Trials of technologies to support HGV decarbonisation

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Abbreviations

The following is a list of abbreviations and associated definitions for terms appearing throughout this document:

Abbreviation	Definition
BET	Battery Electric Truck
BETT	Battery Electric Truck Trial
Bio- (as a prefix, e.g. to "LNG")	A type of the prefixed fuel that is derived from organic matter (biomass), not fossil sources
CET	Catenary Electric Truck
CNG	Compressed Natural Gas
EU	European Union
ERS	Electric Road System
FCET	(Hydrogen) Fuel Cell Electric Truck
Fuel Cell	A device that reacts stored hydrogen with oxygen from the air to provide electrical power
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
HDV	Heavy Duty vehicle – road vehicle over 3.5T, e.g. HGV, buses, coaches and 'vocational' vehicles such as gritters, refuse collection vehicles
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
LCF	Low Carbon Fuels
LNG	Liquefied Natural Gas
OEM	Original Equipment Manufacturers
RTFO	Renewable Transport Fuel Obligation
R&D	Research and Development
SME	Small and Medium Enterprises
TCO	Total Cost of Ownership
UK	United Kingdom
ULEV	Ultra Low Emission Vehicle
WTW	Well to Wheel
ZETs	Zero Emission Trucks

1 Introduction

1.1 Purpose of this paper

The purpose of this paper is to summarise the existing evidence on trials of technologies to support the decarbonisation of Heavy Goods Vehicles (HGVs). Information on these trials can provide the Taskforce with a picture of the direction of travel of the zero-emission truck market and help identify evidence gaps.

The paper covers completed, ongoing and planned trials of four technologies expected to contribute to the decarbonisation of trucks – Battery Electric Trucks (BETs), Hydrogen Fuel Cell Trucks (FCETs), Electric Road Systems (ERS) and Low Carbon Fuels (LCFs).

The Taskforce are invited to take a view on the following questions:

- **Given Scottish strengths and the current state of technological development, are battery electric and hydrogen the technologies the Taskforce wish to focus on for its pathway?**

- **Are the necessary trials underway to inform roll-out of zero emission HGVs in Scotland, or does this Taskforce need to instigate additional trials?**
  - **If the necessary trials are underway but what is needed is better sight of them, what can the taskforce do to achieve that visibility?**
  - **If the necessary trials are not already underway, what can the Taskforce do to instigate them?**

To answer these questions, it may be helpful to consider:

- **What scale or number of trial(s) gives the assurance operators, financiers, and manufacturers need (does the level of assurance differ)?**
- **What vehicle segments/ use cases are a priority for demonstration trials (ie commercially available vehicles, aimed at building confidence)?**
- **What vehicle segments/ use cases are a priority for supplier trials (ie pre-commercial vehicle trials by OEMs working with operators)?**
- **What additional innovation might be required, eg auxiliary equipment?**

1.2 Definitions and assumptions

Zero-emission HGVs are defined as HGVs that have zero tailpipe (pump to wheel) greenhouse gas emissions at point of use. Embodied emissions associated with the creation, maintenance and disposal of vehicles or infrastructure and production and distribution of energy (well to pump) are recognised as being important but are outside the scope of the Taskforce.

This paper focuses on trials of technology solutions expected to make significant contributions to the pathway to zero emission trucks through reducing tailpipe emissions. It does not address technology solutions associated with operational changes such as platooning, smarter logistics, fleet design, efficient driving techniques or co-loading.

Other Heavy Duty Vehicles (HDVs) such as buses and refuse collection vehicles (RCVs) are outside the scope of the Zero Emission Truck Taskforce (ZETT). Buses and RCVs can be considered early adopters for some technologies and provide

learning for HGVs, although they have specific use cases, characterised by back to base schedules, short distances and specific vehicle configurations. Information on bus trials are not included in this paper as buses are the subject of a separate taskforce. Information on RCV trials is limited to trials that involve Scottish partners.

1.3 Methodology

A mixed methods approach has been used to generate the evidence base for this paper. The evidence presented is not exhaustive and relies on information being made public by organisations undertaking the trials.

An initial review of published reports, news sources and organisational websites was supplemented by a small number of interviews with manufacturers of vehicles and powertrain technologies and representatives of stakeholder organisations. Information from interviews has been anonymised where this is not already in the public domain.

2 Trials to support the decarbonisation of HGVs

2.1 Overview of trials

The zero-emission truck market is still at an early stage of development and technological solutions for all use cases (range and weight) are not yet available (see background papers from Taskforce Meeting 1). While LCFs are expected to only play a role in the transition to zero-emission trucks (ZETs), trial data on these are more complete and may provide useful learning for other technologies on trial evaluation and reporting.

Trials take different forms and are undertaken to support different parts of the development process. For this paper, trials have been broadly categorised as follows:

- Supplier – pre-commercial vehicle trials by OEMs in real world conditions.
- Customer pilots – trials of specific vehicle models by a small number of customers for OEMs. The purchase of a small number of vehicles by customers to trial is included in this group.
- Demonstrations – trials involving multiple organisations and locations, often with public funding. These include large scale trials and cover charging/refuelling infrastructure as well as powertrain technology.
- Commercial ventures – vehicles in commercial use using existing charging/refuelling infrastructure
- Customer tests/demonstrators – short term loans to users to familiarise them with new technology.

For each trial evidence has been collected on a range of characteristics that are relevant to the decarbonisation of HGVs in Scotland, including:

- Location
- Partners
- Timings – whether completed, ongoing or planned with start and end dates where applicable
- Vehicles – range, weight and number (in addition to powertrain)
- Trial characteristics – urban/non-urban, distance, terrain, weather conditions (e.g. cold, wind)
- Refuelling/recharging infrastructure used and whether part of trial
- Stated aims of the trial
- Availability of published evidence.

