An ETI Insights Report

energy technologies institute

HEAVY DUTY VEHICLES OVERALL INSIGHTS REPORT

Contents

Heavy Duty Vehicles (HDVs) contribute around **8%** of the UK's **Greenhouse Gas (GHG) emissions.**

The ETI started a programme to investigate how to tackle the **GHG emissions of the HDV sector** in the UK and organised these into **three streams**.

1 An **HDV** efficiency technology demonstration programme targeting a **30%** energy efficiency improvement.

2 A study of the **well-to-motion** implications of natural gas as an HDV fuel.

3 An energy systems analysis of various **zero CO_2** emission HGV energy vectors.

HEAVY DUTY VEHICLES OVERALL INSIGHTS REPORT

The **2025 EU HGV GHG** reduction target is feasible, thus supporting the stringency of this target.

Efficiencies and **natural gas** aren't enough for the **UK** to meet its ambitious net-zero targets in **2050**. Therefore, a new, **low carbon energy source** is needed as soon as possible.

On balance, **natural gas** is a viable opportunity for **GHG reduction** in the mid-term.

Zero (or near-zero) **HGVs** are cost effective in 2050 on a carbon price basis. This is true with an **80%**, UK wide, GHG reduction target (vs **1990** levels); with a net-zero GHG target, zero (**or near-zero**) **HGVs** become an imperative.

CONTEXT

Heavy-Duty Vehicles (HDVs) such as Goods Vehicles (GVs) (both Heavy Goods Vehicles 'HGVs'[1] and Medium Goods Vehicles 'MGVs'[2]), buses, marine vessels, rail locomotives, quarry machinery, construction machinery and agricultural tractors are the backbone of our modern economy but represent a significant challenge when considering the UK's 2050 decarbonisation target.

Traditionally, these vehicles and machines use a diesel engine to generate the power needed to perform their myriad of functions. The energy and power demands of the HDV fleets often exceed the capability or cost-effectiveness of currently known zero tailpipe carbon technologies such as battery electric power and leads to HDVs being referred to as a 'hard to abate' sector.

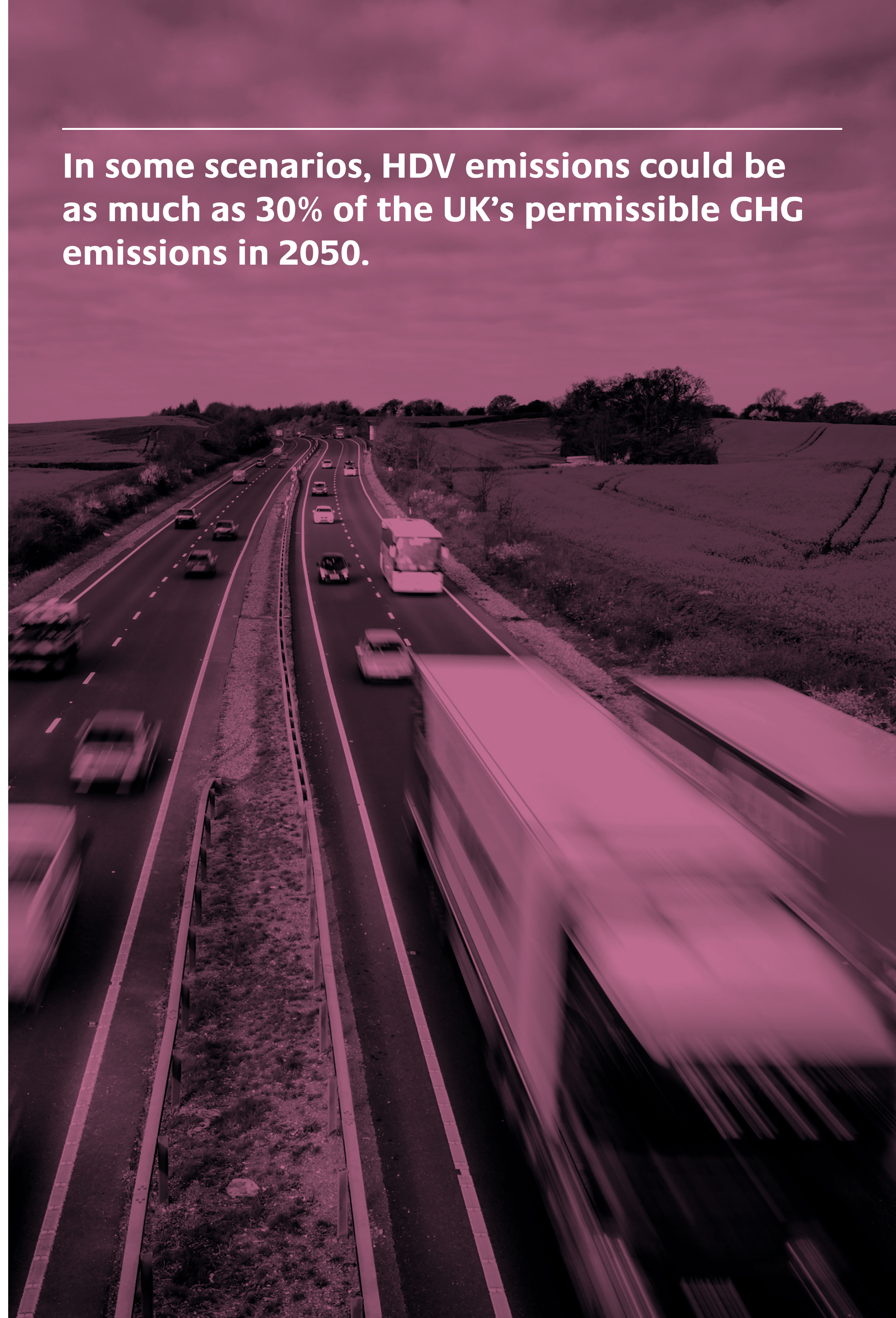
In 2010, the ETI started a programme of work to investigate how to tackle the Greenhouse Gas (GHG) emissions of the HDV sector in the UK. At the outset of the programme, HDVs contributed around 45Mt CO_2 or 8% of the UK's GHG emissions. While this appeared a relatively small proportion, the ETI's energy system modelling showed that this contribution would grow significantly as other sectors decarbonise out to 2050. In some scenarios, HDV emissions could be as much as 30% of the UK's permissible GHG emissions in 2050[3]. This insight report discusses the land vehicle portion of the programme only, i.e. GVs, buses, rail locomotives, quarry machinery, construction machinery and agricultural tractors.

To achieve its Land Programme mission, the ETI partitioned the challenge into several time frames and associated key questions:

Table 1
Key questions table

Approximate Timeframe	Timeframe description	Key questions
2020+	Step 1, be as efficient as possible while using fossil fuels	• How efficient can HDVs be where the adoption of technology is market-driven? I.e. fuel savings compensate for the increase in up-front costs within two years of ownership.
2025-2040	Step 2, consider lower carbon fuels as an alternative to diesel	• Can natural gas deliver a benefit over diesel engines considering a full well-to-motion pathway assessment?
2040-2050	Step 3, consider zero (or near zero) CO_2 emission HGVs	• Can natural gas deliver the UK's 2050 GHG ambitions or are zero (or near zero) CO_2 emission HGVs needed? • If zero (or near zero) CO_2 emission HGVs were implemented in the UK, what would they need to cost and what impact would they have on the UK's energy system?

