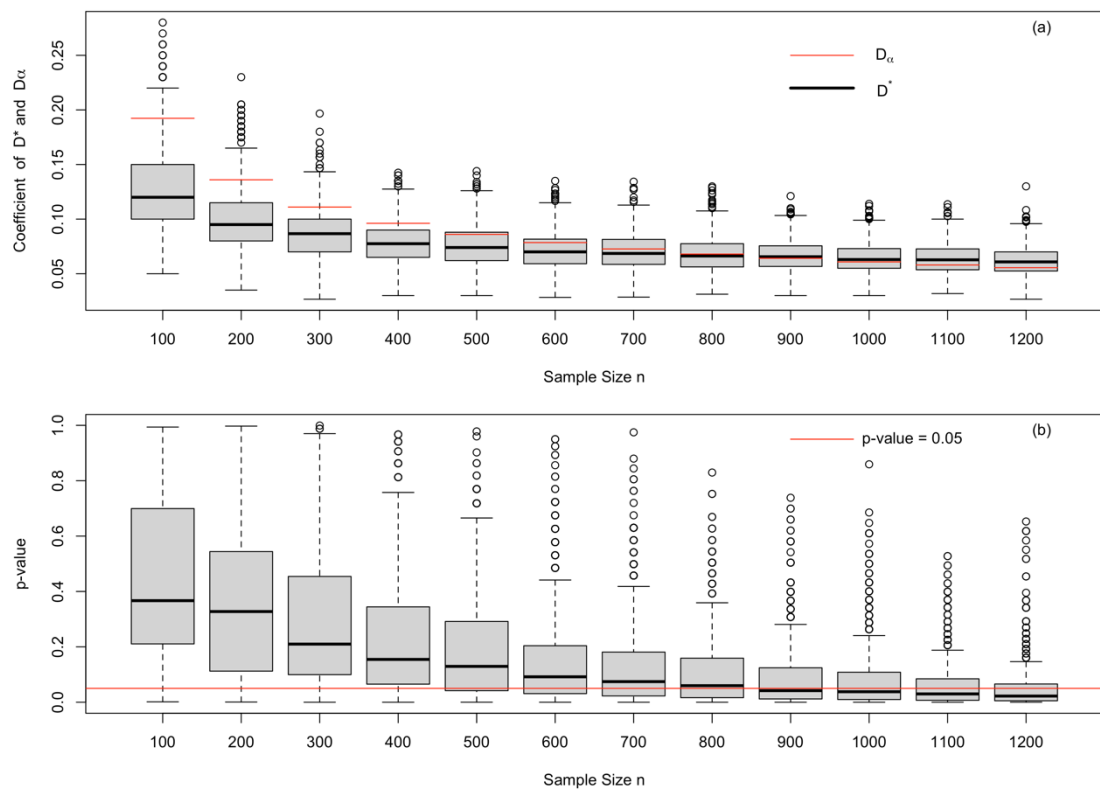


Figure 3-3 Distribution of (a) D^* [top panel] and (b) $p\text{-value}$ [bottom panel] as a function of sample size n

3.3 Results and discussion

3.3.1 Comparison of van emission performance in four countries

The algorithm listed in Table 3-1 has been applied to each Euro standard and class type across four countries to identify candidate high-emitting ('off-model') vehicles and estimate the emission performance of normally behaving vehicles ('on-model') in each fleet. 'Off-model' percentage, 'on-model' vehicles' location and scale parameters derived from the fitted distributions for each fleet are documented in Table 3-3. An illustrative class III Euro 5 and Euro 6a/b fleets' R^2 value plot for each cut-off percentile is shown in Figure 3-4.

Table 3-3 'Off-model' percentage and Gumbel distribution fit parameters of 'on-model' vehicles in Belgium, Switzerland, Sweden and the UK

Country	class II				class III			
	E3	E4	E5	E6a/b	E3	E4	E5	E6a/b

'Off-model'	BE	0%	1%	1%	2%	1%	1%	1%	1%
percentage	CH	0%	0%	0%	36%	0%	0%	0%	21%
	SE	NA*	0%	1%	8%	NA	0%	1%	3%
	UK	1%	0%	0%	3%	1%	1%	0%	4%
Location	BE	9.25	7.98	8.82	3.34	10.66	9.00	10.66	3.23
(g/kg)	CH	15.24	10.18	13.88	1.32	17.57	12.91	13.98	1.95
	SE	NA	9.96	12.60	2.72	NA	10.81	12.33	2.83
	UK	13.91	11.38	14.09	3.94	14.29	10.64	14.16	3.01
Scale	BE	5.61	5.90	6.62	4.31	6.90	6.45	7.92	4.40
(g/kg)	CH	7.97	7.62	9.65	2.17	9.93	8.67	10.07	2.47
	SE	NA	8.81	9.68	4.30	NA	8.66	10.43	4.92
	UK	8.67	9.25	9.67	5.31	11.24	8.69	10.13	4.62

* some data is NA because sample size of this fleet is too small, please see Table A. 1 in the Appendix for details.

The majority of the Euro 3, Euro 4 and Euro 5 van fleets follow the Gumbel distribution, with only 1% or 0% of 'off-model' vehicles identified in these fleets. The explanation for this is that the bulk of the Euro 3-5 diesel vans have high emissions, so the measurements are fitted to Gumbel distributions with relatively high location and scale parameters, as also reported for diesel cars by [Rushton et al. \(2021\)](#). For Euro 6a/b vans, more outliers have been identified, with 'off-model' shares ranging from 1% to 8% for Belgium, Sweden and the UK, while Switzerland is identified to have 36% and 21% 'off-model' vehicles for class II and class III respectively. The majority of the Euro 6a/b fleet of vehicles are relatively clean in comparison with their predecessors, with a proportion of outliers that cannot be fitted into the Gumbel distribution and are therefore regarded as candidate high-emitting ('off-model') vehicles. The steep road grade at the Swiss monitoring sites is proposed as an explanation for the high share of candidate high-emitting ('off-model') in the Euro 6a/b fleet detected at these sites, and the details are provided in section 3.3.2.

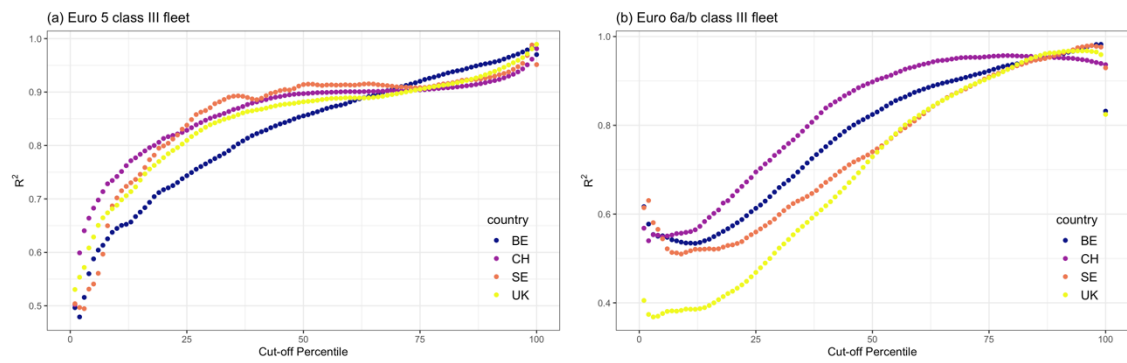


Figure 3-4 Variation in R^2 value as a function of cut-off percentile for (a) Euro 5 class III diesel vans [left]; (b) Euro 6a/b [right] class III diesel vans

The location parameter of Euro 3, 4, 5 and 6ab ‘on-model’ vehicles in the four countries are shown in Figure 3-5 i.e. the emission rates that have been recorded with the highest frequency in the deemed normally behaving fleet. The results for the four countries follow broadly the same trend, with the NO_x emission performance of typical vans remaining broadly stable through Euro standards 3 to 5, with emissions from Euro 5 vans slightly higher than their Euro 4 predecessors. These findings are in-line with other studies ([Chen and Borken-Kleefeld, 2014](#); [ICCT, 2019a](#)). There is observed to be a significant improvement for Euro 6a/b, with an average 76.4% decrease in the fleet weighted location parameter for class III Euro 6a/b vehicles over Euro 5. The Euro 6 emission standard is more stringent with regard to the limit of NO_x (declines from 0.28 g/km (Euro 5) to 0.125 g/km (Euro 6a/b) for class III diesel vans, a reduction of 55%⁸). The implementation of Euro 6 is also directing manufactures to use more effective after-treatment system for NO_x emissions, such as selective catalytic reduction (SCR), lean NO_x trap (LNT), and exhaust gas recirculation (EGR). The integration of these NO_x control systems is observed to be leading to a considerable reduction in real-world NO_x emissions. The scale parameter fitted to Euro 6a/b is also approximately half that of Euro 5 vans’ (see Table 3-3), demonstrating that there is not only a significant decrease in the typical NO_x emission rates, but also that the emission rates in this sub-fleet are becoming more centralized (consistent).

Test conditions (road grade, ambient temperature and VSP) have been found important to diesel van emission performance. NO_x emissions of Euro 3 to 5 vehicles in Switzerland are relatively high as the remote sensing campaigns carried out during 2011 to 2015 were at a site with a steep road grade (9%), and higher road grade is known to elevate NO_x emissions ([Costagliola et al. \(2018\)](#)). The Euro 6a/b ‘on-model’ van emissions in Switzerland are however low in

⁸ Regulation (EC) 715/2007

comparison with other countries, on account of only two third of the vehicles are regarded as ‘on-model’ vehicles (reason discussed in section 3.3.2). The typical NO_x emissions of Euro 5 and Euro 6a/b measured in the UK are considered relatively high in comparison with the other locations, and this may be associated with the lower ambient temperatures. Remote sensing campaigns carried out in the UK in 2017 and 2018 were in wintertime (with ambient temperatures around 10°C, see Table A. 1 in the Appendix), during which 63% and 100% of Euro 5 and Euro 6a/b vehicles were measured. Studies ([Sjödin et al., 2017](#); [Grange et al., 2019](#); [ICCT, 2019a](#)) have however indicated that the temperature dependence of NO_x emissions is stronger for pre-Euro 6a/b vehicles (Euro 3-5) than for Euro 6a/b. [ICCT \(2019a\)](#) suggests that for Euro 6a/b, NO_x emissions are only elevated when the ambient temperature is below 10°C, but for the temperature bins of 10°C-20°C and 20°C-30°C NO_x emissions are almost the same. As the UK measurements were made around the 10°C threshold, this is considered to be associated with elevated NO_x emissions from Euro 5 vans, but has a less impact on their Euro 6a/b counterparts. Belgium has relatively low NO_x emissions despite its high VSP values and high certificated CO₂ emissions. The Belgium measurements were all made on a highway with an average vehicle speed of more than 70km/h, hence high VSP levels for drive-through measurements associated with aerodynamic drag and rolling resistance at these speeds. This finding is also observed in PEMS tests of Euro 5 and Euro 6a/b diesel cars, where vehicles in motorway driving conditions emit less NO_x than those on sections of urban areas ([O'Driscoll et al., 2018](#)). It is hypothesised that high and sustained speed would also provide enough temperature for the NO_x emission control system (e.g., EGR and SCR) commonly deployed to maintain their high efficiency operating temperature ([Yang, Z. et al., 2021](#); [Ntziachristos et al., 2016](#)).

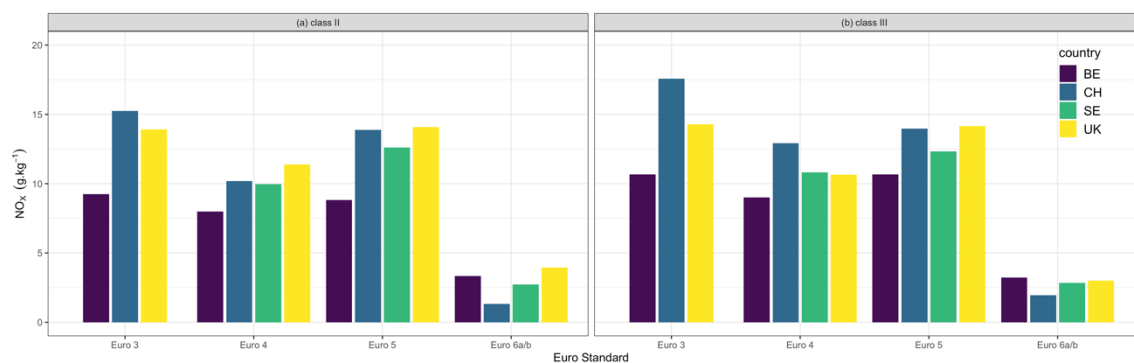


Figure 3-5. Typical NO_x emission rates (g/kg) for normally behaving (a) class II [left] and (b) class III [right] diesel vans by Euro standard and country

3.3.2 Impact of road grade on candidate high NO_x emitting vans

Recent remote sensing campaigns in Switzerland (year 2016-2019) were carried out at six sites with road grades ranging from 2.4% to 9.4%. It is hypothesised that the high percentage of 'off-model' vehicles found in Swiss Euro 6a/b fleet may be related to the steep road grade at some of the campaign sites. Data from Euro 6a/b class II and class III fleet in the Switzerland are classified by road grade and Gumbel distributions fitted and 'off-model' fractions estimated using the maximum R^2 value method (see Table A. 3 in the Appendix). The results illustrate that sites with steeper road grade (4.4% and 9.4%) have a much higher percentage of 'off-model' vehicles, which may partly explain why there are more 'off-model' vehicles identified in the Swiss Euro 6a/b fleet.

Figure 3-6 presents the 'on-model' vehicles in Euro 6a/b class II and class III fleets (see the orange triangular dots in Figure 3-6-a and Figure 3-6-b). NO_x emission rates in sites with relatively gentle slopes (site 1, site 2 and site 3) are higher than uphill sites (site 4, site 5 and site 6). The trend is contrary to findings for Euro 5 vehicles (refer to the blue triangular dots in Figure 3-6-a and Figure 3-6-b), where higher road grade would lead to elevated NO_x emissions ([Costagliola et al., 2018](#)). This is considered to be because SCR system equipped on Euro 6a/b vans can achieve better NO_x reductions when the exhaust temperature is high enough ([Moody and Tate, 2017](#)). When Euro 6a/b vehicles are driven on steep road grade site, the consequent high engine load would result in better effective conversions and catalytic reductions in the SCR system and that may offset the emission increase caused by higher engine load (higher road grade).

[Rushton et al. \(2021\)](#) found that candidate high-emitting vehicle sub-fleets also follow the Gumbel distribution, so vans being classified as 'off-model' vehicles in Swiss Euro 6a/b fleet are also fitted to the Gumbel distribution (results documented in Table A. 3 in the Appendix). The location value of each sub-fleet are regarded as the typical NO_x emission rates of the high emitting vehicles, and illustrated as orange circle dots in Figure 3-6-a and Figure 3-6-b (Euro 5 fleet doesn't have 'off-model' vehicles). In steep road grade (4.4% and 9.4%), the difference between 'on-model' vehicles and 'off-model' vehicles for Euro 6a/b class II vehicles is larger than Euro 6a/b class III vehicles. The results therefore suggest that the NO_x performance of class II Euro 6a/b vans deemed high-emitters are more sensitive to road grade compared with their class III counterparts. Considering these class II and class III fleets were measured in the same driving conditions, the difference in emission performance may be caused by different vehicle characteristics and performance of their respective exhaust

after-treatment systems. However, based on the vehicle make/model information in the remote sensing database and further after-treatment system information (documented in Table A. 4 in the Appendix) extracted from the ADAC⁹ vehicle catalogue or corresponding van brochures, it is found that the almost all popular models (the top-ten most commonly observed) in Euro 6a/b class II and class III vans in Switzerland are equipped with SCR systems, so the relatively poorer emission characteristics of class II vans is not found to be attributed to the type of after-treatment technology, rather their performance in the driving characteristics at this site. Further analysis of the difference between class II and class III in Euro 6a/b fleets is conducted in the next section.