Transferability of evidence from locations outside Scotland is a key issue for the relevance of trial data to the Scottish context. A study by Roland Berger on FCETs[i], assessed transferability across several dimensions: technical features, regulatory framework, use case, stakeholders and political motivation. It found that while European projects can be considered highly transferable, North American trials are less relevant because of their different technical features, regulatory framework and use cases. Evidence from other trials outside of Europe are also likely to be less

transferable for similar reasons. In this paper information on trials in North America from published reports has been included where considered relevant but no additional searches for trials outside Europe were undertaken.

Within Europe, use cases and driving conditions may also differ and data on trial characteristics and vehicle types are useful indicators of relevance to Scotland. For example, different axle configurations may be used in Europe compared to the UK, which may have implications for the location of hydrogen tanks.

The key findings from the evidence are presented in the following sections for each of the four technology types: battery electric trucks (BETs), fuel cell electric trucks (FCETs), electric road systems (ERS) and low carbon fuels (LCFs) and includes trials of associated charging/refuelling infrastructure.[1] More detailed tables providing published information on each of the trials are available in Appendix 1.

2.2 Summary of evidence by technology type

2.2.1 Battery Electric Trucks (BETs)

- Battery electric truck trials have been undertaken for a range of vehicle types, from medium (16t) to very large (27 tonne) rigid trucks with a smaller number testing articulated trucks up to 37 tonnes. Many of these trials are customer pilots and involve a small number of vehicles in urban areas or over short distances.
- In the UK, several large customers are piloting electric trucks. DHL piloted a single Volvo (16t) truck. This has led to an order of 44 trucks for use across Europe. DAF also has 37 tonne electric articulated trucks in use: two with Tesco and five with Amazon.
- In Europe, customer pilots have been reported by OEMs for a range of rigid vehicle types but these appear to involve only small numbers of vehicles. For example, Volvo, Scania and MAN have all trialled very large rigid trucks. It is not clear what distances were covered in these pilots. The MAN eTGM (26 tonne) truck is now commercially available.
- New market entrants are reporting actively trialling vehicles. For example, Volta Trucks, established in 2017, has customer pilots of large rigid trucks in the UK and Norway, with plans to pilot medium rigids in the next two years.
- A number of trials have been completed in urban areas. These include several customer pilots in London, one in Sweden and for the ZEUS (Zero Emission off peak Urban deliverieS) project in Munich. Other rigid truck trials may include urban driving but this is not clear from the available data.
- There have been few large-scale trials of BETs. The recently started UK Battery Electric Truck Trial (BETT) has 20 DAF (19tonne) vehicles in operation across nine companies for one year. The Volvo Lights project in California, running from 2019 to 2022, involved 25 BETs of various configurations deployed between city ports and warehouses up to 110km away. 58 charging stations were also installed as part of this project.
- A number of manufacturers use a ‘try before you buy’ model for smaller operators to test BETs. Volvo is rolling out 19 tonne demonstrators across the

[1] Hybrid vehicles are only included where they are part of a trial that focuses on one of the four main technology types.

UK, with one in Scotland. This will be available to operators for 2 week periods during an overall 12 month period, covering a range of conditions and use cases. DAF operates a similar dealer demonstrator. One-week customer tests of DAF and Electra trucks by hauliers as part of their approach to decarbonising their operations have been reported.

- Refrigerated vehicles were identified by interviewees as an area where real world trial data was not available. DAF is developing a refrigerated vehicle as part of its dealer demonstrator and as part of BETT. Volvo is also planning to develop one in either the 19 tonne or 26 tonne range.
- The availability of depot charging infrastructure appears to be a key limiting factor in both trials and commercial use. Tesco reports using a DAF 37 tonne artic truck on a 30 mile route between a depot and distribution centre in Wales. The recently funded Battery Electric Truck Trial (BETT) also involves public sector operators that are likely to have depot charging, although this is not explicitly mentioned.
- Trials of charging infrastructure are taking place in Germany. Ehaul, which uses swappable batteries, and Hola, which plans to deploy megawatt charging systems (MCS) are focusing on long haul segments. RouteCharge, also a battery swap approach, is aimed at medium distances. A commercial consortium is also trialling a 'change and charge' station for long distance trips in Australia.
- The available evidence indicates that publicly funded trials are more likely to publish their findings. A published paper on the Volvo Lights trial reported that early stakeholder engagement and the need to allow sufficient time for charging infrastructure deployment were key lessons learned. The BETT project has a website that provides ongoing data from the trial and a feasibility study on developing a tool to address gaps in knowledge around vehicle comparison and operational practicalities has also recently been funded.

2.2.2 Fuel Cell Electric Trucks (FCETs)

- FCET trials have mostly been undertaken with larger rigid and articulated trucks. Trials are often several years in duration and involve multiple partners across countries, including a range of vehicle manufacturers.
- In the UK, hydrogen truck trials are primarily at the feasibility stage with funding for three projects by DfT announced in 2021; this includes the Scottish Hydrogen Freight Trial for the 44 tonne segment. A feasibility study that indicated strong customer demand on rural routes in the 18 to 26 tonne segment was mentioned in the interviews. An Electra is also being trialled by a supermarket as part of the Tees Valley Hydrogen Vehicles project.
- According to interviewees, there are no FCETs that have reached the commercial production stage being trialled with customers in the UK. Technology is being developed by OEMs through joint ventures such as cellcentric and H2Accelerate[2] but trials are not expected until after 2025. Other vehicles being built in the UK are in the prototype demonstrator phase.

[2] H2 Accelerate (2022) Accelerating the uptake of green hydrogen for trucking. Available at: https://h2accelerate.eu/?msclkid=6647aa59d04711ecb0bcb5953ee92c1b

Different views were expressed about when customer trials of a 44 tonne articulated truck would be feasible, ranging from 2 to 5 years, with trials of 18 to 26 tonne vehicles viewed as possible within 2 to 3 years.