[1] Maximum Gross Vehicle Weight 17 tonnes to 44 tonnes
[2] Maximum Gross Vehicle Weight 7 tonnes to 17 tonnes
[3] Unless otherwise stated, this insight considers the UK Climate Change Act (2008). The act legislates for an 80% reduction in GHG in 2050 from a 1990 baseline. In June 2019, the UK government passed an update to the act to reach net zero by 2050.



The purpose of this insight report is to provide a narrative across these workstreams and the resulting decarbonisation pathways.

The work to answer these questions was organised into several streams:

1. An HDV efficiency technology demonstration programme targeting a 30% improvement in fuel consumption.

2. A study of the well-to-motion implications of natural gas as an HDV fuel.

3. An energy systems analysis of various zero (or near zero) CO_2 emission HGV energy vectors. Including an assessment of a target cost (on a carbon price basis) and the resulting impact on the energy system (e.g. electricity generation).

The questions and corresponding workstreams were all designed to allow the ETI to consider and propose credible decarbonisation pathways for the UK's HDV fleet out to 2050. The purpose of this insight report is to provide a narrative across these workstreams and the resulting decarbonisation pathways.

The expectation is that vehicles embodying technologies from this programme could be on sale by 2022 and that the full efficiency benefit will be delivered to the market from 2030.

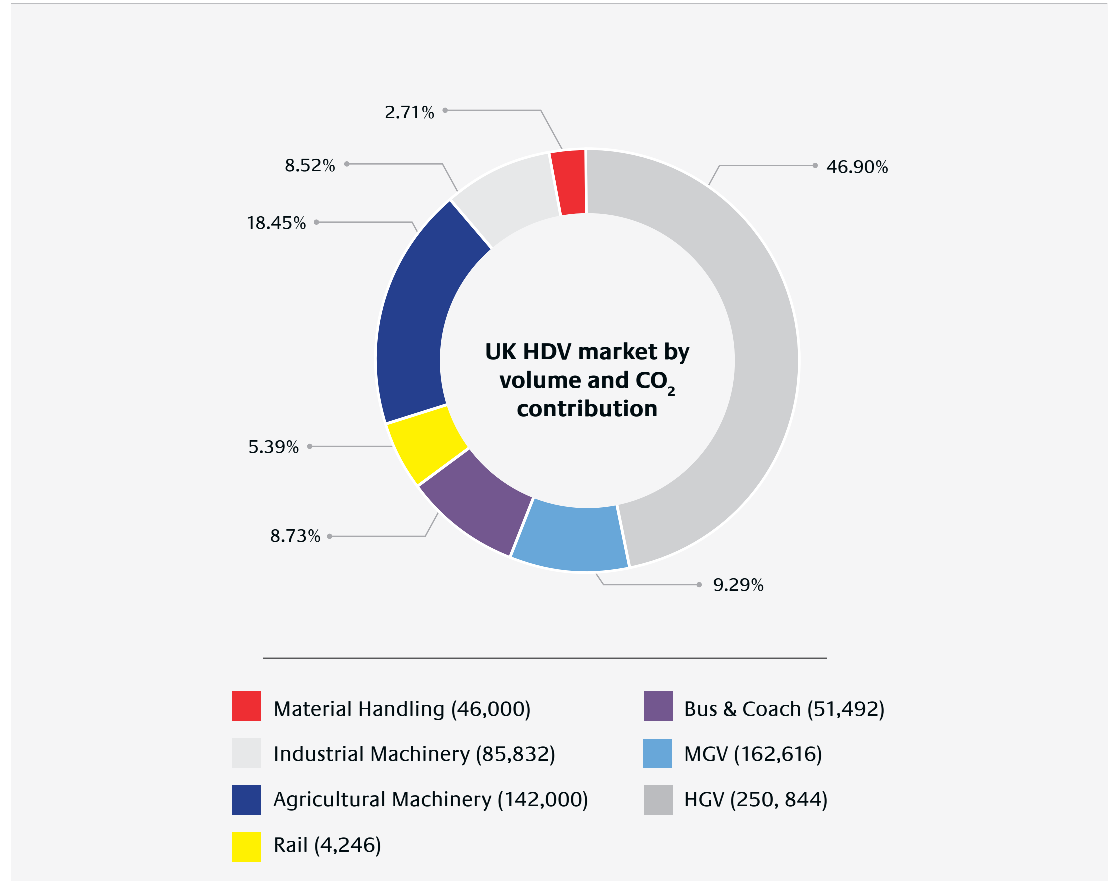
STREAM 1: HDV EFFICIENCY TECHNOLOGY DEMONSTRATION PROGRAMME

The Land HDV Efficiency Programme is a £30M technology development and demonstration programme that targets a fuel efficiency improvement of 30% or more. The programme consists of a series of inter-related projects that are delivered by a range of industry stakeholders on behalf of the ETI who provide investment funding. The programme completes in quarter three of 2019.

The 30% target is a weighted average and applies across a range of HDVs that represent both the on-highway and off-highway UK fleet.

The expectation is that vehicles embodying technologies from this programme could be on sale by 2022 and that the full efficiency benefit will be delivered to the market from 2030 onwards. It is anticipated that these vehicles will be competitively superior products and will be purchased preferentially due to their superior economics and mission performance in use. An important input to the programme is an understanding of the GHG emissions from each of the HDV sectors. This breakdown of emissions is shown in Figure 1.

Figure 1
Breakdown of UK HDV market by volume and CO_2 contribution, the total chart represents 45.3Mt of CO_2



Several conclusions can be drawn from this data:

- While HGVs are a large proportion of the emissions (47%), the other sectors are still significant and the ETI's aspiration to develop broadly applicable technologies is sound.
- The programme should consider technologies and integrated solutions for a range of vehicle types and usage cycles.
- Rail's contribution is relatively small and can be neglected due to other on-going initiatives, such as electrification.
- Material handling also has a small contribution and hence is not a focus of the programme.

Seven vehicles were selected to act as a proxy for the UK fleet as defined within the emissions breakdown above. These vehicle archetypes formed the baseline for any improvements resulting from the ETI's programme and a bar against which to judge the 30% improvement target.

The programme was split into 3 phases:

- Phase 1 - Understand the requirements of each land HDV sector (drive cycles, legislation, customer needs, etc.), while determining and optimising technology combinations for GHG reduction with wide market applicability using a Model-Based Systems Engineering (MBSE) approach.
- Phase 2 - Understand, develop, produce and verify the proposed GHG reduction technologies identified in Phase 1 at the subsystem or component level.
- Phase 3 – Integrate, optimise and demonstrate the technologies on major and whole vehicle systems – culminating in a demonstration on an off-highway Caterpillar AT725 articulated truck. Use the computer models of the remaining six archetypes developed above to assess the benefits across the UK fleet, validating the true benefit of the suite of technologies.