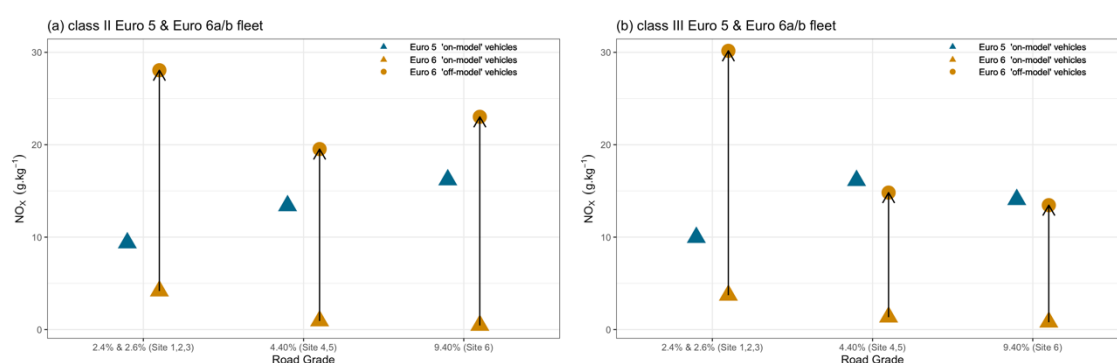


Figure 3-6 Impact of road grade on the typical NO_x emission rates (g/kg) of ‘on-model’ and ‘off-model’ vehicles as a function of road grade in Switzerland for sub-fleets (a) class II Euro 5 & Euro 6a/b [left]; (b) class III Euro 5 & Euro 6a/b [right] (note there are no ‘off-model’ vehicles in Euro 5 fleet)

It’s more likely that these ‘off-model’ vehicles only temporarily emit high rates of NO_x at sites with steep uphill road gradients, rather than they are indeed high-emitters and can be more effectively identified on a steeper road, otherwise the same percentage of ‘off-model’ vehicles would probably be identified at other sites with lower road grade. Accordingly, if the purpose is to have an emission evaluation of typical vehicles in more normal operating conditions, it is advised that remote sensing campaigns be conducted at sites with a gentle slope.

3.3.3 The NO_x performance of normally behaving Euro 6a/b vans by vehicle model and manufacture group

To further investigate Euro 6a/b vans’ emission performance, remote sensing data can be segmented by models or manufacturing groups (“families”) ([ICCT, 2019a](#)). However, further breaking down the fleets within one country and

⁹ <https://www.adac.de/>

analysing its characteristics will not derive any useful conclusion as the sample size is too small, rather the remote sensing data across different countries needs to be combined together. To test if the four countries' data can be merged into one bigger dataset, a two sample K-S test explained in section 3.2.4 is applied. The result shows that for Euro 6a/b class II vans' remote sensing measurements: Belgium, Sweden and the UK follow the same distribution and can be combined into a single dataset. For Euro 6a/b class III vans' remote sensing measurements: all four countries are found to be from the same distribution and can be combined to a single dataset. After combining data from three countries in class II fleet and four countries in class III fleet, the Gumbel distribution and maximum R^2 method is applied to two fleets. A 4% of 'off-model' vehicles is found for each fleet. For class II Euro 6a/b vans, the 4% 'off-model' vehicles accounts for 24% of total NO_x emission, while the 4% 'off-model' vans in Euro 6a/b class III fleet accounts for 21% of total NO_x emission. The Gumbel distribution fitted to both the 'on-model' and 'off-model' vehicles is documented in see Table 3-4. The typical emission rate (location value) for class II vans are slightly higher than class III vans, with a greater spread in the distribution (higher scale value). When analysing the vehicle characteristics, no significant difference is found between 'on-model' and 'off-model' vans (shown in Table 3-4), except that the average engine size of class II 'off-model' vans is lower than the 'on-model' vans.

Table 3-4 Gumbel distribution fit parameters and fleet characteristics of 'on-model' and 'off-model' vans in merged Euro 6a/b dataset

	Class II (BE, SE, UK)		Class III (BE, CH, SE, UK)	
	'On-model'	'Off-model'	'On-model'	'Off-model'
Sample size (n)	5120	214	15777	658
Location parameter(g/kg)	3.30	33.24	3.00	29.36
Scale parameter (g/kg)	4.50	5.87	4.33	4.34
Fit R^2	97.51%	97.97%	97.23%	97.98%
Vehicle age (year)	1	1	1	1
Certificated CO ₂ emission (g/km)	130	131	185	184
Engine size (cm ³)	1698	1554	2106	2083
Rated power (kW)	77	76	107	105
Curb weight (kg)	1505	1493	2139	2169

Engine downsizing is a design strategy to improve fuel efficiency for lighter vehicles by reducing the frictional losses and relative weight of the engine (and total kerb-weight), with a turbocharger helping provide the levels of power demanded ([Manzie, 2010](#)). While reducing CO₂ emissions, a downsized diesel engine is found to increase NO_x ([Johnson, T.V., 2009](#)). However, no research is apparently related to the issues of higher NO_x from Euro 6a/b light-duty vehicles with downsized engines.

To test whether engine size has an impact on NO_x emissions, the merged class II and class III fleet is split into different sub-fleet by models and makes. Table A. 5 in the Appendix lists the top 5 popular models for class II and class III Euro 6a/b vans, and its corresponding Gumbel distribution fit parameters for the 'on-model' vehicles, as well as every model's engine size and vehicle rated power. kW/litre specific power is introduced to represent the power density, with a higher kW/litre being characteristic of a downsized engine. Figure 3-7 demonstrates that the kW/litre specific power of the top 5 models in class II Euro 6a/b fleets are more distributed compared with models in class III fleets. Transit Connect with the highest kW/litre specific power in class II fleet has much higher NO_x emissions. However, that's not the case for large class III Euro 6a/b vans, where both NO_x emissions and the kW/litre specific power of class III Euro 6a/b vans are relatively stable.

A turbocharger maintains the high-power output in a downsized engine by increasing the oxygen concentration in the cylinder and improving combustion efficiency ([Manzie, 2010](#)). Accompanying this process, in-cylinder combustion temperature is increased significantly ([Karabektas, 2009](#)). As a result, the engine-out NO_x emissions are inevitably elevated with the increase of in-cylinder temperature and available oxygen ([Shameer and Ramesh, 2017](#)). Besides, when the vehicle is driven under high load (e.g., at high speed or on a steep road), the maximum exhaust recirculation ratio decreases in the NO_x control system EGR¹⁰ ([Zheng et al., 2004](#)) to maintain stable combustion, which unavoidably leads to the increase of engine-out NO_x emissions. It is suspected that when the engine gets too small relative to the vehicle size and weight, and is driven in a relatively aggressive manner, excessive NO_x emissions might be observed.

¹⁰ EGR (exhaust gas recirculation) is used widely in both gasoline and diesel cars from Euro 3 and Euro 6. It reroutes some of the exhaust gas back into the engine's combustion chamber and dilutes the air/fuel mixture. A lower oxygen content leads to a cooler combustion process, which reduces the production of engine-out NO_x.

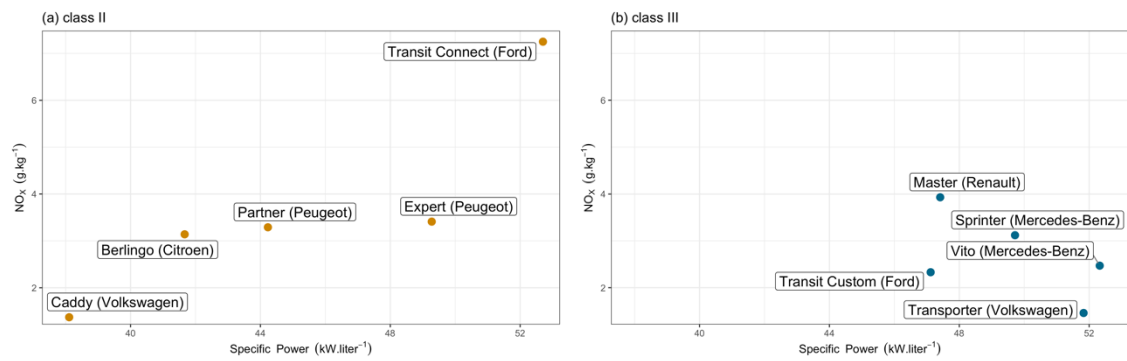


Figure 3-7 Relationship between kW/litre specific power and NO_x emissions (g/kg) for popular models in Euro 6a/b merged fleet: (a) class II [left]; (b) class III [right]

Merged class II and class III Euro 6a/b diesel vans are also segmented by manufacture groups, and then applied to the Gumbel distribution and maximum R^2 value cutting method. Table A. 6 in the Appendix lists 8 popular manufacture groups and their respective brands, which cover over 98% of the remote sensing measurements. Table A. 7 in the Appendix lists the detailed results of the Gumbel distribution fit parameters of ‘on-model’ vehicles for all the popular manufacture groups. Figure 3-8 presents the fuel-specific NO_x emissions of ‘on-model’ vehicles in each manufacture group, ordered by descending NO_x emissions. The width of the bar is the corresponding sample size of a specific manufacture group.

For the most part, manufacture group performance of class III vans is in line with the [ICCT \(2019a\)](#) report, as the number of class III vans outnumber class II vans by 3 times. The emission contribution from Class III van therefore dominates the overall trend of the van fleet. NO_x emissions vary considerably by manufacture group, and even within the same manufacture group between the performance of class II and class III vans. Daimler and Ford are found to have the worst NO_x emission performance in class II vehicles, while their class III vehicles emissions are within the average range. On the other end of the scale, the PSA Group vehicles are relatively clean in class II vehicles but are identified as the third-highest emitting manufacture in class III vehicles. The VW Group is the manufacture with cleanest NO_x emission performance of both class II and class III vehicles.

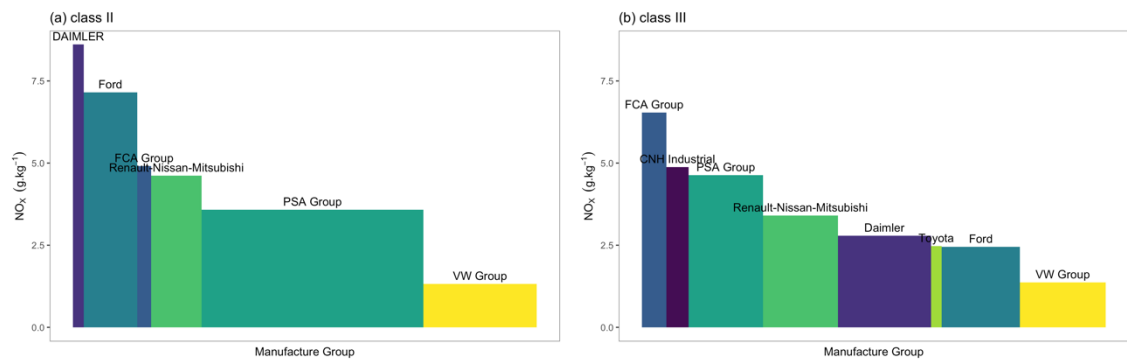


Figure 3-8 NO_x emissions (g/kg) by popular manufacture groups in Euro 6a/b merged fleet: (a) class II [left]; (b) class III [right] (the width of the bar is the corresponding sample size)

3.4 Summary and conclusions

The distribution of diesel van fuel-specific NO_x emissions in g/kg measured by remote sensing is skewed-right. To accurately characterize van emission performance and find the cut-off point for candidate high-emitters, the Gumbel distribution is applied to vehicle emission remote sensing data from four countries. Vehicles that follow the Gumbel distribution are selected to represent the emission performance of the normally behaving vehicles in a fleet, while the vehicles that do not follow the Gumbel distribution are regarded as candidate high emitting vehicles. Euro 5 and older vehicles can be fully described by the Gumbel distribution while a proportion of candidate high-emitters are identified in the Euro 6a/b fleets. The emphasis of this paper is examining the emission performance of the normally behaving vehicles and candidate high-emitters in Euro 6a/b fleet, and the key findings are:

- When comparing the fuel-specific NO_x emissions of the normally behaving vans, a reduction of emissions has only been seen since the introduction of Euro 6a/b standard vehicles, where the emissions is less than one third of the emissions from Euro 5 vans.
- A much higher percentage of ‘off-model’ Euro 6a/b vans has been observed at the measurement sites in Switzerland that had a steeper road grade, and it’s more likely that vehicles at these sites only temporarily emit high rates of NO_x. Based on this it is recommended to conduct remote sensing campaigns at a site with a gentle slope, so the assessment of the vehicles’ emission performance surveyed is in typical driving/operating conditions across a city/region/country.
- Euro 6a/b vans with improved NO_x after-treatment system (e.g., SCR) can offset the emission increasing caused by high VSP or steep road grade, as

high engine load can provide enough exhaust emission temperature for the after-treatment system to work efficiently.

- After combining data from three countries in class II fleet and four countries in class III fleet, a consistent 4% of candidate high-emitters are found in both class II and class III merged Euro 6a/b vans, estimated to account for 24% and 21% total NO_x emissions respectively.
- Differentiating the cross-country merged data by models and analysing the relationship of kW/litre and emissions, illustrates that Euro 6a/b Class II vans are more sensitive to engine size. Rather than attributing the reason to different application and design of emission after-treatment systems, it's considered more likely to be due to the engine downsizing of smaller class II vans.
- The merged data are also segmented by manufacture group. The VW Group is identified as the manufacture with the cleanest emission performance in both class II and class III Euro 6a/b vehicles. Daimler and FCA Group emit most in class II and class III Euro 6a/b fleet respectively.

This paper analyses the real-world emission performance of diesel Euro 6a/b vans, whose type approval test were being conducted under the NEDC drive cycle. The NEDC drive cycle has many cruise and mild acceleration driving conditions, which cannot represent the more dynamic driving that occur when vehicles are recorded by remote sensing device. To establish a more representative pollution test for light-duty vehicles (cars and vans), a new real-driving emissions (RDE) test procedure was introduced in 2017, and will apply to all new vans by the beginning of 2022¹¹. [ICCT \(2019a\)](#) found the vast majority of remote sensing measurements are within normal operating conditions defined in the European RDE regulation. As a result the new Euro 6d-temp and Euro 6d vans with on-road testing are expected to have lower NO_x emissions where emission control systems can operate properly. It is recommended the analytical approach presented in this to identify candidate high-emitters is applied to emerging remote sensing datasets that have significant shares of Euro 6d-temp and Euro 6d vans, to ascertain whether this generation of vehicles have consistently low NO_x emissions, or whether a share of these vehicles with poorer emission performance make a substantial contribution to the total emissions from this sub-fleet.

The EU has founded a project called CARES¹² focusing on using contactless and un-intrusive technologies to monitor and enforce improvements in road vehicle emissions, this includes the application of roadside sampling (remote sensing

¹¹ Commission Regulation (EU) 2017/1151

¹² <https://cordis.europa.eu/project/id/814966>

and point sampling devices) and plume chasing ([Pöhler et al., 2019](#)). In the future, measurement data from a remote sensing device may communicate with other systems and technologies¹³ for market surveillance and enforcement purposes, working towards maintaining a fleet that are in compliance with emission standards. It is suggested the Gumbel distribution could help to characterize the emission performance of the normally-behaving vehicles as well as screen high-emitting vehicles. At local levels, authorities could use the Gumbel distribution to determine the ‘cut-points’ that will help to identify high-emitting vehicles and clean vehicles. For example, a single, high instantaneous recording may not necessarily mean a vehicle consistently emits at an excessive rate but if a vehicle has two remote sensing recordings above threshold, it may be identified as a candidate high-emitter and further investigated by plume chasing ([Pöhler et al., 2019](#)) and/or the registered keeper is directed to get the vehicle tested at an authorized emission testing centre such as garage inspection ([Huang et al., 2018](#)). At a state level, the government could use the Gumbel distribution to characterize the emission performance of a vehicle family, and identify high-emitting vehicle manufactures or models.

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¹³ <https://cares-project.eu/>

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Chapter 4 The CO₂ and NO_x Emission Reduction Potential of the Van Sector: the Impact of Accelerating the Electric Vehicle Transition in Great Britain

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Abstract

As a major emission contributor with significant growth potential, the light goods vehicle (van) sector plays an important part in achieving net-zero. In 2020 the UK government published its plan to phase out sales of new internal combustion engine (ICE) cars and vans by 2030, but the impact of the policy and how far are we to decarbonize the entire van fleet by 2050 is unclear.