- Several consortia-based trials with some support from public funding have been undertaken in Northwest Europe. These include the H2-share project, which trialled a single 27 tonne rigid truck, Hydrogen-region 2, which used a single artic truck and H2-Haul, which has been trialling 16 rigid and articulated trucks up to 44 tonnes.
- Other ongoing European trials involve larger numbers of vehicles. The Hytrucks project commenced in 2020 and involves more than 60 partners. It plans to install 25 hydrogen refuelling stations (HRS) on the TEN-T network and construct 1000 trucks that could be used commercially from 2024. H2ME is a European project that aims to support the deployment of 45 HRS and over 1400 cars, van and trucks by 2023, although it is not clear how many of these are expected to be HGVs.
- The Hyundai Hydrogen Mobility commercial venture is also large scale. It aims to deploy 1600 very large rigid (36 tonne) trucks in Switzerland by 2025 under a pay per use model. Switzerland has a network of 9 HRS. The availability of refuelling infrastructure was cited as a reason to test the vehicles in Switzerland by one Austrian firm, although some of these HRS are privately owned.
- A small number of customer pilots are reported. These include trials of Scania and MAN rigid trucks in Norway and Switzerland.
- Development and trials of articulated FCETs in the UK and Europe is focusing on the 4x2 axle configuration as hydrogen tanks can be placed between the wheels on the chassis. This configuration is widely used in Europe for diesel trucks. For the 6x2 configuration also used in the UK, tank location may compromise payloads under current vehicle regulations.
- FCET trials have been undertaken in North America with articulated trucks over long distances but the results from these may not be easily transferable to Scotland because of differences in truck specifications - the 6x4 axle configurations used in most American trials are not common in the UK - and driving conditions.
- HRS infrastructure is a key element of FCET trials. H2ME, for example, is trialling both on and offsite hydrogen production models. HRS using offsite production often involves hydrogen being transported by tanker to stations – some of which make use of existing diesel refuelling infrastructure. Onsite HRS generate hydrogen by electrolysis at the station; green hydrogen requires the electricity for this to come from renewable sources. Onsite HRS for buses are available in Aberdeen[3]. Mobile refuelling stations, such as the one developed by H2-share are designed for both depot and public use. CNG Fuels announced in 2021 that it would trial hydrogen refuelling at its existing CNG sites in the UK.
- Some information on FCET trials is available from project websites. The H2-share and Hydrogen region 2 trials, for example, have also disseminated

[3] Case-study-Kittybrewster-Aberdeen-hydrogen-refuelling-station_tcm410-563229.pdf (hydrogeneast.uk)

information to stakeholders through conferences and workshops. H2ME has additionally reported emerging findings. It is not clear when DfT funded trials will report or whether these findings will be publicly available.

2.2.3 Electric Road Systems (ERS)

- There are three types of ERS: catenary (overhead lines), conductive (along rails) and inductive (wireless). Trials of all three have taken place.
- In the UK, three feasibility studies are being funded by DfT (two in the south-east and one in the south-west of England). One of these is catenary but the technology for the others has not been specified.
- Catenary trials have been undertaken in Sweden, Germany and the US. These trials all use the Siemens ehighway system and cover small sections of several kilometres on existing motorways. Some findings from trials in Sweden and Germany have been reported. These found that while the technology worked, there were challenges in relation to wear on the pantograph, winter operations and roadside maintenance to be addressed in ongoing research.
- Sweden has also trialled a conductive system which uses an electric rail in the road and an inductive system which uses a wireless approach, both over small distances. A large scale ERS trial is planned for the E20 in Sweden but the technology has not yet been decided.

2.2.4 Low Carbon Fuels (LCFs)

- Two large scale trials of low carbon fuels have been undertaken in the UK; the Low Carbon Truck and refuelling infrastructure demonstration Trial (LCTT) that ran from 2012 to 2016 and the Low Emissions Freight and Logistics Trial (LEFT) that commenced in 2017. Results from both these trials are publicly available.
    - LCTT reported on deployment, environmental, economic, reliability and user outcomes and found that biofuel use was key to CO_2 reductions. The lack of a clear business case for switching was seen as a major implementation barrier.
    - LEFT found that a strong business case for gas powered vehicles using RTFO approved biomethane as a transition technology for long haul/regional operations.[4]
- Recent small scale trials using fuels based on biomethane have also been reported in the UK.

3 Key findings for Scotland

A number of observations can be made based on the review of the available evidence on trials.

[4] This trial also include BETs which are reported separately in Table A1.

3.1 Data and reporting

- A key limitation is the availability of data both on the trial methodology and the results. There is no central resource for trials in the UK or elsewhere. Knowledge of trials may rely on these being reported on organisational or news websites and may be subject to commercial confidentiality. It is therefore not always clear from the information available, what numbers and types of vehicles, refuelling infrastructure and trial conditions (including actual payloads and distances) are being tested or what the outcomes are.
- Trials that are supported by public funding are most likely to publish their findings, although there does not appear to be a common set of metrics used. The most comprehensive trial data is available for LCF trials.
- Larger companies involved in trials or customer pilots are more likely to have access to information that is not publicly available. For the large number of smaller operators in Scotland, access to data on how vehicle performance in real world trials compares to their specifications is needed to support investment decisions. Collating data from customer tests, suitably anonymised, may be one approach for making trial data more widely available to operators.
- Conversely, interviewees indicated that data on existing duty cycles with diesel vehicles would provide information on the actual operator requirements in terms of range, payload and power that could be used in the design of vehicle specifications and trials for zero emission trucks.