The resulting programme is unique in its ambition, depth and breadth. The 'Land-Based Heavy Duty Vehicle Efficiency at the ETI' report[4] documents this work in further detail and is available on the ETI's website.

Programme outputs

The Programme identified and developed several powertrain architectures and a corresponding list of key platform technologies. See Table 2.

Figure 2 shows a schematic of the HGV powertrain architecture as an example.

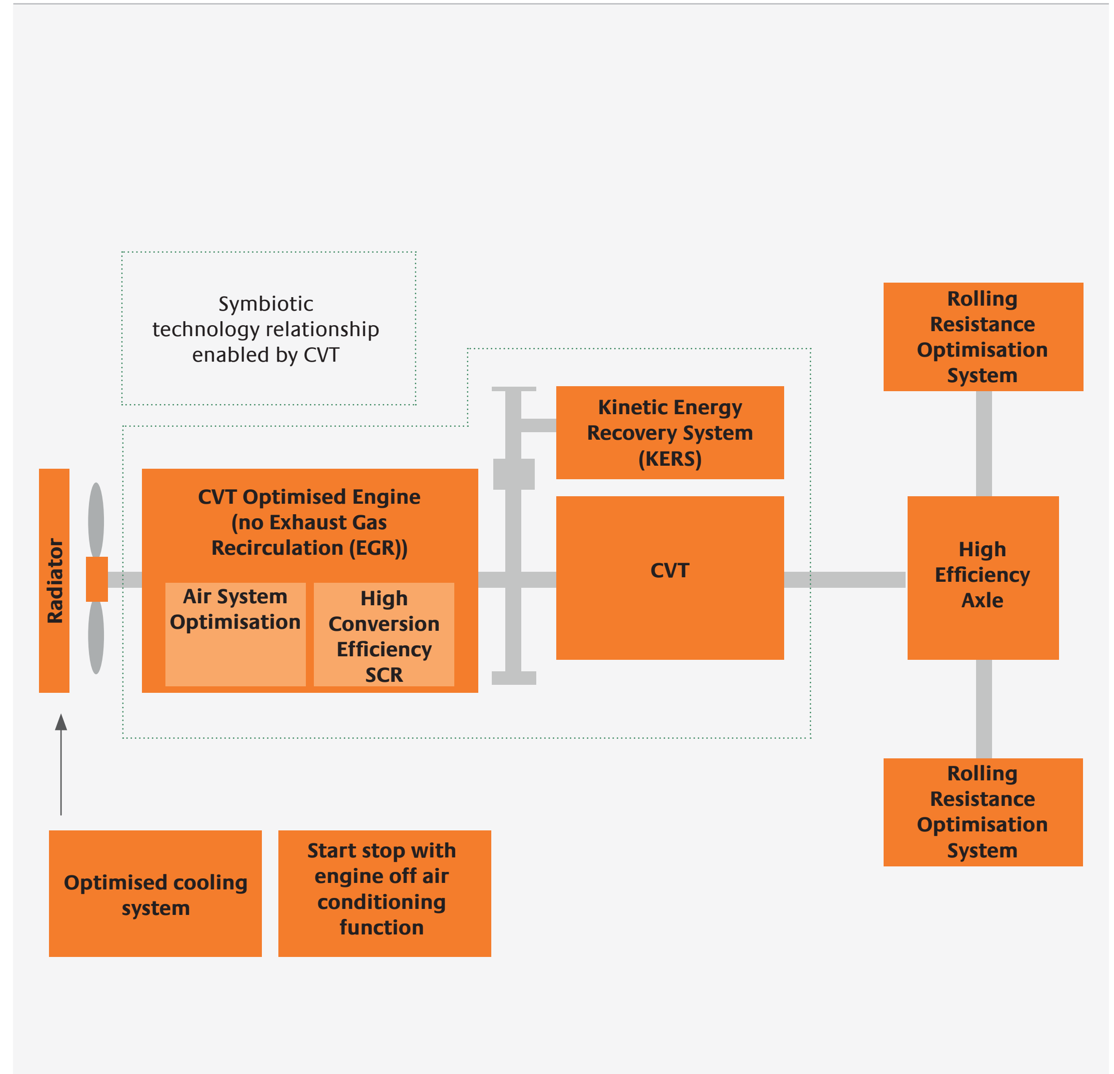
While HGVs are a large proportion of the emissions (47%), the other sectors are still significant and the ETI's aspiration to develop broadly applicable technologies is sound.

[4] https://www.eti.co.uk/insights/land-based-heavy-duty-vehicle-efficiency-at-the-eti

Table 2
Vehicle archetype vs platform technologies matrix

Vehicle Archetype	Key Platform Technologies: High-Efficiency Selective Catalytic Reduction (SCR) (circa 98% conversion efficiency) / High-Efficiency Engine Air System (EAS) / Engine (with no exhaust gas recirculation)	CVT Transmission	KERS (Flywheel energy storage)	KERS (Hydraulic energy storage)	High Efficiency Axle	Rolling Resistance Optimisation System (RROS)	Optimised cooling system and high temperature oils	Start/stop with engine off air conditioning
DAF XF105 HGV	X	X	X		X	X	X	X
Generic MGV	X	X	X		X	X	X	X
Alexander Dennis Enviro 300 Bus	X	X	X		X	X	X	X
John Deere 6150R	X	X			X	X	X	X
CAT 966MWL	X	X		X	X	X	X	X
CAT 320D Hydraulic Excavator	X			X			X	X
CAT AT725 articulated truck	X	X		X	X	X	X	X

Figure 2
New Concept HGV (NC-HGV) powertrain architecture



At the core of the concept is a new and patented Continuously Variable Transmission (CVT) with an input coupled Kinetic Energy Recovery System (KERS). The CVT allows the engine and KERS to be optimised for their performance independent of vehicle load and speed.

Results - Overall Fuel Efficiency Benefit

The target for the programme was to deliver a 30% reduction in fuel consumption, as a proxy for GHG reduction. Table 3 shows the actual performance achieved across the archetypes considered within the HDV fleet. Two fleet fuel efficiency benefit numbers are shown, an upper estimate and a lower estimate. The quoted range considers variations in assumptions, modelling methods and usage cycles. The specific variations are shown in Table 3.

Table 3
Results Table for the UK fleet of HDVs

Vehicle Type	HGV	MGV	Bus	Ag	AT	MWL	HEX	Fleet, %
Make & Model	DAF XF 105		AD Enviro 300	JD 6150	CAT AT725	CAT 966	CAT 320D	
Vehicle Weighting	51	10	10	20	5	1	3	
Upper Fuel Efficiency Benefit, %	11.4	30.4	31.3	35.9	28.3	33.5	25.6	22
Lower Minimum ETI Benefit, %	7.1	17.7	19	17.8	28.3	33.5	25.6	13
Reason for difference/Comments	**Upper benefit** based upon an average of the 75% and 25% payload results from the FIGE cycle at a Cd of 0.53 **Lower benefit** as above but for the ETI cycle	**Upper benefit** based upon Caterpillar modelling and a bespoke drive cycle **Lower benefit** based upon AVL modelling of DAF XF105 over urban and rural section of WHVC	**Upper benefit** based upon Caterpillar modelling and a bespoke drive cycle **Lower benefit** based upon AVL modelling of DAF XF105 over urban section of WHVC	**Upper benefit** includes CVT benefit **Lower benefit** removes CVT benefit as CVTs already available in the market for Ag tractors	High confidence number based upon vehicle testing			

As can be seen, the programme largely achieved its 30% aim across the off-highway vehicles. The more dynamic on-highway vehicles also achieved excellent fuel efficiency numbers; however, the HGV result, while significant, was lower than targeted. This results in a circa 18% improvement across the fleet when weighted by the emission contribution of each vehicle archetype. This is less than the programme target and is largely due to the lower than expected results in the highly weighted HGV sector. The HGV results are discussed in more detail in the next section.