This paper investigates the CO₂ and NO_x emission trend in the van sector in Great Britain from 2020 to 2040 under the 2030 ICE phase-out. The Electric Car Consumer Model (ECCo) model² is used to forecast the future population of different powertrains of vans. The annual vehicle kilometres travelled of vans by primary use is estimated based on the van activity survey³. The instantaneous emission model PHEM and NAEI emissions inventory are used to parameterize real-world driving emission factors of CO₂ and NO_x respectively. Scenarios have been set out to analyse how varying the electrification pace of class III vans, accelerating the market penetration of zero emission vans, and replacing vans with e-cargo bikes in urban areas would impact the CO₂ emission reduction performance. The impact of adapting NO_x emission factors to remote sensing results that better account for the share and emission contribution from “high-emitting” vehicles with faulty or tampered emission controls are also explored.

Baseline scenario results suggest that CO₂ emissions start to decrease in 2025 and the reduction from a 2019 baseline to 2040 is 88.1%. Based on the pace of reduction, it is estimated that the tailpipe net-zero target in the van sector will be reached by 2050. The trend towards an overall decline of NO_x emissions has started in 2022, and the decrease by 2040 compared with 2019 is forecast to be

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² <http://www.element-energy.co.uk/sectors/low-carbon-transport/project-case-studies/>

³ <https://www.gov.uk/government/statistics/van-statistics-2019-to-2020>

97.5%. Scenario analysis indicates that the key factor influencing emission reduction speed of the van sector is a rapid transition of new vehicles sales to zero emission vans by 2030, which is estimated to bring a total economic benefit of £12.9 billion between 2020 and 2040 for the avoided emissions of carbon.

Keywords

Vans; Battery Electric Vehicles (BEVs); Climate Mitigation; Urban Air Quality; NO_x Emissions; Scenario Projections

4.1 Introduction

The light goods vehicles (LGVs) or vans are a type of 4-wheel vehicle constructed for transporting goods and must have a gross weight of 3.5 tonnes or less ([DfT, 2022a](#)). In 2019 there were 4.1 million licensed vans in Great Britain, accounting for 10.7% of the total licensed vehicles ([DfT, 2020e](#)). In addition, vans have reached a record high of 55.5 billion vehicle miles in 2019, making up 16% of all motor vehicle traffic ([DfT, 2020c](#)). Alongside the fastest growth ([DfT, 2020c](#); [DfT, 2020e](#)) of any motor vehicle in population (93%) and traffic (106.2%) over the last 25 years, vans were responsible for about 17.4% of greenhouse gas (GHG) emissions ([DfBEIS, 2021b](#)) and 36.1% of NO_x emissions in 2019 ([NAEI, 2021b](#)) from the road traffic sector (UK figure, Northern Ireland included). To reduce the negative environmental impact of CO₂ emissions, the UK government has introduced a mixture of different policies and grants that could help encourage the wider use of electric vehicles ([Hill et al., 2019](#)). However, the take-up of electric vans has been slow in the van sector. 93.9% of the newly registered vans in Great Britain in 2021 were diesel-fuelled, while battery electric vans only represented 3.6%. By comparison, the battery electric passenger car market has seen continued growth, accounting for 11.5% of newly registered cars in 2021 ([DfT, 2022b](#)).

Transport is currently the UK's worst-performing sector for carbon reduction. The UK's total GHG emissions in 2019 fell by 43.8% compared with 1990 whereas the road transport sector was 0.1% above the 1990 level ([DfBEIS, 2021b](#)). In June 2019, the UK became the first major economy to commit to a 'Net-zero' emissions target by 2050. It is a challenging target for the road transport sector, the largest contributor to the UK's domestic GHG emissions and accounts for about a quarter of emissions in 2019 ([DfBEIS, 2021b](#)). In 2020, to help accelerate the transition to a 'net-zero' society, the government has brought forward the end of sales of new petrol and diesel cars and vans to 2030 (from 2040), with all new

cars and vans being fully zero emission at the tailpipe from 2035⁴. The government ([DfT, 2021a](#); [DfT and OZEV, 2021](#)) and research institutions ([Allwood et al., 2019](#); [CAT, 2019](#); [CCC, 2019](#)) have all published reports on how the road transport sector could reduce energy demand and transfer to renewable energy resources to reach net-zero, but the focus has been limited mainly to passenger cars and heavy goods vehicles, while vans are often generalised with passenger cars in the light-duty vehicles (LDVs) sector as cars make up the majority of licensed LDVs (87.9% in 2021 in Great Britain ([DfT, 2022b](#))). However, vans demonstrate a different fleet composition ([DfT, 2022b](#)) and driving pattern ([Dun et al., 2015](#); [Allen et al., 2018](#); [SMMT, 2020](#)) from passenger cars. Considering vans' contribution to CO₂ and NO_x emissions and its limited studies, it's both timely and considered important to have a robust and detailed analysis of whether the take-up trajectories consistent with phasing out ICE (internal combustion engine) vans by 2030 is fast enough to reach the net-zero target by 2050.

This paper aims to explore the potential emissions impact of an ICE phase-out date for new van sales in Great Britain by 2030. The analysis is conducted by estimating detailed van CO₂ and NO_x emission trends from 2020 to 2040 in terms of different powertrains, class types⁵ and primary usages. Van sales/stock numbers are directly derived from a choice model ECCo under a 2030 phase-out of ICEs ([Pirie et al., 2020](#)). An emission reference model is developed to estimate the total CO₂ and NO_x emissions of the van fleet, with average emission factor derived from the instantaneous emission model PHEM ([Hausberger and Rexeis, 2017](#); [Yang, Z. et al., 2021](#)) and the [NAEI \(2021a\)](#) emissions inventory respectively. Scenarios are then set out to analyse how varying the rate of uptake of large class III electric vans, accelerating the market penetration of battery electric vans, replacing vans with e-cargo bikes in urban areas and adapting NO_x emission factors to remote sensing results would impact the possible emission mitigation level in the van sector. An economic impact analysis of CO₂ and NO_x emissions on public health and the environment under different scenarios is also conducted.

4.2 Research data and methodology

⁴ <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution>

⁵ Vans can be further classified into three sub-categories by reference mass, where class I are vans not exceeding 1305kg, class II are those between 1305kg and 1760kg, and class III are those exceeding 1760kg. Annex I to Regulation (EC) No 715/2007

The reduction potential of CO₂ and NO_x emissions from the van sector in Great Britain during 2020-2040 is predicted under different control strategies and policies. An emission reference model is developed to estimate the total CO₂ and NO_x emissions. A baseline scenario and five alternative scenarios have been designed in section 4.3 to assess the impact of important factors relating to the emission reduction pace.

4.2.1 Van emission reference model

This paper only estimates emissions of CO₂ and NO_x measured at the tailpipe and does not consider any upstream emissions produced (e.g., from electricity generation⁶ or vehicle/battery manufacturers). The tailpipe CO₂ and NO_x emissions from vans are calculated by combining the number of vans on the road and traffic data with emission factors, and the emission reference model is shown as follows:

$$DE_y = \sum_{i,j,k,m,y} FAEF_{i,j,k,m,y} VP_{i,j,k,m,y} FAVKT_{i,j,k,m,y} \quad (Eq. 4 - 1)$$

Where *DE* is the total direct emission; *FAEF* is the fleet average emission factor, *VP* is the number of vans on the road, *FAVKT* is the fleet average annual vehicle kilometres travelled; *i* is the Euro standard, *j* is the van class type, *k* is the fuel type, *m* is the primary use of the vehicle and *y* is the calendar year. It should be noted that as petrol ICE vans only represent 1.9% of newly registered vans and 3.1% of all licensed vans in 2021, and the petrol ICE vans on the road has seen an overall declining trend ([DfT, 2022b](#)), the petrol ICE fleet is combined with the diesel ICE fleet, and the emissions are not considered separately.

4.2.2 Van sales and stock projection

The van sales and van stock numbers are predicted by Electric Car Consumer Model (ECCo) ([Pirie et al., 2020](#)). ECCo is a vehicle uptake model built by Element Energy⁷ and is also used by the Department for Transport (DfT) for policy design. The central part of ECCo is a consumer choice model (see Figure 4-1) that predicts the sales of different car and van powertrain technologies including ICE vehicles and all kinds of alternative fuel vehicles⁸ (AFVs). It accounts for elements such as vehicle attributes (e.g., initial purchase cost,

⁶ The UK's electricity is generated in a number of different ways (35.7% gas, 16.1% nuclear, 28.4% wind & solar and 12.6% other renewables in 2020) and it's moving towards renewable sources. (data from UK Energy in Brief 2021)

⁷ <http://www.element-energy.co.uk/sectors/low-carbon-transport/project-case-studies/>

⁸ Alternative fuel vehicles can be propelled by something other than just petrol or diesel, which includes hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and H2 fuel cell vehicles in this paper.

operation cost, vehicle performance), consumer characteristics, infrastructure (e.g., charging points), economics and grid, policy and incentives (e.g., grants, congestion charge) in the decision-making process. The sales figure generated by the choice model is then passed to a stock model to track vehicle usage through its lifetime.

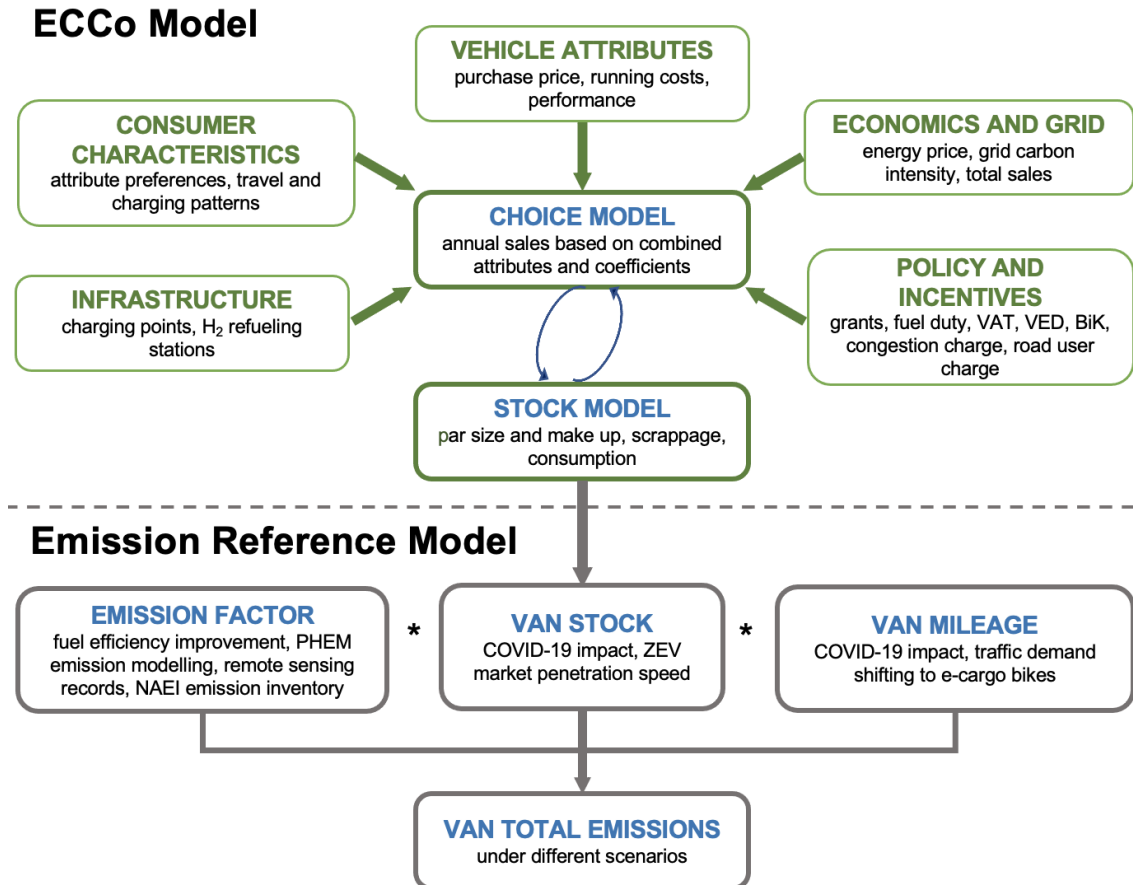


Figure 4-1 Flow chart of ECCo model and emission reference model, adapted from [Pirie et al. \(2020\)](#)

The impact of the coronavirus (COVID-19) pandemic on the van sales is only considered in 2020, because the rapid recovery in new van registrations in 2021, only 3.4% fewer than 2019 ([DfT, 2022b](#)). The fleet composition projection by Euro standard (see Table B. 1 in the Appendix) in the ICE van sector is based on historical and predicted new van sales in the baseline scenario, Euro standard implementation date of class II & class III vans and an average lifetime (age) of 13 years ([Dun et al., 2015](#); [SMMT, 2020](#)). The fleet composition by class type (see Table B. 2 in the Appendix) within each Euro standard of ICE vans is estimated by annual sales of every generic model ([DfT, 2022b](#)) and their corresponding reference mass. It is assumed that Euro 6d-temp and Euro 6d ICE

vans and all the AFVs (HEVs/PHEVs/BEVs/H2 fuel cell vehicles) follow the class type composition of Euro 6c ICE vans.

This paper further classifies the van numbers based on van primary use (shown in Figure 4-2-a). The van activity survey (prior to covid-19 restrictions) carried out by [DfT \(2020d\)](#) suggests that vans are most frequently used for 'carrying equipment, tools and materials' (54%), followed by 'delivery or collection of goods' (16%) and 'private/domestic non-business use' (16%). Due to the increased use of vans for leisure journeys ([Browne et al., 2014](#)), a new primary usage of 'recreational/leisure and holidays' (13%) was introduced in the 2019-2020 survey. The proportions of vans for the top three usages in the 2019-2020 survey have all slightly decreased over the 11 years compared with the van survey conducted by [DfT \(2009\)](#) during 2008-2009. However, the introduction of the new primary usage also limits the comparability. Consequently, an assumption is made that the share of van numbers by primary usage during 2020-2040 will remain the same as in the 2019-2020 van survey ([DfT, 2020d](#)).

4.2.3 Average annual van mileage estimation

Though total distance travelled by van ([DfT, 2020c](#)) and van population ([DfT, 2022b](#)) saw significant growth between 1994 and 2019, the average mileage per van has remained broadly stable ([DfT, 2020d](#)). It is assumed that the annual mileage per van for every usage through 2020-2040 keeps at the same level as in the 2019-2020 van survey ([DfT, 2020d](#)) illustrated in Figure 4-2-b, where vans used for 'delivery/collection of goods' have a much higher average mileage than other usages. In addition, though van statistics by [DfT \(2020d\)](#) indicates that van mileage of ultra-low emission vehicles⁹ (ULEVs) only accounts for 54.2% of non-ULEV van for the time being, the difference of van mileage between different powertrains is not considered in this paper.

⁹ Vans that emit less than 75g of carbon dioxide (CO₂) from the tailpipe for every kilometre travelled.

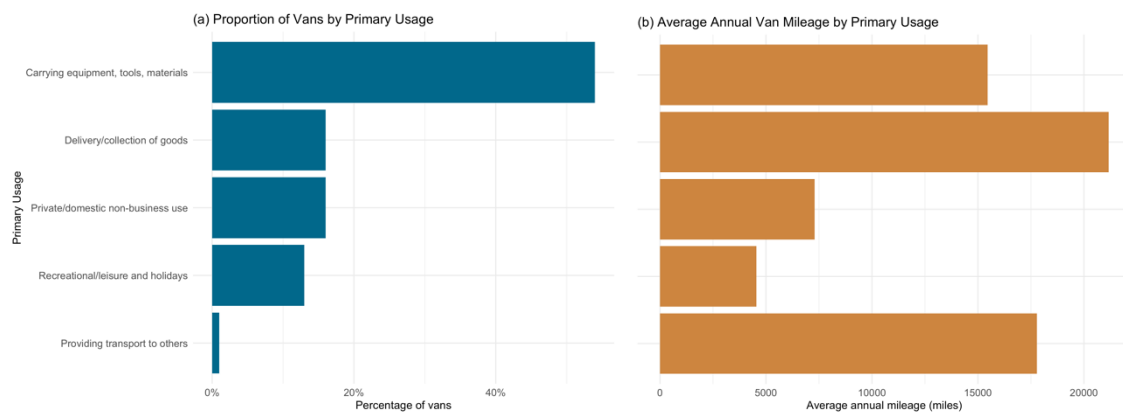


Figure 4-2 (a) Proportion of vans [left] and (b) average annual van mileage (miles) [right] by primary use ([DfT, 2020d](#))

The coronavirus (COVID-19) pandemic has a wide impact on the road traffic sector in 2020 in Great Britain. Car traffic decreased by 24.7% compared to the year 2019, while van traffic experienced a relatively smaller fall of 9.1% ([DfT, 2021b](#)). The volume of van traffic has returned to pre-covid level in 2021 based on DfT statistics ([DfT, 2021c](#)). As a result it is assumed in this paper that the average annual van mileage of every usage was 9.1% lower in 2020 compared with the 2019-2020 van survey ([DfT, 2020d](#)) and during 2021-2040 it remains the same as in Figure 4-2-b.