3.2 Vehicle types and use cases

- Large articulated trucks and very large rigid trucks, which typically undertake long haul trips, are responsible for most of the HGV emissions from the Scottish fleet (see background papers from Taskforce Meeting 1). FCET trials have mainly focused on these segments but it is not clear how close these trucks are to commercial use, the axle configurations used or, for the commercially available Hyundai 36 tonne rigid, the daily distances being travelled. Reported testing of large battery electric artics by Tesco is also over short distances of 30 miles.
- There are a significant number of SMEs transporting freight by road in Scotland (see background papers from Taskforce Meeting 1). Opportunities for smaller operators to test BETs and the availability of real world data on them may improve confidence and make this technology more appealing.
- It was also suggested by interviewees that a ‘try before you buy’ approach could involve a commitment to buy after a short trial period if the vehicle performed to a previously agreed specification.
- No reported trial data for refrigerated vehicles, a key use case for Scottish hauliers, was identified, although these vehicles are included in BETT and OEMs are looking at this segment.
- Although not within scope for the Taskforce and this paper, interviewees indicated that there may be useful learning from trials of buses, RCVs and other HDVs in the public sector, for example in terms of user outcomes for

drivers, and for manufacturers who may also build HGVs. Transport Scotland has provided grant funding for both battery electric and fuel cell powered and dual fuel solutions for these vehicles under its 'Switched on fleets' and 'Switched on Towns and Cities Challenge Fund' initiatives. It has partnered with the Energy Savings Trust who will report the findings from these trials where possible. Public sector HGV fleets are small but will also be included in these initiatives.

3.3 Infrastructure

- Access to charging and/or refuelling will be a key consideration in the success of zero emission trucks. Infrastructure requirements and energy supply will be the subject of forthcoming papers for the Taskforce.
    - Most BET trials, including the ongoing BETT, appear to rely on private, depot-based charging infrastructure that has an installation cost for the operator and limits trial ranges.
    - The picture for hydrogen refuelling is more complex. Trials of both mobile and fixed public HRS for HGVs are being undertaken in mainland Europe but this is at the feasibility stage in the UK. Interviewees also noted that infrastructure supply was potentially more well-developed than vehicle technology and was dependent on there being demand.
    - Biofuel refuelling infrastructure was also cited as a concern for fleet managers, although public access biomethane refuelling stations are under development in the UK.[5]
- Many road freight movements in Scotland are being undertaken over long distances in remote and rural locations (see background papers from Taskforce Meeting 1). The majority of trials for all technologies are being undertaken in urban conditions or over short distances.
- Trials of ERS technology are at the feasibility stage only in the UK and have only been undertaken at small scale elsewhere. The choice of technology, extent and timescale for any deployment at scale are unknown.

[5] Work starts on Scotland's first public-access biomethane refuelling station | GreenFleet, World's largest public access biomethane refuelling station opens | GreenFleet

Appendix

Table A1: Battery Electric Vehicle Trials

Trial	Partners	Location	Type	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
Volvo[ii]	DHL	UK	Customer Pilot	Ongoing (2020-)	16 t truck	Urban	Not available	Not available	Led to order for 44 vehicles
Volta Zero[iii]	DPD	UK	Customer Pilot	Completed (2021)	16 t truck	Urban logistics	Not available	Specifically designed to deliver parcels and freight in inner city locations	Not available
Volta Zero[iv]	UK Crown Estate BEV, Clipper Logistic	UK	Customer Pilot	Ongoing (2022)	16 t truck	Urban	Not available	To deliver goods to retailers as part of efforts to cut congestion and emissions	Not available. Truck due to go into production by the end of 2022
DAF[v]	Amazon	UK	Customer Pilot	Ongoing (2022)	Five Artic 37 t DAF	Middle distance	Not available	Not available	Not available
DAF[vi]	Tesco, FSEW	UK	Customer Pilot	Ongoing (2022)	Two Artic 37 t DAF	30 miles interurban (between depot and distribution)	Charging points at FSEW site	Hope to demonstrate electric HGV transportation is commercially viable	Not available
DAF[vii]	Shred Station, DAF	UK	Operator Test	Completed (2022)	LF, 19 t, rigid 4x2	Drove from Norwich deport to Thetford	Not available	Market exploration	Not available. Will continue to explore the market and begun replacing diesel forklifts with electric
Electra[viii]	AF Blakemore	UK	Operator Test	Completed (2022)	ELECTRA 19 t e-cargo refrigerated vehicle	Week-long trial at distribution centre	Not available	Market exploration	Not available. Will continue to do trials over the next five years to understand potential
BETT[ix]	DAF, Cenex, DfT Funded, nine public sector orgs	UK	Demonstration	Ongoing (2022-23)	20 vehicles (DAF LF, 19 t, rigid 4x2)	Various public sector operations, including use of ancillary battery-operated system, tail lifts, refrigeration	Depot charging assumed but not confirmed	Trial study areas include vehicle operation, economic and environmental performance, user acceptance, as well as life cycle emissions	Live dashboard of trial
Magtec[x]	Magnetic Systems Technology Limited	UK	Demonstration	Ongoing (2021-)	10 vehicles	Use with public sector organisations.	Not available	Develop tool to address gaps in knowledge around operational practicalities. Enhance with vehicle data.	Not available
SEUL – Smart Electric Urban Logistics (LEFT)	UPS, Cross River Partnership, UK Power Networks & UK Power Networks Services	UK	Demonstration	Completed (2017-2020)	17 repowered (Euro V) 7.5t	Real world fleet operations	Depot charging	Test technology in real world operations	LEFT report covers charging infrastructure, energy, emissions and user feedback. Easy extpansion of depot charging noted
MAN[xi]	MAN + 9 companies	Germany	Customer Pilot	Completed (2018)	Rigid 4x2, 26 t (eTGM)	Varying	Not available	Collect data under real world conditions	Now in commercial production
Volvo[xii]	DB Schenker, Volvo, Renova	Sweden	Customer Pilot	Completed (2019)	2 vehicles (16 t and 27t rigid)	Urban, refuse	Not available	Not available	Not available
Scania[xiii]	Scania, ASKO	Norway	Customer Pilot	Completed (2020)	2 vehicles (27 t, 6 x 2*4)	City distribution	Not available	Pilot programme	Not available