HGV fuel economy results in more detail

The results shown in Table 4 were generated by the automotive consultancy, AVL, using two AVL-CRUIS$_{ETM}$ models. The first model represented the baseline HGV and was calibrated to publicly available data and measurements taken from a DAF XF105 HGV. The second model represented the proposed New Concept HGV (NC-HGV) powertrain as shown in Figure 2. The modelling work also considered a range of drive-cycles. Please see the ‘Land-Based Heavy Duty Vehicle Efficiency at the ETI’[5] report for further details on the cycles used. This report is available on the ETI’s website. In addition to the drive cycle sensitivity, the vehicle mass and aerodynamic drag coefficients (Cd) were also varied to ensure robustness. The Cd range was chosen to represent the anticipated performance of aerodynamic treatments considering the 2022+ time frame.

As can be seen from Table 4, the results vary considerably across the cycles, and to a lesser degree with vehicle mass and aerodynamic drag. The cycles that contain more transient use yield larger benefits than those which contain lots of constant speed driving.

In December 2018 the European Parliament, Commission and Council agreed on the final CO_2 emission targets for heavy-duty trucks. The fleet average CO_2 emission reduction targets for new GVs have been set at 15% by 2025, and at 30% by 2030, relative to 2019 emission levels. Manufacturers who fail to meet their targets will pay an ‘emissions premium’ penalty.

Hence, it is worth noting that if the benefits of the 25% aerodynamic drag improvement are included with the other changes then the NC-HGV concept achieves between 13.7% and 15.8% over the EU’s VECTO long haul cycle (2016). Therefore, these results approach the fleet improvement number of 15% by 2025 (from a 2019 baseline) as legislated by the EU commission. This result is only indicative as it uses a Euro 6 baseline, the 2016 VECTO long haul cycle plus a different modelling regime and assumptions to the official VECTO tool. However, it does suggest that the EU target is somewhat feasible.

The ETI work also estimated the payback period for the proposed HGV powertrain architecture based upon fuel savings over the baseline. This work showed that, under some scenarios (i.e. higher fuel prices and higher annual mileages), the proposed concept paid for itself within the targeted two-year period; however, even in the worst payback scenario, breakeven was within the economic life of an HGV.

[5] https://www.eti.co.uk/insights/land-based-heavy-duty-vehicle-efficiency-at-the-eti

Table 4
Fuel consumption results for a range of cycles, payloads and aerodynamic drag coefficients

Vehicle Weight, tonnes	36.9 (75% payload)						
Cd	0.71			0.53 (i.e. 25% reduction on the baseline)			Including Aero Benefit
Vehicle Configuration	Baseline, l/100km	ETI Truck, l/100km	Delta, %	Baseline, l/100km	ETI Truck, l/100km	Delta, %	Delta, %
Drive Cycle: ETI Cycle (Motorway)	37.9	35.9	5.3	35.3	33.1	6.2	12.6
VECTO Long Haul (2016)	40.0	37.3	6.8	37.0	34.5	6.7	13.7
FIGE	37.2	33.5	10.0	34.8	31.0	10.9	16.6
WHVC	45.1	39.1	13.3	43.5	37.4	14.1	17.1

Vehicle Weight, tonnes	23.9 (25% payload)						
Cd	0.71			0.53 (i.e. 25% reduction on the baseline)			Including Aero Benefit
Vehicle Configuration	Baseline, l/100km	ETI Truck, l/100km	Delta, %	Baseline, l/100km	ETI Truck, l/100km	Delta, %	Delta, %
Drive Cycle: ETI Cycle (Motorway)	30.3	28.1	7.3	27.4	25.2	8.0	16.8
VECTO Long Haul (2016)	31.7	29.6	6.7	28.8	26.7	7.3	15.8
FIGE	30.4	27.1	10.9	28.0	24.7	12.0	18.9
WHVC	34.8	30.1	13.6	33.2	28.2	15.0	18.9

Summary

The ETI has conducted an HDV efficiency programme, unique in its breadth and depth, that has attempted to deliver a meaningful impact on the fuel efficiency of the HDV fleet in the UK. The following can be concluded from the ETI Programme:

- The evidence, analysis and technology acceleration has influenced the powertrain research and development of Caterpillar, the world's largest off-highway equipment manufacturer.
- Fuel efficiency gains can be achieved across a range of vehicle types and these gains can be financed by the fuel savings. In some instances, the payback period is acceptable to the first purchaser and, where they are not, the payback period is within the economic life of the vehicle.
- The 2025 EU HGV GHG reduction target is feasible, thus supporting the stringency of this target.
- More publicly available research should be conducted on HGV movements and payloads to enable better research, technology developments and policies in the future (the ETI's support for the Centre for Sustainable Road Freight (www.csrf.ac.uk) is an example of this).
- Delivering double-digit powertrain fuel savings on HGVs is a significant challenge as their diesel powertrains are already well optimised for their motorway dominated usage cycle.
- Accelerating the implementation of lower-carbon fuels or energy carriers is the only practical way of delivering significant (i.e. above 15%) HGV GHG reductions in the mid to longer-term.

STREAM 2: WELL-TO-MOTION IMPLICATIONS OF USING NATURAL GAS AS AN HDV FUEL

Context

In parallel to the efficiency work described above, the ETI also considered natural gas as a possible lower-carbon alternative to diesel fuel. At the point of use, natural gas, which is mostly comprised of methane, contains approximately 25% less carbon when compared to diesel for a given quantity of energy. However, there are several factors that prevent the full GHG benefit of methane gas being realised, including leakage to the atmosphere. Methane is a powerful GHG that varies in its Global Warming Potential (GWP[6]) between 25[7] and 86[8] depending on the timeframe under consideration and the reference used.

The factors that reduce the benefit of natural gas are present throughout the supply chain and in the fuel's use. Therefore, to understand the true economic and GHG impacts of gas as an HDV fuel requires a 'well-to-motion' (WTM) analysis. By consulting with our members in 2013, it was apparent that no such study existed in the public domain.

The ETI commissioned Element Energy to create a WTM model of the UK's natural gas pathways and the associated HDV fleets (including marine vessels). As well as considering the entire gas pathway, the model could also calculate uptake rates based upon economic considerations. To ensure that the outcomes were robust, the work considered three scenarios across both Compressed Natural Gas (CNG) and Liquified Natural Gas (LNG) pathways. The three scenarios were a 'base case', a 'worst case' and a 'best case' — the base case being the most probable outcome.