4.2.4 Van CO₂ and NO_x emission factor

To improve fuel efficiency, the EU has set stricter fleet-wide CO₂ emission targets for new vans, with a 15% reduction from 2025 on and a 31% reduction from 2030 on (based on a 2021 baseline)¹⁰. With the implementation of stricter regulations¹⁰, it is expected the real-world fuel consumption of new conventional cars and vans is going to improve as well. Applicable technologies including downsizing, friction reduction and combustion improvement are going to reduce fuel consumption in compression-ignition diesel engines ([National Research Council, 2015](#); [Hu and Chen, 2016](#)). Based on this the CO₂ and NO_x emissions of all new diesel ICE vans are extrapolated using a compounded reduction of 4.0% per year from 2022 and 5.1% per year from 2025 to reach the goal of an overall reduction of 15% by 2025 and 31% by 2030.

- CO₂ emission factor

The instantaneous vehicle emission model PHEM ([Hausberger and Rexeis, 2017](#)) has proven to be able to accurately simulate the CO₂ emissions of diesel vans

¹⁰ https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en (it is assumed the UK fleet emissions targets will remain aligned to the EU during the modelling period.)

([Yang, Z. et al., 2021](#)). PHEM can provide both second-by-second tailpipe emissions rates (g/s) based on the corresponding engine emission map as well as average emission factors (g/km) over a defined driving cycle. Average CO₂ emission factors of diesel ICE vans simulated by PHEM over the London Drive Cycle (LDC) ([Moody and Tate, 2017](#)) are adopted in this paper (see Table B. 3 in the Appendix).

Petrol HEVs and petrol PHEVs are not included in the PHEM database and the CO₂ emission factors of these two powertrains are estimated based on the second-by-second CO₂ emissions of Euro 6a/b petrol ICE vans from PHEM and the fuel consumption relationship among petrol ICE, petrol HEV and petrol PHEV vans. Based on findings from [Fontaras et al. \(2008\)](#) and [Orecchini et al. \(2018\)](#) it is assumed that the CO₂ emissions of a petrol HEV is 50% of a Euro 6a/b petrol ICE van when the speed is lower or equal to 20km/h. The benefit of hybrid powertrains will gradually disappear as the speed increases, and it is assumed that the emissions will linearly increase when the speed is between 20km/h and 90 km/h, and beyond 90 km/h the CO₂ emissions are the same as petrol ICE vans. The average CO₂ emission factor of petrol HEVs over the whole LDC is regarded as the emission factor of petrol HEV (see Table B. 4 in the Appendix) in this paper. The CO₂ emissions of a petrol PHEV are calculated using the following adapted equation ([Matzer et al., 2019](#)):

$$EF_{PHEV} = k_{EV} * EF_{EV} + (1 - k_{EV}) * EF_{HEV} \quad (Eq. 4 - 2)$$

Where EF_{PHEV} is the weighted average emission factor of petrol PHEV vans, k_{EV} is the share of electrified kilometres of total kilometres driven of a PHEV, an estimate of 33.3% is used in this paper ([Boston and Werthman, 2016](#)). EF_{EV} is the emission factor of a petrol PHEV when it operates as an electric vehicle and the emission is considered to be zero. EF_{HEV} is the emission factor of a petrol PHEV when it's driven in hybrid mode, in this paper the emission factor of the petrol HEV is used. The detailed CO₂ emissions of petrol PHEVs by class type are provided in Table B. 4 in the Appendix.

- NO_x emission factor

The NO_x emission factors of diesel ICE vans (provided in Table B. 3 in the Appendix) in the baseline scenario is directly adopted from [NAEI \(2021a\)](#), which uses the emission factor from the EMEP/EEA air pollutant emission inventory¹¹. The impact of adapting NO_x emission factors to remote sensing results that better account for the share and emission contribution from “high-emitting” vehicles with faulty or tampered emission controls are also explored in one of the alternative

¹¹ <https://www.eea.europa.eu/publications/emep-eea-guidebook-2019>

scenarios. In addition, as the NO_x emissions from petrol HEVs and petrol PHEVs are very low ([Palmer, 2019](#)), it is not considered in this paper.

4.3 Scenario design

In this section, one baseline and several alternative scenarios have been designed to assess the impact of some enablers and barriers affecting the effectiveness of CO₂ and NO_x emission reduction pace of vans. The brief narrative and key assumption of each scenario are stated as follows:

4.3.1 Baseline scenario (BL)

[Pirie et al. \(2020\)](#) uses the ECCo model to estimate the sales and stock of vans under two different scenarios, including a 2035 phase-out of ICEs scenario and an accelerated scenario that phases out ICEs in 2030. The detailed van sales and van stock numbers (see Table B. 5 in the Appendix) of a 2030 phase-out has been adopted in the baseline scenario, as it is consistent with the UK government's commitment to ending the sale of ICEs by 2030. Figure 4-3 presents the predicted total van sales share and van stock number of different powertrains and Euro standards under the baseline scenario of phasing out ICEs (including HEVs/PHEVs) in 2030. A rapid uptake of BEVs is observed in the mid-2020s, and the BEV sales share rises to 86.4% in 2030. The sales of H₂ fuel cell vans starts to grow in 2030 to satisfy the demand of van users who have a higher daily mileage requirement i.e. inter-urban highway driving. The petrol HEV and PHEV uptakes remain low, peaking at 12.6% and 4.6% respectively in 2024 and declining to 0.0% in 2030. It is estimated that there are 5.5 million zero emission vans (including BEVs and H₂ fuel cell vehicles) on the road in 2040 in the van sector, accounting for 89.9% of the whole fleet.

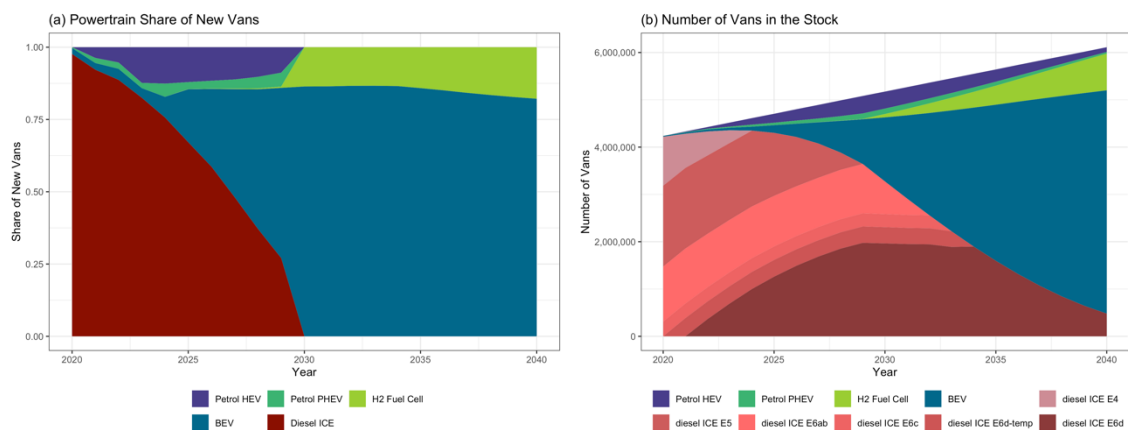


Figure 4-3 (a) Share of new van sales [left]; and (b) number of vans in the stock [right] during 2020-2040, under the baseline scenario

4.3.2 Slow class III electric van uptake scenario (SCIII)

Large vans are dominating the van market ([SMMT, 2019](#)), however the take-up of large electric vans has fallen far short of the level required to reach the ‘phasing out ICE vans by 2030’ goal ([CCC, 2020b](#)). Vehicle statistics from [DfT \(2022b\)](#) shows that class III vans accounted for 66.5% of newly registered vans in 2020 in Great Britain, while the electric class III vans only make up about 30.2% of total new BEV sales (see Figure 4-4). The limited supply of large electric vans and the outright purchase cost are two main barriers acting against the mass adoption of class III electric vans ([Greater London Authority, 2019](#)). In the near future, the transition to BEVs may be limited to smaller class II vans.

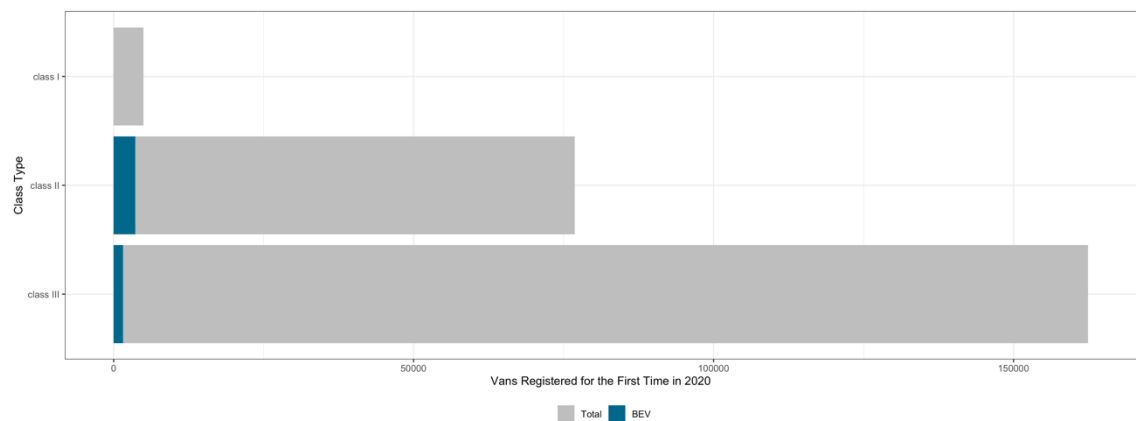


Figure 4-4 Newly registered vans in 2020 in Great Britain ([DfT, 2022b](#))

This scenario has been designed to project a 50% slower electrification transition of class III electric vans. During 2020-2029, 50% of the newly registered class III vans that should have been electric (H_2 fuel cell vans also included) are still considered to be powered by diesel. It should be noted that in this scenario the total number of class III van sales during 2020-2029 are the same as the baseline scenario, only the fleet composition by powertrain technology changes.

4.3.3 Rapid BEV penetration scenario (RB)

The BEV uptake prediction in research literatures has largely proven to be too pessimistic when compared with actual sales figures as they become available. For example, [CCC \(2020a\)](#) in its 6th carbon budget estimates that the share of new BEVs would reach 7% in 2021 for cars, in reality BEVs accounted for 11% of new car sales. The ECCo model ([Pirie et al., 2020](#)) in the baseline scenario predicts 2% of the newly registered vans are zero emission in 2021, however in reality BEVs already accounted for 3.6% of the new van sales in 2021 ([DfT, 2022b](#)).

This scenario is designed to represent a rapid transition to BEVs, suggested to be more realistic following recent sale figures. Market penetration of BEVs for cars and vans under the central scenario in [CCC \(2020a\)](#)'s 6th carbon budget report has been adopted. The BEV sales share starts to increase sharply in the early-2020s, making up 48% of new car sales in 2025 and 97% in 2030, and reaching 100% from 2032 onwards, whereas in the baseline scenario, the market penetration rate of BEVs (H2 fuel cell vehicles included) doesn't see a significant increase until the mid-2020s, and soon reaches 100% in 2030 (see Table 4-1).

Table 4-1 Proportion of new BEV sales in the BL and RB scenario in each year during 2020-2040, and actual figures in 2020 and 2021

Scenario	2020	2021	2022	2024	2026	2028	2030	2032 (and beyond)
BL	2%	2%	4%	7%	27%	49%	100%	100%
RB	2%	7%	12%	31%	56%	74%	97%	100%
Actuals	2%	4%						

4.3.4 Cycle freight in urban areas scenario (CF)

Urban van freight is estimated to represent 14.6% of the total urban traffic in 2019 in Great Britain ([DfT, 2021c](#)) and it contributes significantly to emissions/congestion in cities ([Browne et al., 2012](#)). E-cargo bikes are a potential technical solution to reduce urban freight transport's negative environmental and social impact ([Narayanan and Antoniou, 2022](#); [Philips et al., 2022](#)). They are suitable for delivering small parcels in contained areas, such as in densely populated areas or central business districts ([Verlinghieri et al., 2021](#)). More importantly, they are zero emission and take up less public space. Many studies have suggested the great potential of using e-cargo bikes to carry out urban commercial trips (see Table 4-2).

Table 4-2 Substitution potential of e-cargo bikes in various studies

Authors & Study Location & Project	Methodologies Description	Data Resource(s)	Substitution Potential*
Cairns and Sloman (2019) Great Britain Developing the evidence based on the contribution of the bicycle industry to Britain's industrial strategy	Predicting the substitution potential based on the percentage of all urban vehicle mileage constituted by delivery/service companies, and the potential of replacing delivery/service company trips by (e-)cargo bikes	DfT; LEFV-LOGIC project; CycleLogistics project	1.5-7.5% of mileage
Melo and Baptista (2017) Porto (Portugal) SusCity Project	Predicting the substitution potential based on using microscopic traffic simulation model to assess the network efficiency of using cargo cycles under different scenarios	AIMSUN (a microscopic traffic simulation model) developed for the city of Porto	Up to 10% of vans
Verlinghieri et al. (2021) London (Great Britain) Car-Free Megacities project	Predicting the substitution potential based on the percentage of all urban vehicle mileage constituted by delivery/service, and the percentage of van numbers that could be replaced by (e-)cargo bikes	An e-cargo bike logistics and pedicab company called Pedal Me	10% of mileage
van Amstel et al. (2018) Netherlands LEFV-LOGIC project	Predicting the substitution potential for every primary usage in the van sector based on the percentage of delivery vans in cities and the potential deployment of e-cargo bikes	Balm et al. (2018)	10%-15% of trips

Element Energy (2019)	Predicting the substitution potential by scoring an area against the potential for cycle freight	Scoring	Up to 14% of vans
London (Great Britain)			
Report commissioned by TfL (Transport for London)			
Wrighton and Reiter (2016)	Predicting the substitution potential for every primary usage in the van sector based on the number of trips that has the potential to shift to cargo bikes	NA	51% of trips
European cities			
CycleLogistics			
Gruber et al. (2013)	Based on the weight, volume, and shipment distance of e-cargo bikes	Pilot project in Berlin	19-48% of mileage
Berlin (Germany)			
NA			

* While van mileage, van trips and van numbers are not directly comparable, the 2019-2020 van survey ([DfT, 2020d](#)) suggests that a certain share of vans travel locally would have a much lower share of van total mileage.

In this scenario a lower bound of 10% of total urban van-km ([Verlinghieri et al., 2021](#)) and an upper bound of 48% of total urban van-km ([Gruber et al., 2013](#)) have been adopted to estimate the potential emission reduction of replacing vans with e-cargo bikes. The urban roads¹ in each region and country in Great Britain ([DfT, 2021c](#)) are considered to meet the criteria to encourage cycle logistics. Firstly, annual CO₂ emissions in Great Britain are distributed to each region and country based on its corresponding van traffic share ([DfT, 2021c](#)). Then a 10% substitution potential or a 48% substitution potential is assigned to the urban roads in each region and country to account for the impact of replacing vans with e-cargo bikes. The van mileage share by region and country, and the proportion of van mileage driven on urban roads in each region and country are considered to be stable during 2020-2040, and the figures in 2019 are used and stated in Table B. 6 in the Appendix. A gradual (linear) growth of the van-km share in urban areas of e-cargo bikes is assumed, starting from 0% in 2020 up to 10% and 48% in 2040.