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Trial	Partners	Location	Type	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
Route Charge[xiv]	Not available	Germany	Demonstration	Completed (2020)	18 t	Medium distances	Battery swap may not be fully automatic	Pilot project	Available in paper referenced
Volta Zero[xv]	Norwegian Post	Nordic Countries	Customer Pilot	Completed (2021)	16 t	Inner-city mail, parcel pick-up and drop-off	Not available	Purpose built truck for trial	Not available
Ehaul[xvi]	Bosch, Fraunhofer IVI, TU Berlin, Logistics Partners	Germany	Demonstration	Ongoing (2021-24)	2 vehicles (up to 44 t)	Long (300 km+)	Automatic battery changing station for HGVs	Proof of concept, real world tests over multiple months of two stations, development of business model	Not available
HOLA[xvii]	Frauenhofer Institute and 12 consortium partners	Germany	Demonstration	Ongoing (2021-24)	8 CCS, 4 MCS compatible	Real logistics operations	2CCS (first) and 2 Megawatt Charging Systems (MCS) at four locations on A2 – 2 on motorway, 2 on logistics hubs	Gather the urgently needed experience in the construction and operation of high-performance charging parks and create a basis for a nationwide expansion of the new technology	Publications on website referenced
ZEUS[xviiixix]	Colruyt Group	Germany	Demonstration	Completed (2019-2020)	MAN eTGM (26 t)	Off-peak, urban	Not available	Data on new emission off peak deliveries	Output said to include guidelines and an impact estimation toolkit based on scalable use cases for off-peak deliveries and stakeholder needs
Inland Empire (Volvo Lights) [xx]	South Coast Air Quality Management District, Volvo & 12 others	USA (California)	Demonstration	Completed (2020)	23 Volvo VNR (>15 t)	Between ports and four freight handling facilities in inland Empire (110 km)	Not available	To get cleaner trucks on the road to transport goods from ports to the Inland Empire	Not available
Port of Oakland[xxi]	Peterbilt, Port of Oakland, ZANZEFF, STE	USA (California)	Demonstration	Completed (2021)	10 trucks	Haul cargo within the port's maritime area	10 charging points at STE	Monitor how effectively trucks operate when hauling fully loaded containers and emission reductions	Not available
Volvo Lights[xxii]	South Coast Air Quality Management District, Volvo & 12 others	USA	Demonstration and Training	Ongoing (2019-2022)	Volvo VNR (Class 8) – 25 BEV, 29 BE freight handling vehicles	Various projects (including training)	58 vehicle chargers, 1.8 MW solar installation	Not available	Key findings reported in publication. Early stakeholder engagement and the need to allow sufficient time for charging infrastructure deployment were key lessons learned. [xxiii]
Vision Electric[xxiv]	Janus, Qube, OZ Minerals	Australia	Supplier Led	Ongoing (2022-23) (12m)	Unknown	Long (3,000 km+)	Battery 'change and charge' station to be constructed Aug-22	Not available	Not available
Volta Zero[xxv]	Volta	USA (LA)	Demonstration	Planned (2023)	100 vehicles (class 7, 12-15 t)	Not available	Not available	US customers to evaluate trucks	Not available
Ports Long Beach / LA[xxvi]	Electrify America, NFI Industries Collaborate	US (California)	Demonstration	Ongoing (2021-23)	60 trucks	Service Ports of Los Angeles and Long Beach	34 ultra-fast DC chargers	Plans for nations largest charging infrastructure project to support heavy-duty trucks	Not available

1 t has been used as an abbreviation for tonne throughout

Table A2: Fuel Cell Electric Vehicle Trials

Trial	Partners	Location	Type	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
H2GVMids[xxvii]	Numerous	UK	Feasibility study	Completed (2021-22)	44 t	Green hydrogen truck demonstrator	Not available	Carry out pre-deployment work on a hydrogen fuel cell truck demonstration, involving the full value chain for hydrogen HGV operation, development and refuelling for a hydrogen truck with a lease-based deliver model	Not available
Tees Valley Hydrogen Vehicles Project[xxviii]	Electra	UK	Customer pilot	Ongoing (2022)	Electra FCEV (refrigerated)	Major supermarket trialling the truck	Depot refuelling	Data collection in real world use	Not available
Hyfuels trial[xxix]	CNG Fuels (Hyfuels)	UK	Feasibility study	Planned (2022)	< 26 t	Hydrogen fuel trial	HRS at existing CNG sites	Help inform hauliers	Findings will be used to inform government, industry and customers on the effectiveness of hydrogen solutions and will outline infrastructure consideration for a hydrogen refuelling network.
Scottish Hydrogen Freight Trial (SHyFT) [xxx]		UK	Feasibility study	Not available	44 t	Not available	Not available	Develop a viable scale trial for Scotland with appropriate early adopters for Arcola Energy's FCEV powertrain in the 44 t truck segment	Not available
UK Aggregated Hydrogen Freight Consortium[xxxi]		UK	Feasibility study	Not available	All	Not available	Not available	A study into a nationwide deployment of hydrogen freight vehicles and associated hydrogen refuelling station networks	Not available
H2-Share[xxxii]	VDL (DAF), Ballard	Germany, France, Belgium, Netherlands	Demonstration	Completed (2017-2021)	1 rigid 6x4 truck (27 t)	Not available	Mobile refuelling station of 2 units/containers function as hydrogen storage/refuelling station. Tank container can fill three trucks/buses from internal storage, has to be transported to be refilled	To facilitate the development of a market for low-carbon HDT on hydrogen for logistic applications and gain practical experience in different regions creating a transnational living lab	Information on project website. [xxxiii] Includes deliverable on monitoring and end user experience.[xxxiv] Main finding from the demonstration projects presented in final conference (slides available)[xxxv]
REVIVE[xxxvi]	E-trucks Europe / Renova, Suez, SEAB SPA, ASM Merano, Antwerp, Amsterdam, Breda, Groningen, Proton Motor Fuel Cell	Belgium, France, Sweden, Italy	Demonstration	Completed (2018-2021)	15 vehicles	Tests fuel cell refuse trucks in urban settings. HDT for zero emission waste collection in urban areas. Planned in sites across Europe over four years.	Not available	Not available	Not available