The 'Natural Gas Pathway Analysis for Heavy-Duty Vehicles' report documents this work. The report along with the models and resources developed are available on the ETI's website[9].

Findings

The modelling shows that natural gas reduces the GHG emissions from land-based HDVs over the WTM pathway in both the base case and best-case scenarios. Only in the worst-case does natural gas have higher GHG emissions; however, this scenario can easily be avoided. The fleet level benefit for land-based HDVs across the three scenarios is shown in Figure 3. Figure 3 is the result of both the WTM GHG emission of each vehicle type (including all the land HDVs) and the rate at which they are deployed into the fleet. In the model, a natural gas vehicle is deployed into the fleet when it is cheaper to operate than a diesel equivalent with some inertia applied to the switching process. For on-highway GVs this calculation includes the lower rate of tax applied to natural gas by the UK Treasury.

Figure 3 shows modest improvements in the fleet GHG performance in the 2035 timeframe for the base and best cases. This is limited by the degree of vehicle deployment within the fleet, which in turn is a result of the economics. In Figure 3, the land HDV fleet take-up of natural gas is approximately 30%. Please note that at the time of writing the inclusion of natural gas within the EU GHG regulation for on-highway heavy-duty vehicles is being considered.

Table 5 shows the base case benefit of natural gas in an HGV application in 2035 and provides context for the maximum benefit that could be derived if a 100% uptake was achieved within the fleet. Table 5 also shows a sensitivity to the GWP assumed for methane. Even when a 20-year timeframe is used, LNG is equivalent to diesel and CNG still provides significant GHG reductions.

[6] Global warming potential (GWP) is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide.
[7] 100 year Global Warming Potential (GWP) of methane is 25 times worse than CO_2 reference 2007 IPCC AR4 report
[8] 20 year GWP of methane is 86 reference 2014 IPCC AR5 report
[9] https://www.eti.co.uk/library/an-eti-perspective-natural-gas-pathway-analysis-for-heavy-duty-vehicles

Figure 3
Emissions from the UK fleet of land-based HDVs, based upon the calculated WTM performance (with a methane GWP of 25) and an economic uptake model. The figure compares the fleet emissions when natural gas vehicles are available for selection and when they are not available. The percentages refer to the increase/reduction in emissions in 2035 compared to the diesel-only scenario.

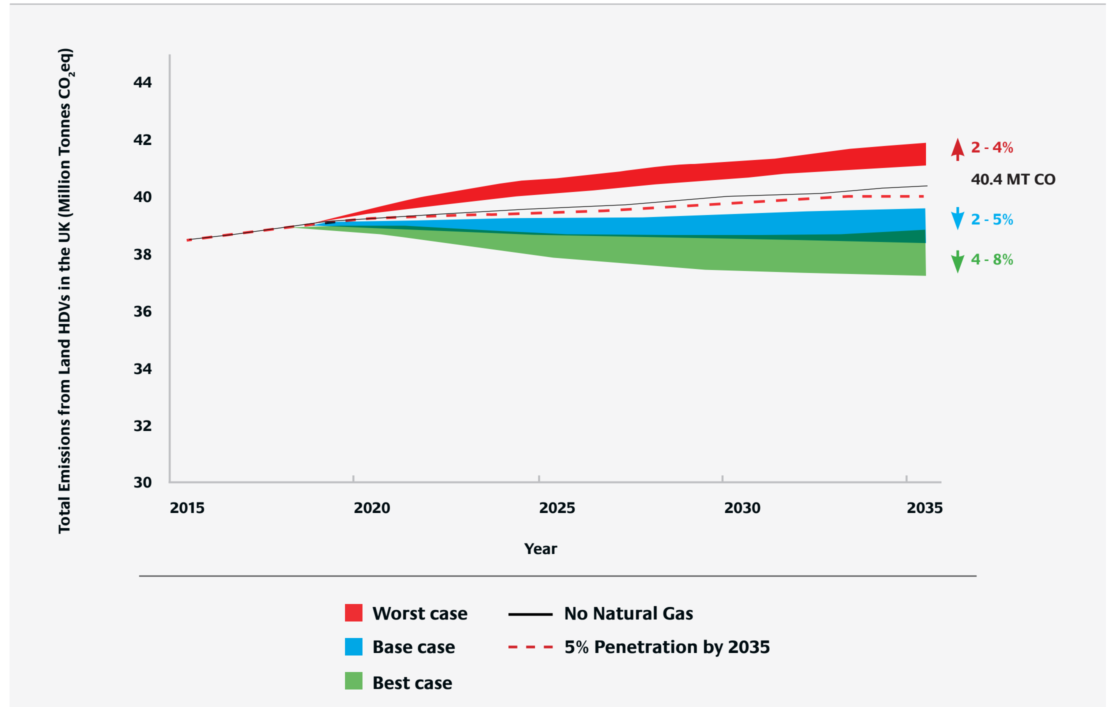


Table 5
Potential GHG savings per HGV in the baseline scenario when compared to the reference diesel pathway in 2035

Gas type	Engine type	Potential GHG saving from diesel counterfactual (100 year GWP of 25[10])	Potential GHG saving from diesel counterfactual (20 year GWP of 86[11])
Compressed Natural Gas (CNG)	Dedicated gas, spark-ignited	20%	13%
	High-Pressure Direct Injection (HPDI)	24%	13%
Liquified Natural Gas (LNG)	Dedicated gas, spark-ignited	13%	0%
	HPDI	16%	0%

[10] 100 year Global Warming Potential (GWP) of methane is 25 times worse than CO_2 reference 2007 IPCC AR4 report
[11] 20 year GWP of methane is 86 reference 2014 IPCC AR5 report

The key system GHG sensitivities are as follows:

- Cycle specific powertrain technology selection and pathway optimisation are key to providing GHG emission benefits over given usage cycles, with High-Pressure Direct Injection (HPDI) and dedicated spark-ignited gas engines providing the highest benefit.
- Retrofit dual-fuel engines have been shown to have high methane emissions[12], often being worse than baseline diesel powertrains on a GHG emission basis. Effective testing procedures and legislative certainty are required to ensure emissions conformity and facilitate market development.
- Employing 'best practices' at LNG, CNG and combined L-CNG stations is a key driver in providing pathway benefits. Vapour recovery systems should be implemented at all LNG stations and the economic proposition and expected utilisation should be aligned.
- CNG stations should be connected to the highest pressure tier of the grid where possible or employed in combination with an L-CNG station as an easy step to reduce emissions associated with compression, at least until the carbon intensity of the grid is significantly lower than today.

Much deeper GHG reductions can be achieved by using bio-methane as a fuel. However, there are concerns over the capacity for this to be generated sustainably in the desired quantities as well as the stability of supply of any imported fuel. Furthermore, the ETI's modelling suggests that any UK produced biomass is better utilised in a Bio-Energy with Carbon Capture and Storage (BECCS) process to generate negative carbon emissions. Given these perspectives, biogas was not considered a full-scale energy vector for the HDV fleet. However, biogas may well form part of a solution through blending with natural gas or as a range extender fuel. Please see the report 'Natural Gas and Bio Gas Pathway Analysis for Heavy-Duty Vehicles'[13] on the ETI's website for more information.