4.3.5 Combined scenario: best case (BC)

A best case scenario has been designed to represent the situation of combining all the advantages from the previous scenarios: a rapid BEV penetration (RB scenario) and an encouragement of e-cargo bikes (CF scenario). In the BC scenario, the BEV sales share starts to increase sharply in the early-2020s, making up 48% of new car sales in 2025 and 97% in 2030, and reaching 100% from 2032 onwards. In addition, urban van traffic in each region and country will experience a gradual (linear) substitution of e-cargo bikes, starting from 0% in 2020 up to 48% in 2040.

4.3.6 Adapted NO_x emission factor scenario (AEF)

NO_x emission factors in the baseline scenario are directly adopted from [NAEI \(2021b\)](#), which shows little improvement between Euro 5 and Euro 6a/b/c vans (see Table B. 3 in the Appendix). However, studies have indicated that since the implementation of the much more stringent Euro 6a/b emission standard, the real-world van NO_x emissions have decreased significantly ([Chen et al., 2020](#); [Ghaffarpasand et al., 2020](#); [Yang, Z. et al., 2022](#)). To analyse whether a lower NO_x emission factor is the breaking point to reduce total NO_x emissions, the NO_x emission factors from remote sensing measurements captured in Great Britain

¹ Urban roads: Major and minor roads within an urban area with a population of 10,000 or more. These are based on 2011 Census definition of urban settlements.

during 2012-2019 ([Yang, Z. et al., 2022](#)) are used to parameterize the NO_x emissions of diesel ICE vans in this scenario.

Remote sensing systems only report the fuel-specific NO_x emissions (g/kg), and the distance specific NO_x emissions (g/km) are generated based on the equation and parameters provided by [Davison et al. \(2020\)](#). The distribution of NO_x emissions is skewed-right and follows the Gumbel distribution ([Rushton et al., 2021](#); [Yang, Z. et al., 2022](#)), therefore the location parameter of the fitted Gumbel distribution is used to represent the NO_x emission value of the normally behaving vehicles in a fleet. The remote sensing dataset doesn't include measurements from Euro 6c, Euro 6d-temp and Euro 6d diesel ICE vans, so the simulated average NO_x emission factors from PHEM over the LDC are used. However, the input data of Euro 6d-temp and Euro 6d vans in PHEM are not from neither chassis dyno tests nor portable emissions measurement system (PEMS) tests, but only a representation of the emission standard. As a result, the emission factors simulated by PHEM are multiplied with a conformity factor of 2.1 for Euro 6d-temp and 1.5 for Euro 6d for real-driving emissions (RDE)². The detailed NO_x emissions of diesel ICE vans adopted in this scenario are provided in Table B. 3 in the Appendix.

4.4 Results and discussions

4.4.1 Baseline scenario results

The predicted trend of CO₂ emissions in Great Britain under the baseline scenario is illustrated in Figure 4-5-a. Year 2019 is used as the reference year because the traffic in 2020 was heavily impacted by Covid-19 and cannot represent the normal level of emissions at present. The total CO₂ emissions peak at 20.1 million tonnes (Mt) in 2024, is then forecast to decrease. By 2040 the CO₂ emissions are only 11.9% of the 2019 level. Based on this pace of reduction, it is estimated the tailpipe net-zero target in the van sector will be reached by 2050. Figure 4-5-a also shows the overall CO₂ emission contribution by powertrain and Euro standard. Diesel ICE Euro 5 vans have the largest share of CO₂ emissions from 2020 (40.4%) to 2025 (30.9%) and following that, diesel ICE Euro 6d vans contribute the most (from 30.5% in 2026 to 80.6% in 2040). The annual CO₂ emissions from HEVs & PHEVs is relatively low, peaks in 2040 at 19.4% while the absolute emissions are already very low. [Küfeoglu and Khah Kok Hong \(2020\)](#) argue that changing the driving behaviour of HEVs/PHEVs can impact the reduction of GHG emission reduction pace but we consider the impact in the van

² COMMISSION REGULATION (EU) 2017/1151

sector to be small. Increasing the fuel efficiency of diesel ICE Euro 6d vans and scrapping the Euro 5 diesel vans are two priorities to reduce CO₂ emissions.

Figure 4-5-b shows the NO_x emission trajectory of the van sector in the baseline scenario. NO_x emissions peak at 91.3 kilotons in 2022 and then have a rapid decline. In 2040 the NO_x emissions would reach a reduction of 97.5% compared with the 2019 level. Euro 5 is contributing the biggest part of NO_x emissions from 2020 to 2026, mainly because diesel ICE Euro 5 vehicles are the most polluting vans ([Chen and Borken-Kleefeld, 2014](#); [ICCT, 2019a](#)). Contribution of NO_x made by Euro 6d vans are relatively low compared with its CO₂ contribution, as there has been great improvement with regard to NO_x emissions. Therefore, to reduce the impact of NO_x emissions on public health and the environment, it is recommended to replace the old Euro 5 diesel vans as soon as possible. Policies such as Low Emission and Clean Air Zones ([Defra, 2018](#); [DfT, 2020a](#)) are aimed at the transition to clean vehicles. In addition, emission contribution by primary usage is also analysed. The primary usage which accounted for the greatest proportion of CO₂ and NO_x emissions is 'carrying equipment, tools and materials' (61.1%), followed by 'delivery/collection of goods' (24.4%) and 'private/domestic non-business use' (8.3%).

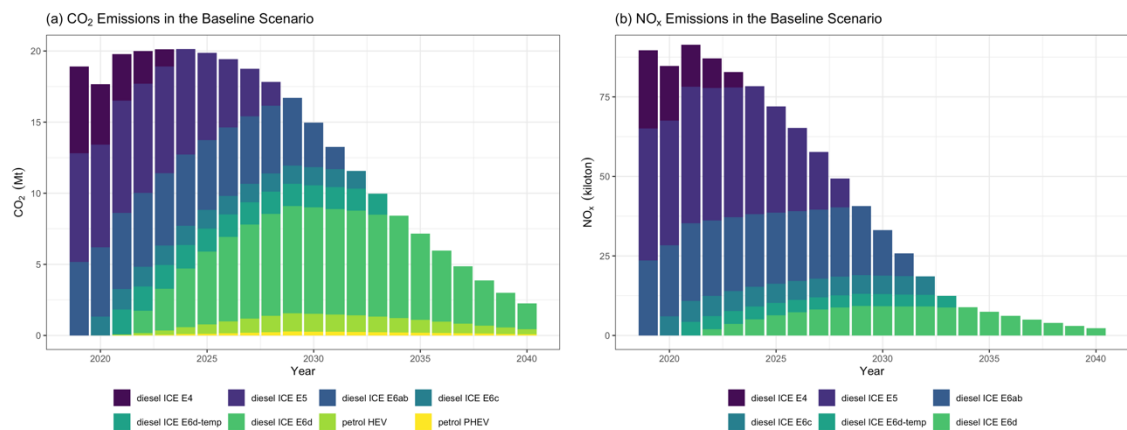


Figure 4-5 (a) Annual CO₂ emission contribution by Euro standard and powertrain during 2020-2040 [left]; (b) annual NO_x emission contribution by Euro standard during 2020-2040 [right]

4.4.2 Alternative scenario results

Figure 4-6-a demonstrates the reduction (or increase) of CO₂ emissions in the van sector during 2020-2040 under four alternative scenarios, compared with the baseline scenario. For the SCIII scenario, in 2040 the total CO₂ emissions from the van sector is 3.0 Mt. The result indicates that a 50% slower transition to class III BEVs would increase the CO₂ emissions by 31.5% in 2040 compared with the

baseline scenario. Results in the CF scenario have indicated that a 10% of urban van-km substitution potential of e-cargo bikes would decrease the total CO₂ emissions in Great Britain by 3.7% in 2040, substituting 48% of urban van-km would decrease the total CO₂ emissions by 17.8% in 2040 compared with the baseline scenario. A rapid transition to zero emission vans (RB scenario) appears to be a more effective way to reduce emissions, in 2040 the total CO₂ emissions from the van sector are only 0.7 Mt, a reduction of 69.7%. As for the best case (BC scenario) that combines the advantages of both replacing vans with e-cargo bikes and a rapid electrification of van fleet in the early 2020s, the total CO₂ emissions from the van sector are only 0.3 Mt, a reduction of 87.5% is achieved compared with the baseline scenario.

In addition to annual CO₂ emissions, the cumulative emissions are also worth attention as [Matthews et al. \(2009\)](#) have noticed a linear relationship between temperature change and cumulative emissions. [CCC \(2020a\)](#) also indicates that it is the cumulative total long-lived GHGs (e.g., CO₂ burnt by fossil fuels) that determine the peak global temperatures. Figure 4-6-b is the cumulative CO₂ emissions of baseline and four alternative scenarios. Compared with BL scenario, cumulative CO₂ emissions in SCIII scenario are 17.0 Mt higher. In the case of CF scenario, a cumulative emission reduction of 3.7 MtCO₂ is reached in 2040 for a 10% of van-km substitution potential of e-cargo bikes and 17.6 MtCO₂ for a 48% substitution potential. Great Britain could reach a cumulative emission reduction of 43.4 MtCO₂ in 2040 in the case of RB scenario. The difference in cumulative CO₂ emissions between BL and BC scenarios after 20 years is approximately 61.0 Mt, which is equivalent to 13.4% of the total GHG emissions in Great Britain in 2019.

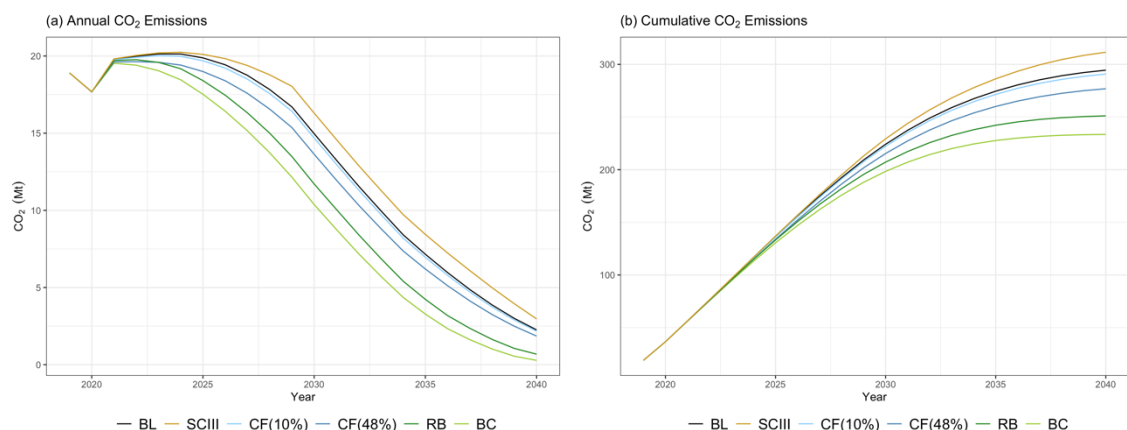


Figure 4-6 (a) Annual CO₂ emissions [left]; (b) cumulative CO₂ emissions in Great Britain in 2040 [Right], under different scenarios

To achieve the UK's long-term climate change objectives, carbon budgets were introduced in the Climate Change Act 2008³, where a five-year, statutory cap on the total GHG emissions is set to assess whether the UK is on track towards the target of at least 100% reduction of 1990 levels (Net Zero) by 2050⁴. Table 4-3 summarizes the GHG emission contribution of the van sector under different scenarios for the 4th-6th carbon budget. The results have shown that the GHG contribution from the van sector would decrease for the 4th-6th carbon budget, if the government is consistent with its 2030 ICE phase-out plan. The gap between the alternative scenario and the baseline (BL) scenario has been widened over time, indicating any policy implemented or technology improvement will take time to produce a noticeable effect. Among all the alternative scenarios, RB would ease the heavy burden of mitigating the total GHG emissions, especially for the 6th carbon budget, where the emissions from the RB scenario are almost 14.3 MtCO₂ lower than in our baseline scenario over the 6th Carbon Budget period. The BC scenario combining all the advantages from CF and RB scenario is found to reduce 19.1 MtCO₂ over the 6th Carbon Budget period.

Table 4-3 CO₂ emission contribution from the van sector for 4th-6th carbon budget under different scenarios

	BL	SCIII	CF(10%)	CF(48%)	RB	BC
4 th carbon budget (2023 to 2027)	5.0%	5.1%	5.0%	4.8%	4.7%	4.4%
5 th carbon budget (2028 to 2032)	4.3%	4.7%	4.2%	3.9%	3.4%	3.0%
6 th carbon budget (2033 to 2037)	3.8%	4.4%	3.7%	3.3%	2.3%	1.8%

A detailed analysis of the CO₂ reduction potential by region and country in the CF scenario is presented in Figure 4-7. Figure 4-7-a shows the reduction percentage of CO₂ compared with the baseline scenario under a potential 48% of van-km in urban areas delivered by e-cargo bikes. Though the absolute CO₂ emissions in London is low in comparison with other regions, it is considered to have the greatest potential to reduce CO₂ by encouraging e-cargo bikes, because 87.3% of its traffic occurs on urban roads. North West, North East, Yorkshire and the Humber, and West Midlands are also considered to be suitable to encourage

³ <https://www.legislation.gov.uk/ukpga/2008/27/contents>

⁴ <https://www.theccc.org.uk/about/our-expertise/advice-on-reducing-the-uks-emissions/>

cycle freight. Figure 4-7-b shows the absolute CO₂ emissions by region in 2040 if 48% of the urban van traffic is replaced by e-cargo bikes, where South East has the highest emissions (0.3 MtCO₂) among all the regions and countries, followed by East of England and South West.

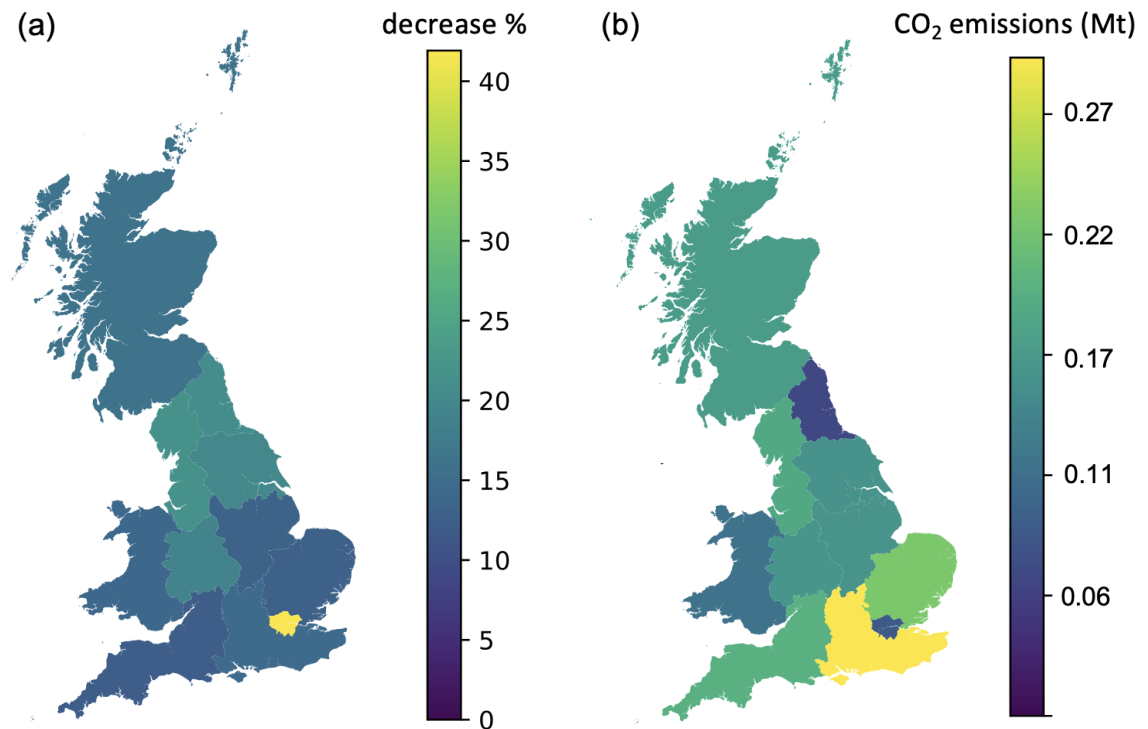


Figure 4-7 (a) CO₂ emission reduction potential compared with the baseline scenario under a 48% of van-km substitution in each region and country in 2040 [left]; (b) absolute CO₂ emissions under a 48% of van-km substitution in each region and country in 2040 [right]

Figure 4-8 shows how different NO_x emission factors could influence the emissions reduction pace in the van sector. For the adapted NO_x emission scenario, the NO_x emissions have a faster reduction speed than in the baseline scenario, and reach a reduction of 98.4% in 2040 compared with the 2019 level. The main difference between these two scenarios is the emission contribution made by Euro 6a/b and Euro 6d diesel ICE vans, where the emission factor from the baseline scenario (NAEI emission factor) is much higher than in the AEF scenario (RSD emission factor). In both BL and AEF scenarios, diesel ICE Euro 5 vans contribute a significant amount to total NO_x emissions.