Trial	Partners	Location	Type	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
H2-Haul[xxxvii]	BMW Group Logistics, Coop, Colruyt Group, Carrefour, Air Liquide, ErlingKlinger, Bosch, PowerCell	Belgium, France, Germany, Switzerland	Demonstration	Ongoing (2019-2024)	16 vehicles (rigid/artic up to 44 t but data on truck specifications not published anywhere publicly)	Not available	Fixed infrastructure	Not available	Project website as referenced but no trial reports accessible.
Waterstofregio 2.0 (Hydrogen Region 2) [xxxviii]	VDL (DAF), Colruyt Group, Ballard	Belgium	Demonstration	Completed (2016)	44 t Artic (Tractor) 4x2	Not available	Fixed infrastructure	Not available	Website reports developments (in Dutch) including workshops and networks. Reports that project has been a source of knowledge and experience, technology exported and knowledge expanded to >100 companies
ASKO distribution logistics trucks[xxxix]	Scania, Hydrogenics, ASKI	Norway	Customer Pilot	Ongoing (2017-2024) Demonstration started in 2019	4 vehicles (rigid 6x2m 27 t)	Scania trucks for Norway's largest grocery wholesaler, focused on resource efficiency, low emission and sustainable development for the wholesaler	Fixed infrastructure	Not available	
Hyundai Hydrogen Mobility[xl]	Hyundai, H2Energy, Association pro H2 Mobility Switzerland, Hydrospide, Alpiq, Linde	Switzerland	Commercial	Ongoing (2020-)	1,600 (by 2025), Rigid 4x2 (inc. refrigerated) but also expected to add 6x2 rigid and 4x2 artic (with 1,000 km range)	Trucks offered to companies through pay-per-use mode	Not available	Not available	First seven trucks delivered to clients in October 2020, 50 trucks were to be delivered until the end of 2020
Esoro hydrogen truck for Coop (part of H2-Share)[xlixlii]	Coop, ESORO (MAN), H2Energy, Emoss, Swiss Hydrogen, PowerCell	Switzerland	Demonstration	2017 (no longer fully operational)	Rigid 4x2, 34t	The deployed truck has a refrigerated body and a refrigerated trailer. Cooling systems and hydraulic lifts are included	Not available	Not available	Not available
AZETEC[xliii]	Freightlines / Daimler, Bison Transport, Trimac Transportation, Ballard	Canada	Design and manufacture HDT FCH hybrid trucks	Ongoing (2019-2022)	2 vehicles (tractor 6x4)	Not available	Refuelling infrastructure will leverage existing oil and gas infrastructure under a 'drop and swap' model that will move fuel between a centralised depot and the facility	Demonstration expected July 2021 – December 2022. By project completion, trucks will have travelled over 500,000 km and carried 20 million tonne-km of freight	Note that around 50 trucks, using five tonnes of hydrogen per day, would be needed to make fuel distribution cost-efficient

Trial	Partners	Location	Type	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
ZANZEFF[xliv]	Toyota, Kenworth, UPS, TTSI, Southern Counties Express	USA	Demonstration	Start year 2019	10 vehicles (tractor 6x4)	Estimated range of more than 450 km per fill	Two large new capacity heavy-duty refuelling stations will be developed by shell	Not available	Not available
GTI[xlv]	Transpower (Navistar), Peterbilt. TTSI, Daylight Transport LLC, Hydrogenics, Loop Energy	USA	Demonstration	Completed (2018-2020)	5 vehicles (tractor 6x4)	Not available	Existing infrastructure is used for charging and mobile H2 fuelling infrastructure is provided	Not available	Not available
Anheuser Busch[xlvixlvii]	Nikola, Anheuser Busch, Bosch	USA	Customer pilot	Ongoing (2018-)	Up to 800 vehicles (tractor 6x4)	Not available	Hydrogen supply provided on site	Support company sustainability goals	Trial project in 2019 saw partners complete the first zero emission beer delivery in St Louis with total of 800 trucks on order reported.
HECTOR[xlviii]	Project consortium of several waste management companies, local authorities, research and data analysis providers and Aberdeen City Council as lead partner	Belgium, France, Netherlands, UK, Germany	Demonstration	Ongoing 2019-2023	8 vehicles	Testing garbage trucks in various settings. Operating in urban and rural areas on fixed and flexible schedules while using existing HRS infrastructure	Not available	Not available	Not available
Bayernflotte[xlix]	MAN, Forvia, 5 customers, Bavarian Ministry of Economic Affairs, Regional Development and Energy	Germany	Demonstration	Planned 2024-2025	MAN trucks	Real world operations	Not available	Not available	Not available
Hyundai [l]	Hyundai ZCIENT fuel cell, Gebruder Weiss	Switzerland	Customer pilot	Ongoing 2021-2022	36 t	70,000 km covered in short distance general cargo on daily basis, including hilly terrains	9 HRS in Switzerland	Not available	Only news article referenced available; this reported no problems.
H2ME1/2[li]	EU Project	EU (10 countries)	Demonstration (Large-scale)	Ongoing 2015-2023	Cars, vans, trucks. >1,400 vehicles	Not available	45 HRS, BOC HRS Aberdeen (H2ME 1), ITM 3 HRS Birmingham, London, Swindon (H2ME 2)	Aimed to support early phase of roll-out when limited infrastructure and high TCO limiting deployment	Emerging results published in reference provided
Hytrucks[lii]	60+ partners with EU and national funding	Netherlands, Belgium and Germany	Demonstration (Large-scale)	Begun in 2020	1,000 (by 2025)	TEN-T network	25 filing stations	Normal commercial operations from 2024. The production of 40 tonnes of clean hydrogen per day to be delivered to filling stations	The roll-out of 25 hydrogen filling stations. Construction of 1,000 hydrogen powered trucks