Summary

On balance, natural gas is a viable opportunity for GHG reduction in the mid-term. Indeed, the EU's 2030 30% GHG reduction target for heavy goods vehicles can be achieved if the ETI's modelled efficiency gains are combined with the NG GHG gains calculated by this stream of work. I.e. combining the 13.7% efficiency gain over the VECTO cycle from stream 1 with the 16% benefit of LNG using an HPDI engine from this work, thus totalling an improvement of almost 30%.

[12] https://www.lowcvp.org.uk/assets/reports/LowCVP%202016%20DfT%20Test%20Programme%20Final%20Report.pdf
[13] Reference/link

STREAM 3: A SYSTEMS ANALYSIS OF ZERO (OR NEAR ZERO) CO_2 EMISSION HGV ENERGY VECTORS

Context

Stream 1 showed what can be achieved in the short-term using powertrain technologies that are able to fund themselves through their fuel savings. The work in Stream 2 showed the potential of natural gas to further improve the GHG performance of UK HDVs in the short to mid-term. Therefore, the next step was to consider what the longer-term solution for HDVs could be (i.e. out to 2050). Not only was this question important for UK's 2050 climate goals, but it is vital in plotting a viable transition from today's HDV fleet to that of the 2050s.

At the time of writing, there are several candidate technologies worthy of consideration. They range from high-efficiency gas-powered vehicles, via internal combustion and battery hybrid powertrains, through to complete tailpipe decarbonisation using either hydrogen or electricity. Traditionally, electric HDVs have been considered unfeasible due to cost and weight. However, battery costs are reducing quickly, and alternatives such as pantograph dynamic charging are being trialled in Europe and the US. Fuel cells are also expensive, but again, costs are falling as passenger car companies commit large R&D resources to improve performance and cost.

Using electricity or hydrogen (or a mix) alters the energy vector for HDVs away from imported hydrocarbons. The electricity and hydrogen must be generated and distributed, resulting in a deeper connection between the HDV fleet and the UK's energy system as a whole. To understand the viability of a technology and its impact within the energy system, the ETI uses its Energy System Modelling Environment (ESME) model.

The ETI would normally estimate a 2050 cost range for each HDV propulsion technology and any associated re-fuelling infrastructure (e.g. battery electric vehicle and charge points) and enter these into its ESME model. The ESME tool is a cost minimising model that seeks to build plausible energy systems that achieve an 80% reduction in GHG in 2050 vs a 1990 baseline. To do this the model has access to hundreds of technology options across electricity generation, heat, industry, transport etc. If a particular technology is selected by ESME then, by definition of the cost minimisation routine, it is cost-effective across the UK's 2050 energy system as a whole. To overcome the uncertainty in estimating demands and costs in 2050, ESME is a probabilistic tool and accepts ranges on its inputs and generates a corresponding range of plausible outputs (i.e. a Monte Carlo approach). In all instances the ESME model creates an energy system that is more expensive than a counterfactual where no GHG reductions are mandated. Therefore, there is cost associated with achieving the UK's 2050 target. For more information on ESME and the ETI's 'clockwork' and 'patchwork' 2050 energy system scenarios please see https://www.eti.co.uk/options-choices-actions-2018.

In addition to the normal ESME approach above, a target cost which facilitated mass deployment of very low GHG vehicles was generated in order to understand what such a mass deployment might do to the rest of the energy system. This is essentially the reverse of the standard ESME process. This was for the following reasons:

- At the time of the work, the 'traditional' ESME approach didn't routinely select zero (or near zero) CO_2 emission HDVs.
- A target cost is independent of potentially erroneous long term cost estimates.
- A target cost helps refocus the vehicle and energy supply industries away from an incremental technology approach and towards a carbon price-driven future where more radical change may be appropriate.
- A target 'cost to society' based upon all other aspects of the energy system provides confidence to policymakers that potential policies are cost-effective and represent good value for the UK.

The Stream 3 work focussed on the >33 tonne HGV sector because it is the highest emitting HDV sector and one that isn't easily satisfied by simply scaling up passenger car technologies (e.g. battery-electric technology), but where these technologies are still plausible.

The new approach forces the >33 tonne HGVs within ESME to use each of the energy vectors listed below sequentially:

- Electricity (either battery-electric or dynamically charged, e.g. pantograph);
- hydrogen utilised in a fuel cell; and
- plug-in hybrid with a natural gas engine where there is a 65:35 split on energy consumption between natural gas and electricity respectively.

Forcing an energy vector and looking at the costs where it becomes feasible allows both the energy system impacts to be understood whilst setting a target cost for that particular energy vector. The approach used was developed in ESME specifically for this work. Therefore, this work set out to address the following questions:

- What is the maximum cost a zero (or near zero) CO_2 emission HGV can be in 2050 in order to achieve mass-market deployment (assuming the whole fleet is constructed of these vehicles) within the UK energy system when there is a carbon emissions constraint?
- How does the construction of the wider UK energy system affect the cost and the type of zero (or near zero) CO_2 emission HGVs?
- What effect does the selection of zero (or near zero) CO_2 emission HGVs have on the rest of the energy system?

Table 6
Modelled transport and system scenarios

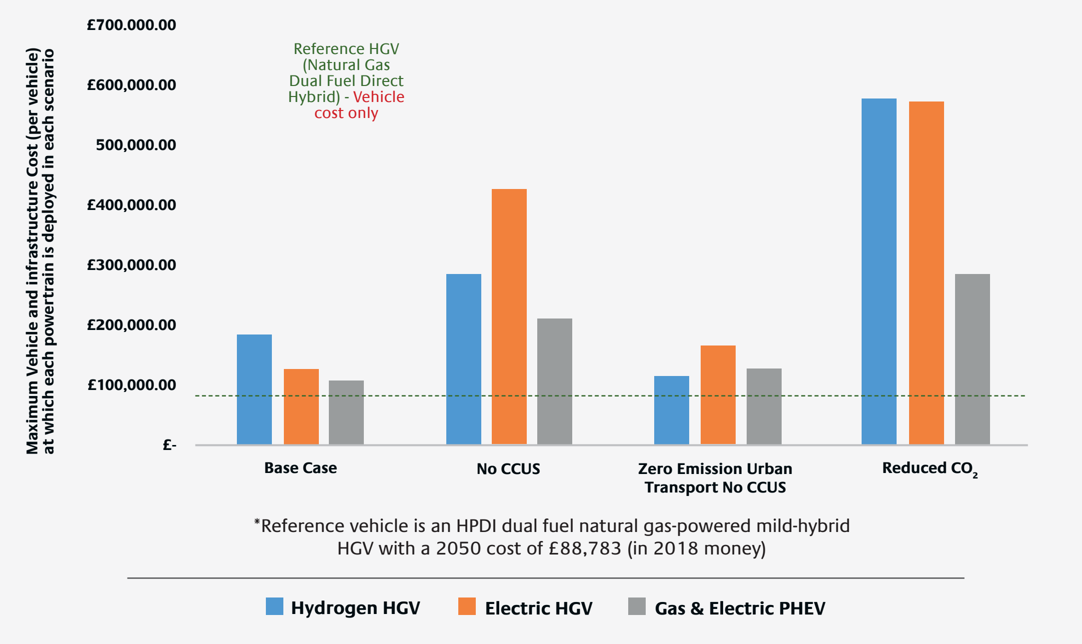
Scenario	Transport Sector				System and Overall Constraints	
	HGV Sector	MGV Sector	LGV (Van) Sector	Car Sector	Other System Restrictions	CO_2 Target
Base Case	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No other restrictions	80% reduction of GHG from 1990 levels
No CCUS	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	All technologies which use and store carbon (CCUS) are unable to be selected	80% reduction of GHG from 1990 levels
Zero Emission Urban Transport	No restrictions over vehicle selection	Progressive CO_2 reduction from today concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2020 target of $147gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2021 target of $95gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	No other restrictions	80% reduction of GHG from 1990 levels
Zero Emission Urban Transport No CCUS	No restrictions over vehicle selection	Progressive CO_2 reduction from today concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2020 target of $147gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	Progressive CO_2 reduction from the 2021 target of $95gCO_2/km$ concluding in all new vehicles sold from 2040 must be $0gCO_2/km$	All technologies which use and store carbon (CCUS) are unable to be selected	80% reduction of GHG from 1990 levels
Reduced CO_2 Target Sensitivity	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No restrictions over vehicle selection	No other restrictions	Increased GHG target to 90% reduction of GHG from 1990 levels