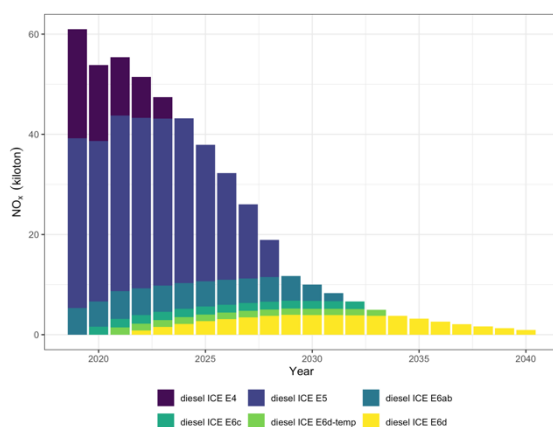


Figure 4-8 NO_x emissions by Euro standard in the adapted NO_x emission factor (AEF) scenario

4.4.3 Economic impact analysis

Incorporating the monetary impact on changes of CO₂ and NO_x emissions resulting from alternative scenarios ensures a proper policy appraisal. For appraisal of the changes of CO₂ emissions, the ‘carbon value’ is used as the road transport sector is a non-traded sector ([DfBEIS, 2021c](#)). Carbon values represent the monetary value per tonne of carbon dioxide equivalent (£/tCO₂e), and the carbon values between 2020-2040 (in 2020 prices) used in this paper were developed by [DfBEIS \(2021d\)](#) and are listed in Table B. 7 in the Appendix. An example of the central estimate of CO₂ changes in the RB scenario is given in Table B. 8 in the Appendix. Furthermore, external cost of changes in NO_x emissions is appraised using the ‘damage cost’ approach, which has been commonly used in transport policy appraisal ([Brand, 2016](#); [Lott et al., 2017](#)). Damage costs represent the monetary impact values per tonne of emission, including the impact of air pollutant on human health, productivity, wellbeing and the environment ([Defra, 2021a](#)). The NO_x damage costs for road transport sector used in this paper were developed by [Ricardo \(2020\)](#), and are listed in Table B. 7 in the Appendix. Total monetary impact of the change of NO_x emissions from the van sector are calculated in line with the UK government guidance ([Defra, 2021a](#)), and an example of the central estimate of the NO_x reduction in the AEF scenario is given in Table B. 9 in the Appendix.

Results in Table 4-4 have shown monetary savings or damages for the alternative scenarios compared to BL. The associated extra cost of a slower transition to class III BEVs during 2020-2040 is £5,120 million (low £2,562 million, high £7,687 million). Accelerating the market penetration of zero emission vans in the early 2020s could bring a total economic benefit of £12,872 million (low £6,440 million, high £19,323 million). And a 48% of van-km replacement by e-cargo bikes in urban areas could save £5,122 million (low £2,562 million, high £7,687 million).

The reduction of NO_x caused by adopting lower NO_x emission factors in the AEF scenario could avoid a damage cost totalling £4,125 million (low £372 million, high £15,807 million) compared to the baseline scenario. The estimation of the economic benefits of different alternative scenarios could support the decision-making process of public policies or subsidies that accelerate the shift to zero emission vans.

Table 4-4 Total monetary savings of alternative scenarios compared with the baseline scenario between 2020 and 2040

Alternative scenario	Central estimate of carbon value (million)	Carbon value sensitivity range (million)	
		Low	High
SCIII	-£5,120	-£2,562	-£7,687
RB	£12,872	£6,440	£19,323
CF(10%)	£1,068	£534	£1,603
CF(48%)	£5,122	£2,562	£7,687
BC	£17,994	£9,002	£27,009
AEF	£4,125	£372	£15,807

4.5 Conclusion

This paper projects the future trend of tailpipe CO₂ and NO_x emissions from the van sector during 2020-2040 consistent with a 2030 ICE phase-out plan. Detailed van CO₂ and NO_x emissions in terms of different powertrains, class types and primary use are estimated. Important factors regarding future emission projections have been captured and several alternative scenarios have been designed based on that. The key findings of the paper are:

- The phase-out of ICEs (including HEVs/PHEVs) in 2030 will lead to major CO₂ and NO_x emission reductions, and the net-zero target in the van sector will be reached by 2050 in all scenarios.
- Decarbonize the vans used for 'carrying equipment, tools and materials' is a primary task as they are responsible for 61.1% of the total CO₂ and NO_x emissions.
- Increasing the fuel efficiency of diesel ICE Euro 6d vans and scrapping the diesel ICE Euro 5 vans are two priorities to reduce CO₂ and NO_x emissions. The total CO₂ emissions from HEVs/PHEVs are very low.

- Even though large class III vans dominate the diesel van market, a 50% slower electrification transition of class III BEVs would not significantly impact the pace of reaching net-zero, as long as all the non-zero emission vans are phased out in 2030. The associated extra cost of a slower transition to class III BEVs during 2020-2040 is £5,120 million.
- A rapid transition to BEVs in the early 2020s would ease the burden of achieving the 4th-6th carbon budget and save £12,872 million.
- Encouraging the uptake of e-cargo bikes in urban areas could decrease the total CO₂ emissions by up to 17.8%, and bring a total economic benefit of £5,122 million, compared with the baseline scenario.

Surface transport is currently the highest GHG emitting sector in the UK. Among the main source of surface transport emissions, vans are the only transport mode whose absolute GHG emissions were still growing between 1990 and 2019 ([DfBEIS, 2021a](#)). Unlike passenger cars that could reduce emissions by ‘avoiding travel’ (reduce the amount of mobility required) ([Sikarwar et al., 2021](#)) and ‘shifting travel’ (transfer from car use to sustainable mode of transport) ([Cuenot et al., 2012](#); [Brand et al., 2021](#)), demand-side reduction potential ([Creutzig et al., 2016](#)) for light commercial traffic is considered to be small, as trends in van traffic is closely linked to business activities ([Guo et al., 2016](#)) and would increase with the economy ([DfT, 2020c](#)). The focus to achieve net-zero by 2050 in the van sector is the transition to zero emission vehicles. Compared with the baseline scenario in this study, it is shown that a fast BEV adoption in the early 2020s will not only avoid the sudden phase out of ICE vans in 2030 but also bring significant monetary benefit with regard to the CO₂ emission mitigation in the van sector.

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Chapter 5 Summary and Discussion

The three papers included in this thesis revolved around the theme of having a representative real-world emission study of the van fleet in the UK. The aim was to provide an accurate estimation of the real-world NO_x and CO₂ emission factors of the van fleet, explore how the external factors would affect the emission performance of vans, develop a reliable evidence-based knowledge of the van fleet composition and use, and project the future van emission pathways under different scenarios. This concluding chapter discusses how the original objectives have been accomplished, the contributions to practice and to knowledge, reflections on the results and on the entire research, and the outlook for future research directions.

5.1 Accomplishment of objectives

This section revisits the research objectives identified in **Chapter 1**, provides links across different chapters, and examines how each of the objectives has been addressed in the research. Table 5-1 outlines the accomplishment of the objectives.

Table 5-1 Accomplishment of objectives

Chapter	Data	Model	Objective
Chapter 2	Chassis dynamometer data; model simulation results	PHEM	O1+O2
Chapter 3	Remote sensing measurements	Gumbel distribution; K-S test	O1+O2
Chapter 4	Model simulation results; Remote sensing measurements; Van sales & stock prediction; Van traffic data	PHEM; Gumbel distribution; ECCo model	O1+O3

- **Objective O1: Develop an accurate estimation of real-world van CO₂ and NO_x emission factors.**

Two methods have been presented to develop the real-world NO_x and CO₂ emission factors of vans in this work. The methods selected were instantaneous emission model PHEM and remote sensing measurements.

Chapter 2 validated PHEM's ability to predict NO_x and CO₂ emissions by comparing transient emission data from laboratory (chassis dynamometer) tests over the London Drive Cycle (LDC) with PHEM simulation results over the same driving cycle. The second-by-second measured CO₂ data and modelled CO₂ data have shown to be highly consistent for both Euro 5 and Euro 6a/b diesel vans. Validation results demonstrated PHEM's capability to deliver a reliable, transient estimation of real-world CO₂ emissions for different speed ranges. On the other hand, the instantaneous measured NO_x emissions were found highly dynamic depending on various driving conditions and different NO_x after-treatment systems applied on vans. Though it was challenging to have a precise simulation of transient NO_x emissions in certain situations, PHEM proved its ability to capture the trend and dynamics of the measurements.

Chapter 3 used remote sensing results from four European countries (Belgium, Sweden, Switzerland and the UK) over the period 2011-2019 to assess NO_x emissions from vans. The distribution of NO_x measurements is skewed-right and follows the Gumbel distribution, therefore the Gumbel distribution was introduced to characterize the fuel-specific NO_x emission rates (g·kg⁻¹) of diesel vans and screen candidate high emitting vehicles. Vehicles that follow the Gumbel distribution were selected to represent the emission performance of the normally behaving vehicles in a fleet, while the high-emitting outliers that do not follow the Gumbel distribution were regarded as candidate high emitting vehicles. The location value of fitted Gumbel distribution was used to describe the fleet-wide NO_x emission factor of diesel vans. Statistical analysis indicated that pre-Euro 6a/b vehicles (Euro 3–5) can be fully described by the Gumbel distribution while a proportion of candidate high-emitters were identified in Euro 6a/b fleets.

Overall, PHEM was considered to be a suitable modelling tool and capable of simulating instantaneous CO₂ emissions from diesel vans. And real-world remote sensing measurements described by the Gumbel distribution were used to represent fleet-wide NO_x emission factors. When predicting the total van emissions in Great Britain in **Chapter 4**, the average emissions over the LDC simulated by PHEM were used to represent the CO₂ emission factors of diesel vans. Location values of fitted Gumbel distribution based on remote sensing results provided the fleet-wide description of NO_x emissions of diesel vans.

- **Objective O2: Assessing the uncertainty associated with real-world NO_x emission estimation.**

Chassis dynamometer results, instantaneous emission model PHEM and remote sensing measurements have been selected to study the factors affecting the NO_x emission performance of diesel vans.

In **Chapter 2**, laboratory (chassis dynamometer) data were used to verify PHEM's capability of simulating van's fuel consumption and tail-pipe emission performance. Laboratory tests include emission data from a Euro 5 diesel van equipped with a EGR tested over the entire LDC, and data from a Euro 6a/b diesel van tested over the suburban sub-cycle (free-flow and AM peak) of the LDC in both un-laden and full-laden conditions. Laboratory results have shown that the efficiency of a NO_x control system is related to the vehicle speed. For the Euro 5 diesel van equipped with a EGR, NO_x emissions were highest when the vehicle was driven at high speed (high engine load), as the EGR system would be temporarily switched off to maintain the performance of the engine during high load operation ([Zheng et al., 2004](#)). For the Euro 6a/b diesel van equipped with a SCR, NO_x emissions were highest when the un-laden vehicle was driven in AM peak with low speed, stop-and-go conditions. It was hypothesised that low engine load (un-laden and urban driving) operations would result in cooler exhaust temperatures and the SCR system not meeting its operational temperature to achieve effective conversions and catalytic reductions ([Koebel et al., 2002](#)).

In **Chapter 2**, the emission performance of a Euro 6a/b class III refrigerated van were simulated by the validated model PHEM. The impact of extra engine load of the refrigeration unit, additional cargo weight, ambient temperature and driving conditions on NO_x emission performance have all been studied. CO₂ emissions of vans with TRUs were found to be 15% higher than standard vehicles, with NO_x emissions estimated to be elevated by 18%. Results have shown that the burden of additional emissions of a refrigerated van becomes more significant in higher ambient temperature as the refrigeration load increases. Stop-start driving conditions and heavier cargo loading were also shown to elevate emissions. The result confirms the need to take into account the impact of auxiliary systems when predicting van emissions such as air-conditioning system and electric seat ([Zachiotis and Giakoumis, 2019](#)).

Remote sensing measurements analysed in **Chapter 3** were taken from various sites of four countries, which provided an opportunity to study the impact of ambient temperature and road grade on NO_x emission performance. It was found that high NO_x emissions are associated with low ambient temperatures for both Euro 5 and Euro 6a/b diesel vans, and Euro 5 vehicles demonstrate stronger temperature dependence than Euro 6a/b. In addition, higher road grade would elevate NO_x emissions for pre-Euro 6a/b (Euro 3-5) vans however decrease NO_x

emissions for Euro 6a/b vans. It was suspected that the SCR system applied on Euro 6a/b diesel vans can achieve better NO_x emission reduction efficiency.

As discussed above, ambient conditions (e.g., road grade, ambient temperature), driving conditions (e.g., speed and acceleration), and vehicle specifications (e.g., auxiliary electrical devices, added cargo weight and increased frontal area) all have an impact on the engine-out NO_x emissions. More importantly, we should consider the fact that the efficiency of different NO_x abatement technology varies according to the operational temperatures in the after-treatment systems.

- **Objective O3: Predicting the future van emission trend.**

The estimation of total CO₂ and NO_x emissions from vans during 2020-2040 was made by combining the number of vans on road and traffic data with emission factors. The van sales and van stock numbers were predicted by Electric Car Consumer Model (ECCo) under a baseline scenario of phasing out ICEs (including HEVs/PHEVs) in 2030 ([Pirie et al., 2020](#)). The annual vehicle kilometres travelled of vans by primary use were estimated based on the van activity survey conducted between 2019-2020 by [DfT \(2020d\)](#). As **Chapter 2** has demonstrated PHEM's capability to deliver a reliable, transient estimation of real-world CO₂ emissions for different speed ranges, the representative emission factors of CO₂ were parameterized by PHEM. For NO_x emission factors, NAEI emissions inventory ([NAEI, 2021a](#)) and remote sensing results from **Chapter 3** were used to characterise the NO_x emission factors in the baseline scenario and an alternative scenario respectively.

In **Chapter 4**, key enablers and barriers affecting the effectiveness of emission reduction pace of vans based on van's fleet composition and use were identified. Scenarios have been set out to analyse how varying the electrification pace of class III vans, accelerating the market penetration of zero emission vans, and replacing vans with e-cargo bikes in urban areas would impact the CO₂ emission reduction performance. The impact of adapting NO_x emission factors to remote sensing results that better account for the share and emission contribution from "high-emitting" vehicles with faulty or tampered emission controls was also explored. The emission changes of CO₂ and NO_x emissions resulting from alternative scenarios were then appraised based on carbon values ([DfBEIS, 2021d](#)) and damage costs of NO_x ([Defra, 2021a](#)).

Results suggested that CO₂ emissions start to decrease in 2025 in the baseline scenario. Based on the pace of reduction, it was estimated that the tailpipe net-zero target in the van sector will be reached by 2050. The trend towards an overall decline of NO_x emissions has started in 2022 and it has an even faster reduction pace than CO₂ emissions. Scenario analysis indicated that the key factor

influencing emission reduction speed of the van sector is a rapid transition of new vehicles sales to zero emission vans by 2030, which was estimated to bring a total economic benefit of £12.9 billion between 2020 and 2040 for the avoided emissions of carbon.

5.2 Contributions to practice and knowledge

This thesis has made contributions around the theme of understanding the real-world NO_x and CO₂ emissions of vans. The implications for policy and contributions to methodological knowledge are summarised as follows.