1 t has been used as an abbreviation for tonne throughout

Table A3: ERS Vehicle Trials

Trial	Partners	Location	Type	Timings	Vehicles	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
UK Electric Road System[liii]	Numerous	UK	Feasibility	Not available	Not available	Not available	Not available	Identify the optimum technological, economic and environmental recommendations for an Electric Roads System Demonstrator.	Not available
ElectroRoad[liv]	Numerous	UK	Feasibility	Not available	Not available	Not available	Not available	Complete a comprehensive study of an innovative Electric Road System applied to 44 t Heavy Goods Vehicles as a cost effective and feasible solution.	Not available
A34 Catenary Cable System[lv]	Numerous	UK	Demonstration / Feasibility Study	Not available	Not available	Not available	Not available	Examine the feasibility for an Electric Road System demonstrator on appropriate sections of the A34.	Not available
Swedish eroads[lvi]	Swedish Transport Administration (STA), Siemens, Scania	Sweden	Demonstration	Completed (2016-2020)	3 vehicles (hybrid, 20kWh battery)	2 km, 1 lane	50-60 m spaced poles	Test technology, identify and address issues	Publication reports technology works, some design issues corrected, winter running tests 2019-20.[lvii] Summary findings also in wider study on Swedish and German ERS. [lviii]
Swedish eroads - eArlanda[lix]	Swedish Transport Administration, Elways, e-Traction	Sweden	Demonstration	Completed (2017-2021)	1 vehicle (18 tonne electric (e-Traction converted DAF truck))	2 km (near airport)	50 m sections, can be operated separately, 15 cm wide rail	Test technology, identify and address issues	Publication reports technology works, some design issues corrected, winter running tests 2019-20.[lx] Summary findings also in wider study on Swedish and German ERS. [lxi]
German ehighways - ELISA[lxii]	Siemens, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Federal Ministry of Transport	Germany Frankfurt-Darmstadt	Demonstration	Ongoing (2017-2022)	5 vehicles	6 km	Not available	Not available	Summary findings in wider study on Swedish and German ERS. [lxiii]

Trial	Partners	Location	Type	Timings	Vehicles	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
German ehighways - FESH[lxiv]	Siemens, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Federal Ministry of Transport, Kiel University, Dresden technical University	Germany Hamburg-Lubeck	Demonstration	Ongoing (2017-2022)	1 vehicle from 2020	5 km in both directions	Not available	Not available	Summary findings in wider study on Swedish and German ERS. [lxv]
German ehighways - ewayBW[lxvi]	Siemens, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Federal Ministry of Transport	Germany Gernsbach-Kuppenheim		Ongoing (2017-2023)	5 vehicles	2 directions, 3.4 km highway with tight curves,bridges	Not available	Not available	Summary findings in wider study on Swedish and German ERS. [lxvii]
Smartroad Gotland[lxviii]	Electreon AB led consortium, funded by STA	Sweden		Ongoing (2020-2023)	40 tonne truck (+bus)	1.6 km between airport and town (800 m either direction)	Not available	Not available	Website publishes news
US ehighway[lxix]	Siemens, South Coast Air Quality Management District	California	Demonstration	Completed (2017)	3 vehicles (big rig, 1 diesel hybrid, 1 BEV, 1 LNG hybrid)	1 mile, urban heavy congestion	Not available	Primary goal is to promote the implementation of zero emission goods movement technologies	2018 annual report states the demonstration was successful in proving out the operation of the vehicles and infrastructure. It was decommissioned.

1 t has been used as an abbreviation for tonne throughout

Table A4: Low Carbon Fuel Vehicle Trials

Trial	Partners	Location	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
McAuliffe[lxx]		UK – HS2 Midland Site		Not available	Trialling fossil-free HVO fuel to replace diesel	Investing £10.5m in fuel-efficient plant and machinery	Not available	Potential to cut CO_2 emissions by up to 90% compared to diesel
LCCT[lxxi]	DfT, OLEV, Innovate UK, DHL, Eddie Stobart, John Lewis, Muller Wiseman, Tesco Engineering, United Biscuits. Total of 35 companies took part	UK	Completed (2012-2016)	355 vehicles were dual-fuel, by gas and diesel, 6 were powered by gas alone and 10 by a combination of diesel and cooking oil. There were no applications from companies looking to run electric or hybrid vehicles	£23.4m trial funded by a combination of government agencies and industry participants		Not available	Improvement in CO_2 emissions, reduction in engine noise and a reduction in other emissions across the different technologies on trial. Some fleets saw an improvement of 12% from tank to wheel, and 9% on well-to-wheel, with the average being lower - 3% tank to wheel and there was no average well-to-wheel reductions. The trials didn't produce the amount of savings that were hoped, with the biggest saving from biofuels.