As well as modelling each of the energy vectors listed above, the modelling was repeated across several scenarios to capture key sensitivities and likely future outcomes. These scenarios are detailed in Table 6.

The work was conducted in such a way as to avoid the detail of the exact implementation of the vehicle powertrain. For example, it does not delineate between pantograph charged trucks and full battery-electric trucks; just that the energy vector is electricity (or hydrogen) and it sets an overall target cost. How the cost is deployed to best achieve very low emissions is a recommended future project. Furthermore, the work doesn't account for the embedded GHG in the vehicles and infrastructure and this also needs to be included in any future study.

The full report 'Future HGVs in the Context of the Energy System'[14] is on the ETI's website.

Figure 4
Cost targets for a range of 2050 scenarios. The 'Zero-Emission Urban Transport' scenario is admitted because ESME does not select zero (or near zero) CO_2 emission HGVs when the light-duty fleet is zero-emission and Carbon Capture Usage and Storage (CCUS) is deployed.



Findings

The work answered the questions that were set out as follows:

What is the maximum cost a zero (or near zero) CO_2 emission HGV can be in 2050 in order to achieve mass-market deployment (assuming the whole fleet is constructed of these vehicles) within the energy system when there is a carbon emissions constraint?

The Stream 3 work has shown that a fleet of zero (or near zero) CO_2 emission HGVs, and their supporting infrastructure, contribute towards the overall decarbonisation of the UK's energy system across most of the 2050 scenarios considered. The costs at which they are competitive depends on the energy vector selected. This is because ESME has already accounted for any generating plant capital and the on-going energy cost to generate the vector. Figure 4 shows those scenarios where the cost targets on a per-vehicle basis are higher than the cost of a reference HGV (which represents the combination of the Stream 1 and Stream 2 findings).

Zero (or near zero) CO_2 emission HGVs were deployed to some extent at costs greater than the baseline in 4 of the 5 scenarios. The only scenario that saw zero deployments was when the GHG target was set at 80% of 1990 levels, full-scale Carbon Capture and Storage (CCS) was available and all light-duty vehicles were zero-emission. Please note that the target cost includes the vehicle cost and amortisation of the energy distribution system to transport the energy from the point of generation to the vehicle.

Many of these cost targets are high enough that they exceed industry cost estimates for these powertrains in 2050. Therefore, these targets suggest that the mass adoption of zero (or near zero) CO_2 HGVs is cost-effective on a carbon price basis. This is especially true given the recent update to the Climate Change Act to achieve a 100% reduction in UK GHG emissions by 2050.

How does the construction of the wider energy system affect the cost and the type of zero (or near zero) CO_2 emission HGVs?

The work has shown that low-cost hydrogen use in HGVs is predicated on the deployment of CCS, as without CCS, UK hydrogen production would need to be through electrolysis. Utilising electricity in order to produce hydrogen to further produce electricity to power a vehicle is inefficient. The lower-cost target for a hydrogen vehicle and the supporting infrastructure when CCS is not available to ESME reflects this. One pathway to support the additional requirement for hydrogen, which hasn't been explored in this work, could be through imports, but as with biomass, the quantity available in 2050 is difficult to quantify.

What effect does the selection of zero (or near zero) CO_2 emission HGVs have on the rest of the energy system?

The ESME analysis has shown that deploying any of the three HGV options (hydrogen, electric, gas and electric PHEV) has little overall impact on the high-level electricity generation system in 2050. The hydrogen generating system, in percentage terms, is impacted to a greater degree with a doubling in capacity needed when hydrogen HGVs are deployed. The baseline hydrogen system consists of mostly green hydrogen and this is completely consumed by heavy industry. The ESME cost minimisation chooses to decarbonise HGVs prior to using hydrogen for heating homes.

However, in the case of the electricity vector, the infrastructure options available for electricity use in HGVs could have impacts in the lower tiers of the energy system. This is because charging or electricity demand load profiles are an important factor, which, if they aren't carefully managed could add to the required peak electricity generation capacity. Furthermore, local infrastructure issues are likely to be the constraint and should be investigated in any further work.

Summary

This work has shown that zero (or near zero) CO_2 emitting HGVs can contribute to the decarbonisation of the UK. Furthermore, they can do so at a cost that is lower than other energy system options. The UK has recently strengthened its decarbonisation legislation to drive the UK to net-zero by 2050. Furthermore, whilst CCS is seen as strategically important, vital large-scale demonstrations are not yet in progress. The work has shown that when either CCS is removed from the energy system or the UK GHG target becomes more stringent than the 80% assumed, zero (or near zero) CO_2 emission HGVs become imperative.

The impact on the electricity generating system of both hydrogen and electricity HGV energy vectors is relatively small, i.e. neither require major changes to the generating system to enable them. Therefore, from an electricity generation perspective, this decarbonisation option can be invoked relatively late in the journey to meeting the UK's 2050 objectives. However, the use of hydrogen for HGVs approximately doubles the amount of hydrogen generation required compared to that used in the decarbonisation of heavy industry.

The deciding factor for the energy vector (or vector mix), is likely to be in the cost, efficiency and roll out timeframe of the local distribution systems needed to link the national level assets to the vehicle refuelling/recharging points. The Stream 3 work provides a target price for any such infrastructure choices and is a good basis for further work in this area.

[14] Reference – also ref to insight?

OVERALL DISCUSSION

The three streams of work, when combined, start to create a narrative about how the UK might transition to a 2050 fleet of low carbon land-based HDVs. However, there are some additional influences and considerations worthy of discussion.

Megatrends

There are several trends that are often quoted concerning HDVs. These can act to increase or reduce demand and some are listed in Table 7.