5.2.1 Policy

This section reflects on the usefulness for practitioners and the possibilities to transfer the results of the analyses into policy strategies. At the micro-level, the importance of a separate focus on vans with refrigeration units is explained and elaborated upon. From a macro point of view, the new statistical method provides a more robust description of fleet emission behaviour. In addition, van fleet's unique characteristics (e.g. powertrain composition and primary usage) is presented, providing a reference to develop targeting policies to deliver zero emission van transport.

- Micro-level

Demand for grocery home deliveries has surged since the outbreak of COVID-19, resulting in a significant growth in the deployment of refrigerated vans. Therefore, it is both timely and considered important to assess the real-world refrigerated van emissions with a finer degree of accuracy than current studies present. Firstly, this study estimated that CO₂ emissions of vans with TRUs are 15% higher than standard vehicles, with NO_x emissions elevated by 18%. The result confirms the need to take into account the impact of additional engine load when predicting van emissions in this and other sectors such as ambulances which are relatively heavy, high powered vehicles. Secondly, findings of the impact of TRUs on fuel consumptions can be used to optimize fuel-saving strategies for e-commerce, to support progress to a sustainable net-zero society. This could include, for example, investigating whether a longer but faster food distribution route via motorway could reduce fuel consumption and emissions, or how the setting temperature in the insulated box of a refrigerated van and the door opening frequency could influence the energy consumption.

- Macro-level

This thesis applied the Gumbel distribution to on-road remote sensing measurements to have a robust description of fleet-wide emission performance of vans. Derived results such as real-world emission factors differentiated by fuel, Euro standard and class type can be used as inputs of emission inventories, and emission performance broken down on vehicle manufacturer/model level can be used for market surveillance. The impact of road gradient, ambient temperature and vehicle speed on emissions were also evaluated. All these valuable information is important to have a comprehensive understanding of traffic-related air pollution and assist the local governments in policymaking decisions to control emissions, such as whether to include vans in Low Emission and Clean Air Zones restrictions.

In addition, the Gumbel distribution was used to filter out candidate high-emitting vehicles from the remote sensing records. The NO_x emission contribution made by candidate high-emitters was assessed. For class III Euro 6a/b diesel van fleet, it was estimated that 4% of candidate high-emitters account for 21% total NO_x emissions. The findings confirm that the identification, follow-up testing and repair of high emitters with faulty or tampered emission controls is of great importance to improve air quality.

Furthermore, this thesis identified the key barriers and enablers affecting the emission reduction speed of vans. Several scenarios have been designed based on vans' unique fleet characteristics (e.g. powertrain composition, primary usage and BEV transition speed), and the total CO₂ and NO_x emission trend in the van sector in Great Britain from 2020 to 2040 was estimated. This research has practical implications on the key factors influencing the emission reduction speed in the van sector. And the inclusion of the carbon value calculation and damage cost calculation of NO_x provide a reference for policy appraisal.

5.2.2 Methodology

In what follows, the methodological contributions made in this thesis are highlighted. These methodological contributions could be extended to applications in other relevant contexts.

- Validation of PHEM

This thesis validated PHEM's ability to simulate transient tail-pipe CO₂ emissions of vans and quantify the impact of changing vehicle weights and carrying loads. Due to the cost or the feasibility of the test conditions, vehicle emission measurement campaigns are not always an option. In this case, micro-scale emission models are a powerful approach to predict vehicle emissions and evaluate environmental policies. The validated instantaneous emission model

PHEM enables a detailed understanding of vehicles with extra load under various driving conditions for future research.

- Dynamic ‘cut point’ for the identification of candidate high-emitters

This thesis used the Gumbel distribution to determine a dynamic cut point of candidate high-emitters. Most of the early studies used arbitrary predetermined cut points to identify high emitting vehicles ([Pujadas et al., 2017](#); [Huang et al., 2019](#)), regardless of the fact that even normally behaving vehicles’ emission performance may differ due to the large variability of the campaign sites’ driving and ambient conditions. The Gumbel distribution helps to develop a more robust statistical analysis of normally behaving vehicles and effectively distinguish candidate high NO_x emitters, based on a specific fleet’s emission performance.

- Determination of maximum sample size for K-S test

Remote sensing measurements often need to be combined together to have a sufficient sample size for more differentiated analysis. The two-sample Kolmogorov-Smirnov test (K-S test) is therefore applied to investigate whether two fleets share a statistically similar distribution and can be combined to one. This thesis addressed the ‘large-sample, small p-values’ problem when conducting the K-S test, which is when the sample size are too large, even minuscule difference becomes statistically significant and leads to the rejection of the null hypothesis. In this research, Monte Carlo simulation at a sample size of 500 is proposed when applying K-S test to big sample remote sensing dataset, to increase the credibility of large sample research.

5.3 Reflection

This section touches upon a number of interesting issues which require further discussion: the selection of representative emission factor for a fleet, the estimation of real-world emissions after considering all the factors, and the uncertainty when estimating the total emission trend of Great Britain.

Previous studies have found out the NO_x emissions from remote sensing measurements are not normally distributed, rather skewed right ([ICCT, 2018](#); [Chen et al., 2019](#)). This study used the location and scale parameters of the fitted Gumbel distribution to describe the fleet-wide emission performance, where the location parameter describes the emission rates that have been recorded with the most frequency and scale parameter determines the statistical dispersion of the probability distribution. However, most of the studies to date still use the average emission rate as the representative emission factor of a fleet ([Carslaw, D. et al., 2011](#); [Chen and Borken-Kleefeld, 2014](#)), which is higher than the

location value of the Gumbel distribution. The application of Gumbel distribution provides a more relevant description of fleet emissions, but it also limits the comparability of this research to other remote sensing studies.

The second issue refers to the impact of external factors on vehicle emissions. We found that it was quite challenging to attribute the variability of vehicle emissions to a single reason, considering the NO_x after-treatment system, ambient and driving conditions are all affecting the emission performance. For example, higher engine load is often considered to be associated with high NO_x emissions ([Carslaw, D.C. et al., 2011](#)) for diesel Euro 3-5 LDVs however our research found that for Euro 6a/b diesel vans, remote sensing measurements with high engine loads have relatively low NO_x emissions. It was hypothesised that high engine load would also provide enough temperature for the NO_x emission control system (e.g., SCR) to maintain their high efficiency operating temperature ([Moody and Tate, 2017](#)), which may offset the emission increase caused by high engine load. Given the complexities of engine specifications and after-treatment systems, this research can only deduce the potential reason for the change of the vehicle emission performance.

Finally, there are some uncertainties when estimating the total van emissions in Great Britain during 2020-2040. This thesis has adopted the ECCo model ([Pirie et al., 2020](#)) to predict the future van population of every powertrain in the baseline scenario and designed several alternative scenarios to identify the key enablers and barriers affecting the BEV transition speed. However, the actual pace of BEV adoption and van total population still remain uncertain when considering all the technology efficiency improvement, mode choice and social-cultural factors ([Brand et al., 2019](#)).

5.4 Limitations and recommendations to future research

This research contributes to the knowledge of the real-world emission performance of vans. It started with estimating the elevation of refrigeration load on vans, and then developed representative average emission factors for vans and projected the future van emission trend in Great Britain. Although every effort has been made to better connect these three papers, the lack of remote sensing data needed to validate the simulated emissions of refrigerated vans in **Chapter 3** and lack of data needed to develop a more accurate van emission estimation including a subsegment for grocery delivery van emissions in **Chapter 4** are two of the key areas for improvement. The limitations could be addressed if refrigerated vehicles are identified in the remote sensing dataset, and percentage

of vans by grocery delivery and van annual mileage by grocery delivery are made available.

At the time of remote sensing data collection there were only a small fraction of Euro 6c vans (and no vans against the Euro 6d-temp and Euro 6d) being observed. Considering type-approvals of Euro 6c (and onwards) are conducted under the more dynamic WLTP test cycle and the RDE test procedure on Euro 6d-temp and Euro 6d are also posing challenges to manufacturers, additional remote sensing analysis of later Euro 6 categories and in time Euro 7¹ is required to assess whether the more stringent type-approval tests have further reduced the real-world NO_x emissions of diesel vans.

The Gumbel distribution has been used to identify candidate high emitting vehicles from diesel van fleet based on remote sensing measurements in this research. Whether the Gumbel distribution can increase the screen accuracy compared with a fixed cut point has not been validated. It is suggested to conduct a single-blind test when remote sensing sample with vehicles that are “known” high-emitters (e.g. vehicles measured by remote sensing were also measured by PEMS) are available.

No research has studied the impact of test conditions (road grade, ambient temperature and speed) on the emission performance of high emitters with faulty, deteriorated or tampered emission after-treatment system. As only a proportion of candidate high-emitters were identified in Euro 6a/b remote sensing measurements, the sample size was too small to conduct the analysis. It is suggested to scale up the remote sensing campaigns to increase the number of observations, and segment the candidate high-emitting vehicles by VSP value, road grade, ambient temperature and make/model for further analysis.

This thesis found that the impact of external factors on diesel Euro 5 vans could be different from diesel Euro 6a/b vans. For example, NO_x emission rates from Euro 6a/b in sites with relatively gentle slopes are higher than uphill sites. The trend is contrary to findings for Euro 5 vehicles, where higher road grade would lead to elevated NO_x emissions. It is hypothesised that the SCR systems equipped on Euro 6a/b vans can achieve better NO_x reductions when the exhaust temperature is high enough. Given the complexities of engine specification and after-treatment system, further engine dynamometer tests are needed to understand and validate our assumptions.

¹ https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12313-European-vehicle-emissions-standards-Euro-7-for-cars-vans-lorries-and-buses_en

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Supplementary material to Chapter 2

Calculation procedure of refrigeration load

Take total refrigeration load in 40°C ambient temperature as an example:

- Transmission load

The heat gain transferred through walls, floor and ceiling is calculated as:

$$Q_1 = \frac{UA\Delta T}{1000} \quad (1)$$

Where

Q_1 = transmission load, kW

U = overall heat transfer coefficient, W/(m²·K)

A = outer area of surface, m²

ΔT = difference between outdoor air temperature and setting temperature of refrigerated box, K

The heat transfer coefficient for a wall with n flat parallel surfaces of materials is given by:

$$U = \frac{1}{\sum_{i=1}^n \frac{x_i}{k_i}} \quad (2)$$

Where

x_i = wall thickness of material i , m

k_i = thermal conductivity of wall material i , W/(m·K)

When calculating the temperature difference ΔT , solar heat is considered.

Table S. 1 Temperature difference of every outer surface of frozen compartment

	Sun effect ^c , K	Surface temperature ^d , K	ΔT_{frozen} ^e , K
Roof ^a	9	322.15	67
Floor	0	313.15	58
Door	4	317.15	62

Wall, Front	0	313.15	58
Rear ^b	0	275.15	20
Right side	4	317.15	62

^a schematic diagram of the insulated box is showed in Figure 2-6

^b adjacent to chilled compartment held at 2°C (275.15 K)

^c sun effect parameters can be found from table 3, chapter 24 in Handbook – Refrigeration ([ASHRAE, 2018](#))

^d ambient temperature is set to 40°C (313.15 K)

^e frozen compartment setting temperature: -18°C (255.15 K)

Table S. 2 Heat transmission in frozen compartment per hour

	U, W/(m ² ·K)	A, m ²	ΔT , K	Load*10 ⁻³ , kW
Roof	0.38	0.6	67	15.28
Floor	0.38	0.6	58	13.22
Door	0.38	1.08	62	25.44
Wall, Front	0.38	1.8	58	39.67
Rear	0.38	1.8	20	13.68
Right side	0.38	1.08	62	25.44
Safety factor, 20% ^a				26.55
Total transmission load $Q_{1_{frozen}}$ *10 ⁻³ , kW				159.29

^a a safety factor of 20% is often used to allow for possible difference between design criteria and practical situation ([ASHRAE, 2018](#))

Table S. 3 Temperature difference of every outer surface of chilled compartment

	Sun effect ^b , K	Surface temperature ^c , K	$\Delta T_{chilled}$, K ^d
Roof	9	322.15	47
Floor	0	313.15	38
Door	4	317.15	42

Wall, Front ^a	0	-255.15	-20
Rear	3	316.15	41
Right side	4	317.15	42

^a adjacent to frozen compartment held at -18°C (255.15 K)

^b sun effect parameters can be found from table 3, chapter 24 in Handbook – Refrigeration ([ASHRAE, 2018](#))

^c ambient temperature is set to 40°C (313.15 K)

^d chilled compartment setting temperature: 2°C (275.15 K)

Table S. 4 Heat transmission in chilled compartment per hour

	U, W/(m ² ·K)	A, m ²	ΔT , K	Load*10 ⁻³ , kW
Roof	0.38	1.2	47	21.43
Floor	0.38	1.2	38	17.33
Door	0.38	2.16	42	34.47
Wall, Front	0.38	1.8	-20	-13.68
Rear	0.38	1.8	41	28.04
Right side	0.38	2.16	42	34.47
Safety, 20%				24.41
Total transmission load $Q_{1chilled}$ *10 ⁻³ , kW				146.49

$$Q_1 = Q_{1frozen} + Q_{1chilled} = 0.31 \text{ kW}$$

- Product load

We consider that groceries are moved into the box in setting temperature, so product load is not considered.

- Infiltration air load

The heat gain from air infiltration is considerable when the vehicle is used for short delivery rounds and has to open doors frequently. A simplification of the equation is given by [ASHRAE \(2018\)](#):

$$Q_3 = \frac{t_o}{3600} q_3 \quad (3)$$

Where

Q_3 = infiltration air load, kW

t_0 = door opening time, s

q_3 = heat gain during door openings, kW

$$q_3 = 0.577WH^{1.5} \left(\frac{q_s}{A} \right) \left(\frac{1}{R_s} \right) \quad (4)$$

Where

W = doorway width, m

H = doorway height, m

$\frac{q_s}{A}$ = sensible heat load of infiltration air per square metre of doorway opening, kW/m²

R_s = sensible heat ratio for infiltration from outdoors to refrigerated space

Table S. 5 Infiltration air load of both frozen and chilled compartments

	Frozen compartment	Chilled compartment
Door width W^a , m	0.5	0.5
Door height H^a , m	1.5	1.5
sensible heat load per square metre $\frac{q_s}{A}^b$, kW/m ²	37	18
sensible heat ratio R_s^b	0.74	0.74
Door opening time per hour t_0^c , s	240	240
Infiltration air load $Q_{3\text{frozen}}, Q_{3\text{chilled}}$, kW	1.77	0.86
Total infiltration air load Q_3 , kW		2.63

^a the dimension of door is smaller than the dimension of body box and it's set to be 0.5m wide and 1.5m high

^b sensible heat load per square metre and sensible heat ratio can be found in fig.9, table 9 and table 10, chapter 24 in Handbook – Refrigeration ([ASHRAE, 2018](#))

^c we assume that the driver will keep the frozen compartment door and one of the chilled compartments door open for 1 minute per customer. So the door opening time is 240s per door per hour

- Precooling load

The precooling load is the heat that must be removed from the vehicle box body to bring its interior surfaces to the planned setting temperature before loading product. Precooling load is not considered because our focus is emissions on the delivery route.