Trial	Partners	Location	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
LEFT[lxxii]	Eight consortia with 30 organisations	UK	Completed (2017-2020)	Range of methane, hydrogen-diesel, battery and range-extended electric vehicles. Fleets of 1 to 59 HGVs/vans.	In service data collection and emissions testing	Not available	Trial, develop and demonstrate low emission vehicles in the freight, logistics, utilities and emergency industries	Evidence on reduced running costs for BEVs. Strong business case and positive driver feedback for transition technologies with planned expansion of use and refuelling infrastructure. For information on individual trials see rows below and report. Need for public refuelling hydrogen infrastructure for (dual) fuel combustion – FCETs not trialled.
Geely[lxxiii]	Geely, Circle K Denmark, Aalborg University, Fonden Green Hub	Denmark	Ongoing (2022-2023/4)	2 Emgrand methanol sedans, M100 heavy-truck	Alternative fuel / methanol vehicles.	Port of Aalborg agreement with developer of renewable energy to produce green e-methanol for the transport industry to be completed by 2025 and produce 75,000 t of e-methanol per year	The carmaker's methanol cars promise a 70% reduction in CO2 compared to gasoline	No evidence from trial. In a previous trial undertaken by Geely in Iceland, the Emgrand methanol sedans achieve average well-to-wheel emissions of 46 g of CO_2 per km.
Arla[lxxiv]		UK	Completed (2020)	2 specifically-adapted tankers that run biofuels will transport milk to processing sites	Dairy farm 'fuel station' to convert cow poo into power. Cow waste will be delivered to an anaerobic digestion plant, where it will be broken down into components and converted to usable fuel. The manure of 500 cows will create 27,000 kg of biofuel	Not available	Not available	Referenced source indicates that the trial would reduce Arla's carbon impact by 80 tonnes
Amey[lxxv]	Amey, Kent County Council, New Era Fuels, Green Biofuels	UK	Completed (2021)	Not available	Trial biofuels across highways maintenance fleet and reduce CO2 emission by up to 90%. The trial will use Green D + HVO. It will reduce NOx through oxidisation. It is best used in Euro VI engines.	Not available	Up to 90% less CO2 and up to 86% reductions in PM25 and PM10 and up to 30% reductions of NOx.	Referenced source reported daily emission testing to be carried out during the first four weeks of the trial.
Dedicated to Gas (LEFT) [lxxvi]	Air Liquide, Kuehne + Nagel, Wincanton, Asda, Brit European, Howard Tenens and Great Bear will all test HGVs	UK	Completed (2017-2020)	81 vehicles, 12 to 44 t	Gas powered HGVs. Ten vehicle configurations to be trialled using CNG, LNG and biomethane. Trial will test liquid nitrogen cooling system for trailer refrigeration. Trialled two dual fuel (DF) LNG vehicles - powered mainly by liquefied methane, but also combust a small quantity of diesel fuel in a compression-ignition engine. Could not run on either gas or diesel alone.	LEFT reports experience of public refuelling	Trial, develop and demonstrate low emission freight vehicles (LEFT)	Data collected for nine months. Generate modest WTW GHG savings of 8-14% if fossil-based LNG is used. With biomethane can increase to 65% or more. LEFT results reported for SI CNG and LNG projects together. Trials consumed 23-27% more energy than diesel, but using RTFO certified biomethane achieved 69-81% Well to Wheel (WTW) GHG savings. Dedicated gas vehicles emit lower GHG emissions only in higher speed cycles, at city/urban speeds. Biomethane would give substantial WTW saving on all cycles. Trial participants ordered 200 more CNG/LNG trucks.
John Lewis Partnership (JLP)[lxxvii]	JLP, CNG Fuels	UK	Ongoing (2014 -)	Scania P340	JLP have rolled out biomethane gradually over 8 years and use in 85 Scania P340 trucks.	CNG Fuels stations at Leyland and Northampton UK. Biomethane is produced from waste foodstocks and can reduce well-to-wheel GHG emissions	Committed to change the fleet of 600 trucks to gas HGVs fuelled by biomethane by 2028	Gas trucks cost 25% more than diesel vehicles, but is offset by fuels savings as they pay 30-40% less for biomethane on a pence per mile basis. Recover investment within two years. The lifetime cost is 24% lower than a diesel equivalent.

Trial	Partners	Location	Timings	Vehicles[1]	Trial Characteristics	Charging Infrastructure	Aims	Evidence / Key Findings
						by 84% compared to mineral diesel.		
London Borough of Hackney[lxxviii]	Green Biofuels Ltd / Neste	UK	Not available	200 HDV in vehicle fleet	Used FAME biodiesel in blends of up to 100% for many years and have recently trialled and deployed HVO across commercial vehicle fleet.	Depot refuelling assumed but not stated	To minimise interim emissions until zero emission (electric) technology available.	Fuel offers well-to-wheel CO2 emission savings of 80% compared to diesel. Requires no additional maintenance or changes to operational procedure. Cost of fuel per litre is higher so there is no whole life cost saving
CNG Vehicles[lxxix]	Not available	Not available	Not available	Not available	Trial of bio-gas trucks - compared transport performance and total cost against baseline diesel trucks	Not available	Not available	30% lower cost fuelling gas trucks per tonne km of transport work compared to diesel trucks. CNG carbon emission were 19% lower than baseline diesel, bio-gas was 74% lower. When total cost is considered (capital and refuel cost), excluding labour and maintenance, to a diesel trucks the break even period of a bio-gas trucks is 2 years. The amount of biogas available isn't enough to convert all diesel tractor units in the UK.
Scania CNG / Farrall[lxxx]	Farrall Group, CNG Fuels	UK	Reported 2022	Not available	Not available	Not available	Could see a reduction of 90% CO_2 produced per truck per year	Not available
Maximising CNG Benefits - (LEFT)[lxxxi]	CNG Fuels, John Lewis Partnership & University of Cambridge	UK	Completed (2017-2020)	Not available	Trialled SI CNG HGVs over 12 months of in-service trials.	Experience of public refuelling reported	Trial, develop and demonstrate low emission freight vehicles (LEFT)	Results reported for SI CNG and LNG together. Trials consumed 23-27% more energy than diesel, but using RTFO certified biomethane achieved 69-81% Well to Wheel (WTW) GHG savings. Dedicated gas vehicles emit lower GHG emissions only in higher speed cycles, at city/urban speeds. Biomethane would give substantial WTW saving on all cycles. Trial participants ordered 200 more CNG/LNG trucks.
HyTime - Hydrogen-Diesel Dual Fuel Vehicles (LEFT)[lxxxii]	Ulemco, Aberdeen City Council, Commercial, London Fire Brigade, Ocado, Veolia, Westminster City Council & Yorkshire Ambulance Service	UK	Completed (2017-2020)	HGV and RCV	Trialled DF hydrogen vehicles. Inject hydrogen into the engine to displace 15-60% of the diesel fuel. Can run on diesel only but not 100% hydrogen.	Experience of onsite refuelling and public refuelling reported	Trial, develop and demonstrate low emission freight vehicles (LEFT)	Difficult in hydrogen availability at public refuelling stations meant a lower level of operation in dual-fuel mode than intended. WTW GHG emissions would rise by 10-30% (grey hydrogen), with green hydrogen would be savings of 10-35%. 96% of hydrogen used in the trial was from onsite electrolysis. Operational cost identified as a factor.

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