- Total refrigeration load

$$Q = Q_1 + Q_3 = 2.93 \text{ kW}$$

Appendix to Chapter 3

Table A. 1 Summary of remote sensing fleet characteristics and test conditions in Belgium, Switzerland, Sweden and the UK

Country		Class I				Class II				Class III			
		E3	E4	E5	E6a/b	E3	E4	E5	E6a/b	E3	E4	E5	E6a/b
Fleet characteristics													
Measurement	BE	EDAR: 2019											
instrument and year	CH	RSD 4600: 2011-2015; RSD 5000: 2016-2019											
	SE	RSD 5000: 2016, 2018											
	UK	RSD 4600: 2013,2015; RSD 5000: 2017,2018; FEAT: 2012,2013,2017,2018											
Sample size(n)	BE	106	414	484	434	263	1016	2257	2700	389	2040	7812	7361
	CH	137	135	122	164	576	1288	2427	883	3894	9956	16616	4233
	SE	12	24	22	NA	91	243	1035	1212	132	422	1772	1919
	UK	305	866	1513	201	599	3478	7030	1422	392	3227	12098	2940
Average vehicle age	BE	15	10	5	1	14	10	5	1	15	10	5	1
(years)	CH	13	10	4	2	12	8	5	2	13	8	5	2
	SE	12	7	4	NA	12	7	3	1	12	7	3	1
	UK	9	6	3	1	9	6	3	1	9	6	3	1
Certificated CO ₂	BE	146	135	121	113	210	183	149	132	252	228	207	186
emission	CH	154	136	117	115	147	158	140	129	221	234	212	185

(g/km)	SE	NA	131	111	NA	155	151	140	118	232	226	204	173
	UK	128	129	122	101	155	168	156	130	219	219	207	184
Test conditions													
Ambient	BE	22.5	22.7	23.0	22.2	22.5	22.6	22.9	23.2	22.5	22.5	22.9	23.0
temperature	CH	22.8	21.2	23.6	24.5	20.7	22.3	23.4	25.1	21.2	22.0	23.4	25.2
(°C)	SE	19.2	19.9	22.9	NA	20.4	19.4	19.6	21.2	21.7	21.4	20.7	21.6
	UK	17.1	14.2	12.1	10.5	17.9	14.6	11.5	10.3	17.2	14.1	11.4	10.2
Road grade	BE	2.0	2.0	2.0	2.0	1.9	2.0	2.0	2.0	1.9	2.0	2.0	2.0
(%)	CH	8.0	7.8	6.0	8.9	8.6	7.5	6.5	4.8	8.5	7.7	6.5	4.5
	SE	3.6	3.6	3.1	NA	3.3	3.3	3.3	1.6	3.2	3.2	3.2	1.2
	UK	2.6	2.2	2.1	1.4	2.4	2.3	1.9	1.8	2.4	2.0	1.8	1.6
VSP	BE	18.8	15.1	14.4	16.3	16.1	17.2	16.0	15.4	15.2	17.6	15.5	15.6
(kW/ton)	CH	16.6	15.7	14.7	17.7	15.5	14.8	14.2	12.6	15.5	14.7	13.7	11.6
	SE	9.4	12.5	11.0	NA	11.1	10.6	10.7	12.0	10.1	11.7	10.6	12.0
	UK	9.0	8.8	8.4	11.4	7.9	7.6	7.9	9.0	7.3	7.1	8.1	8.5

Table A. 2 The fraction of primary NO₂ in NO_x (f_{NO2}) by Euro standard and class type

	Class I	Class II	Class III
Euro 3	12.96%	11.36%	13.53%
Euro 4	27.94%	25.68%	28.12%
Euro 5	25.25%	21.06%	19.10%

Table A. 3 Gumbel distribution fit parameters and VSP values for ‘on-model’ and ‘off-model’ Euro 6a/b and Euro 5 vehicles by road grade in Switzerland

Road grade and Site	Class II					Class III				
	Off-model percentile	Vehicle status	Sample size (n)	NO _x (g/kg)	VSP (kW/ton)	Off-model percentile	Vehicle status	Sample size (n)	NO _x (g/kg)	VSP (kW/ton)
	Euro 6a/b									
2.2% & 2.4% (site 1,2,3)	11%	‘On-model’	215	4.18	9.8	2%	‘On-model’	728	3.72	9.0
		‘Off-model’	26	28.06	11.7		‘Off-model’	15	30.16	9.4
4.4% (site 4,5)	30%	‘On-model’	245	0.94	11.0	32%	‘On-model’	1623	1.36	11.8
		‘Off-model’	105	19.53	13.0		‘Off-model’	764	14.82	11.6
9.4% (site 6)	45%	‘On-model’	95	0.46	17.3	16%	‘On-model’	318	0.81	16.3
		‘Off-model’	78	23.02	19.2		‘Off-model’	61	13.46	15.7
	Euro 5									
2.2% & 2.4% (site 1,2,3)	0%	‘On-model’	387	9.38	9.6	0%	‘On-model’	2058	9.97	8.8
4.4% (site 4,5)	0%	‘On-model’	555	13.4	12.3	0%	‘On-model’	4795	16.13	11.9
9.4% (site 6)	0%	‘On-model’	1146	16.2	16.8	0%	‘On-model’	7220	14.07	16.3

Table A. 4 Popular models in Swiss Euro 6a/b class II and class III vans and corresponding after-treatment system information

Class II			Class III		
Model (make)	Sub-fleet Share	Equipped with SCR or not	Model (make)	Sub-fleet Share	Equipped with SCR or not
Caddy (Volkswagen)	40.32%	SCR	Transporter (Volkswagen)	14.85%	SCR
Kangoo (Renault)	11.33%	SCR	Vito (Mercedes-Benz)	12.10%	SCR
Transit Connect (Ford)	9.97%	SCR	Transit Custom (Ford)	10.19%	SCR
Partner (Peugeot)	7.25%	SCR	Trafic (Renault)	9.39%	SCR
Nv200 (Nissan)	5.89%	No SCR	Daily (Iveco)	6.15%	Some with SCR, some not
Doblo (Fiat)	5.66%	SCR	Master (Renault)	5.58%	SCR
Citan (Mercedes-Benz)	4.42%	No SCR	Crafter (Volkswagen)	5.25%	SCR
Combo (Opel)	4.19%	SCR	Ducato (Fiat)	5.22%	SCR
Berlingo (Citroen)	2.94%	SCR	Vivaro-B (Opel)	4.96%	SCR
Proace (Toyota)	2.15%	SCR	Transit (Ford)	2.86%	SCR

Table A. 5 ‘On-model’ Gumbel distribution fit parameters and fleet characteristics by top 5 Euro 6a/b models

	Model (make)	Sample size (n)	Sub-fleet share	Off-model percentile	Fit R^2	Location (g/kg)	Scale (g/kg)	Engine size (cm ³)	Engine power (kW)
Class II	Caddy (Volkswagen)	1267	21.97%	1%	98.77%	1.37	2.96	1968	75
	Partner (Peugeot)	782	13.56%	2%	98.07%	3.29	4.55	1560	69
	Berlingo (Citroen)	694	12.04%	1%	97.40%	3.14	4.52	1560	65
	Transit Connect (Ford)	582	10.09%	2%	98.54%	7.25	6.80	1499	79
	Expert (Peugeot)	423	7.34%	1%	99.28%	3.41	4.31	1867	92
Class III	Transit Custom (Ford)	1812	10.79%	3%	96.86%	2.33	4.42	1995	94
	Transporter (Volkswagen)	1573	9.36%	8%	97.25%	1.46	3.17	1968	102
	Sprinter (Mercedes-Benz)	1554	9.25%	1%	98.96%	3.12	3.95	2293	114
	Vito (Mercedes-Benz)	1358	8.08%	4%	98.08%	2.47	3.40	2064	108
	Master (Renault)	1207	7.18%	1%	97.63%	3.93	5.08	2299	109

Table A. 6 List of manufacturer groups and brands

Manufacture Group	Make Name	Manufacture Group	Make Name
CNH Industrial	Iveco	PSA Group	Citroen, Opel, Peugeot, Vauxhall
Daimler	Mercedes-Benz	Renault-Nissan-Mitsubishi	Mitsubishi, Nissan, Renault
FCA Group	Fiat	Toyota	Toyota
Ford	Ford	VW Group	Man, Volkswagen

Table A. 7 ‘On-model’ Gumbel distribution fit parameters by popular Euro 6a/b manufacture group

	Manufacture group	Sample size (n)	Off-model percentile	Fit R^2	Location (g/kg)	Scale (g/kg)
Class II	PSA Group	2499	1%	98.09%	3.58	4.69
	VW Group	1277	2%	98.74%	1.32	2.90
	Ford	601	2%	98.36%	7.15	6.71
	Renault-Nissan-Mitsubishi	569	7%	97.38%	4.62	5.53
	FCA Group	158	4%	98.25%	4.91	4.53
	DAIMLER	122	1%	97.64%	8.61	8.93
Class III	Daimler	3239	2%	98.50%	2.79	3.76
	VW Group	2985	6%	97.41%	1.37	3.03
	Ford	2721	4%	97.01%	2.45	4.28
	Renault-Nissan-Mitsubishi	2608	3%	96.96%	3.40	4.52
	PSA Group	2583	1%	98.33%	4.63	5.40
	FCA Group	847	1%	98.19%	6.54	6.37
	CNH Industrial	779	1%	97.53%	4.88	6.22
	Toyota	375	12%	97.74%	2.47	3.39

Appendix to Chapter 4

Table B. 1 ICE diesel van fleet composition projections by Euro standard during 2020-2040

Euro standard & registration year	Percentage (%)										
	2019	2020	2021	2022	2023	2024	2026	2028	2030	2032	2034 (and beyond)
Euro 4 (2007-2011)	32.7%	24.5%	16.8%	11.7%	6.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Euro 5 (2012-2016)	40.0%	40.5%	39.7%	38.1%	37.1%	36.6%	24.5%	9.3%	0.0%	0.0%	0.0%
Euro 6ab (2017-2019)	27.2%	27.5%	27.0%	25.9%	25.2%	24.9%	24.7%	26.5%	20.8%	0.0%	0.0%
Euro 6c (2020)	0.0%	7.5%	7.3%	7.0%	6.9%	6.8%	6.7%	7.2%	8.5%	10.7%	0.0%
Euro 6d-temp (2021)	0.0%	0.0%	9.1%	8.8%	8.5%	8.4%	8.3%	9.0%	10.5%	13.3%	0.0%
Euro 6d (2022-2029)	0.0%	0.0%	0.0%	8.5%	16.1%	23.3%	35.7%	48.0%	60.2%	76.0%	100.0%

Table B. 2 Van fleet composition projections by class type for different powertrains and Euro standard

	Diesel ICE vans				Petrol PHEV, petrol HEV and BEV & H2 fuel cell vehicle
	E4	E5	E6a/b	E6c, E6d-temp, E6d	
Class I	3.9%	4.4%	2.4%	2.0%	2.0%
Class II	35.8%	35.3%	31.1%	31.5%	31.5%
Class III	60.3%	60.3%	66.5%	66.5%	66.5%

Table B. 3 CO₂ and NO_x emission factors (g/km) of diesel ICE vans by Euro standards and class types

	E4	E5	E6b	E6c	E6d-temp	E6d
CO₂ emission factors¹						
Class I	126.25	114.25	118.30	117.23	115.39	112.95
Class II	171.78	169.00	171.49	169.91	166.78	163.64
Class III	232.01	243.91	231.70	229.58	225.36	221.12
NO_x emission factors in the baseline scenario²						
Class I	0.831	1.15	0.96	0.96	0.496	0.248
Class II	0.831	1.15	0.96	0.96	0.496	0.248
Class III	0.831	1.15	0.96	0.96	0.496	0.248
NO_x emission factors in the AEF scenario³						
Class I	0.77	0.67	0.40	(0.28)	(0.17)	(0.11)
Class II	0.69	0.80	0.22	(0.22)	(0.18)	(0.11)
Class III	0.76	1.04	0.21	(0.27)	(0.16)	(0.10)

¹ PHEM only provides fuel consumption factors (g/km). To predict CO₂ emission factors (g/km), the fuel conversion factor of diesel is taken from the [2021 Government GHG conversion factors \(for most users\)](#), where 2.97 is used for diesel fuels.

² NAEI emission factors are adopted.

³ NO_x emission rates of Euro 4-Euro 6b are remote sensing results. NO_x emission rates in the brackets are simulated results from PHEM, and a conformity factor of 2.1 for Euro 6d-temp and 1.5 for Euro 6d have been applied to simulated results.

Table B. 4 CO₂ emissions (g/km) of petrol HEV and PHEV vans by class types

	Class I	Class II	Class III
Petrol HEV	100.14	122.05	177.81
Petrol PHEV	66.80	81.41	118.60

Table B. 5 Vans sales and stock by powertrain during 2020-40, under the baseline scenario

Powertrain	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040
Van sales											
Diesel ICE	290,359	350,948	313,496	259,272	173,327	0	0	0	0	0	0
Petrol HEV	0	20,912	52,172	51,314	47,856	0	0	0	0	0	0
Petrol PHEV	870	8,664	18,951	11,934	18,648	0	0	0	0	0	0
BEV	6,112	15,152	29,684	119,020	225,354	415,226	423,385	431,226	436,304	443,038	451,187
H2 Fuel Cell	0	0	17	482	1,394	65,328	65,377	66,987	76,546	87,813	97,903
Van stock											
Diesel ICE	4,218,697	4,330,935	4,348,440	4,214,579	3,884,044	3,273,429	2,558,814	1,897,744	1,316,991	838,179	479,842
Petrol HEV	0	36,040	137,980	239,921	333,624	360,396	332,594	288,317	228,594	161,664	100,911
Petrol PHEV	1,030	16,475	43,248	64,871	95,762	114,297	106,060	92,673	75,168	55,604	36,040
BEV	17,505	41,188	83,406	280,079	671,367	1,355,090	2,162,378	2,936,716	3,643,093	4,245,469	4,721,193
H2 Fuel Cell	0	0	0	1,030	3,089	71,050	202,852	333,624	473,664	622,971	774,337

Table B. 6 Urban traffic contribution in each region and country in Great Britain in 2019

Region / country	Total van traffic share	Urban traffic share
North East	3.6%	43.0%
North West	10.6%	44.9%
Yorkshire and the Humber	8.8%	41.3%
East Midlands	8.3%	27.3%
West Midlands	9.1%	40.2%
East of England	11.9%	26.9%
London	6.6%	87.3%
South East	16.0%	30.3%
South West	10.1%	25.8%
Wales	6.0%	29.6%
Scotland	9.1%	33.3%
Total / Average	100%	37.1%

Table B. 7 Carbon values per tonne of CO₂ and damage costs per tonne of NO_x in the road transport sector

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Carbon values (£/tCO₂e), in 2020 prices (DfBEIS, 2021d)																					
Low	120	122	124	126	128	130	132	134	136	138	140	142	144	147	149	151	153	156	158	161	163
Central	241	245	248	252	256	260	264	268	272	276	280	285	289	293	298	302	307	312	316	321	326
High	361	367	373	378	384	390	396	402	408	414	420	427	433	440	447	453	460	467	474	482	489
NO_x damage cost (£/ton), in 2017 prices (Ricardo, 2020)																					
Low	817																				
Central	9,066																				
High	34,742																				

* Policy analysis used high and low ranges as part of sensitivity analysis to account for uncertainties. For carbon values, a plus or minus 50% sensitivity range has been deemed appropriate around the central series. For NO_x damage costs, sensitivity range explored the uncertainty around the NO_x exposure and health impact.

Table B. 8 Central estimate of total benefits of the change in CO₂ emissions in the RB scenario compared with the BL scenario

	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040
Annual CO ₂ savings (tonnes)	0	226,227	954,939	1,971,158	2,828,599	3,257,775	3,146,299	3,005,326	2,785,320	2,232,219	1,572,502
Carbon value	£241	£248	£256	£264	£272	£280	£289	£298	£307	£316	£326
Carbon value rebased to 2022	£247	£254	£263	£271	£279	£287	£296	£306	£315	£324	£334
Total benefit (million)	£0	£58	£251	£534	£789	£935	£932	£918	£877	£723	£513
Total present value benefit (million)	£12,872										

* All figures are rounded, but exact values were used in calculations.

** Only calculation of the even-numbered years is shown in this table due to page layout limitation.

Table B. 9 Central estimate of total benefits of the change in NO_x emissions in the AEF scenario compared with the BL scenario

	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040
NO _x emission reduction (tonnes)	30,851	35,606	35,201	32,912	30,389	23,163	11,919	5,080	3,525	2,243	1,284
NO _x damage costs road transport	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066	£9,066
Damage costs rebased to 2022	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270	£10,270
uplift factors	1.0612	1.1041	1.1487	1.1951	1.2434	1.2936	1.3459	1.4002	1.4568	1.5157	1.5769
Damage costs uplifted	£10,899	£11,339	£11,797	£12,274	£12,770	£13,286	£13,823	£14,381	£14,962	£15,566	£16,195
Total benefit (million)	£336	£404	£415	£404	£388	£308	£165	£73	£53	£35	£21
discount factor	1.0000	0.9335	0.8714	0.8135	0.7594	0.7089	0.6618	0.6178	0.5767	0.5384	0.5026
Total discounted benefit (million)	£336	£377	£362	£329	£295	£218	£109	£45	£30	£19	£10
Total present value benefit (million)	£4,125										

* All figures are rounded, but exact values were used in calculations.

** Only calculation of the even-numbered years is shown in this table due to page layout limitation