Whilst it is difficult to predict the resulting balance of these effects, it is the ETI's assumption that none of these effects will reduce HDV GHG emissions to the degree required and that energy vector and powertrain changes are required under all scenarios. These changes will not be uniform and large off-highway vehicles are likely to transition more slowly than road vehicles.

Considering road freight in isolation (rather than all HDVs), Figure 5 shows some of the higher-level system approaches that could contribute to a reduction in energy demand (tonne. kilometres). Whilst some of these approaches can deliver double-digit savings, any increase in freight efficiency from such approaches is unlikely to exceed the demand increase by much, i.e. the total freight demand will be of the same order of magnitude as today. Therefore, the conclusions made under the Stream 3 work are relevant even if systemic gains are made. This is not to say these changes aren't important; they represent some of the largest and most cost-effective efficiency gains that can be made within the system. However, on their own, these actions aren't enough.

In addition to decarbonisation, the trends that will most affect the design of a new energy vector and corresponding powertrain system are likely to be air quality, driverless vehicles and innovative logistics system designs (or worksite systems in the case of off-highway vehicles).

Structural changes to the HDV industry

There is potential for disruption to the industry through new business models; for example, the combined supply of vehicle and its energy.

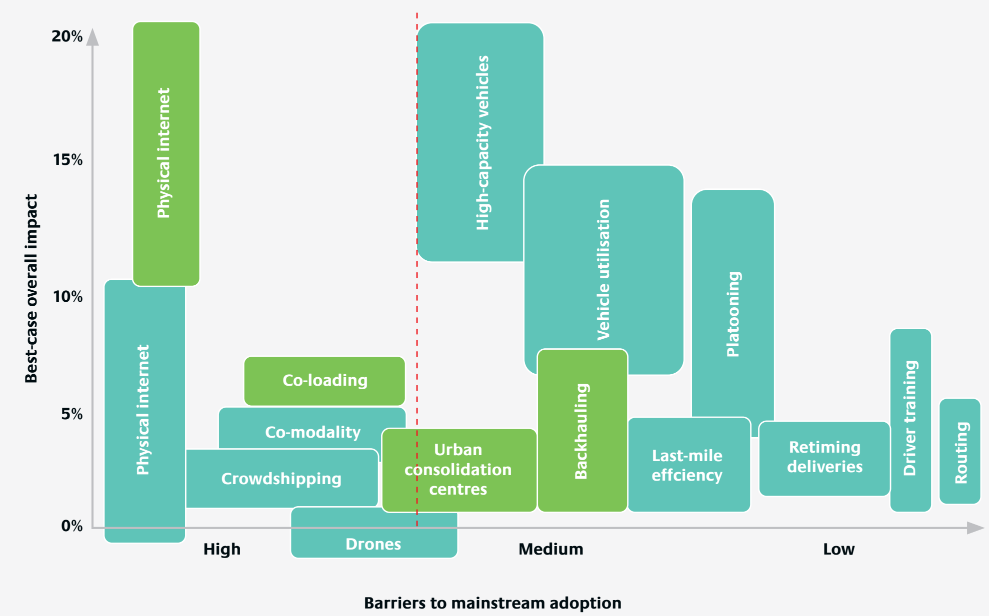
Table 7
Non-exhaustive list of megatrends and their likely effects

Trend	Type/Effect on Land HDVs
Compressed Natural Gas (CNG)	Demand growth
	Demand growth
Liquified Natural Gas (LNG)	Demand growth
	Demand growth
Driverless vehicles and automated machine operations	Removing the driver lowers the operating costs, which leads to lower transport costs and hence the potential to increase demand
Decarbonisation	Demand reduction
Demand for improvements in air quality	Demand reduction
3d printing/additive manufacturing of goods nearer sources of demand	Demand reduction
Logistics innovations such as the 'Physical Internet'	Demand reduction
Improved asset utilisation (e.g. load sharing, high capacity vehicles)	Demand reduction

Such an approach allows a longer-term view to be taken on technology selections and margins enhanced by supplying more of the value chain to the end customer.

The huge on-going investments by the passenger car industry in batteries, electronics and motors will continue to drive down the costs and drive up the performance of these items with significant improvements likely in the 2030 to 2040 timeframe if not before.

Figure 5
Systemic improvements in freight efficiency



Notes: The measurements shown in blue can be implemented by a single carrier, while those in green require external collaboration across companies, either horizontally or vertically across the supply chain. The red line designates the barrier between measures that are realised in the scenario assessment (Chapter 3). Measures to the right of the line are realised only in the Reference Scenario, and many only partially, while those that become feasible in the Modern Truck Scenario are shown to the left of the line.

Source: Based on a slide by Dr Phil Greening, centre for Sustainable Road Freight, in his presentation at the IEA-JRC joint workshop, "The future role of trucks for energy and environment," November 8, 2016 (summary and presentations available online at: www.iea.org/workshops/the-future-role-of-trucks-for-energy-and-environment.html).

Source: https://www.iea.org/publications/freepublications/publication/

The HDV industry is likely to benefit from such investments due to the modularity and scalability of these components. Whilst it is true that engine technologies have been shared between passenger cars and HDVs (in both directions), the engines and transmissions couldn't previously be scaled in such a modular way, for example an HGV doesn't use two passenger car engines, it uses a bespoke larger unit. This results in expensive and bespoke engine and powertrain development programmes for HGV OEMs. These high-cost investments have historically created a barrier to entry for new market entrants. However, electric components and fuel cells are much more modular and can, therefore, be scaled more easily by using multiple units. This will stimulate much higher component sharing between cars, trucks, tractors, etc. and could reduce the cost of developing an HDV - removing a barrier to entry for new market players.

This modularity will also allow vehicles to be configured more readily for particular uses and local energy system preferences. For example, one location may require a hydrogen fuel cell range-extended battery truck, another a full battery truck and another a natural gas range-extended truck. These options could be offered as plug-and-play options as part of a common truck architecture and electrical backbone.

Transition Considerations

Investment in natural gas as an on-highway Heavy Duty (HD) fuel shouldn't become a barrier to further investments in zero (or near zero) CO_2 emission technologies such as electric power or hydrogen. Any deployment of natural gas as a fuel for HDVs needs, therefore, to recover infrastructure and vehicle costs quickly (i.e. by circa 2030 – 2035) so that the investment doesn't create a legacy that prevents investment in very low GHG solutions, such as electricity or hydrogen. In reality, natural gas and bio-methane may well persist at lower consumption levels as a fuel, initially as an electric hybrid and eventually as a range extender fuel for use alongside an electric powertrain.

The vehicle adaptability afforded by the electrification of the powertrain could be an important feature to allow the market to transition from a mid-term solution (e.g. natural gas) to its future, low carbon 2050 state. This is because any infrastructure rollout will take time to implement, particularly if it involves hydrogen pipelines or pantograph charging networks. If this infrastructure is built, vehicles will need to remain cost and operationally effective.

Flexibility in the infrastructure roll-out is also valuable, such that any technology breakthroughs in the 2030-2040 timeframe can be accommodated with relative ease. An example of this would be to build high power connections (10's of MWs) between the national grid and the road network at key locations. These connections could then provide power to rapid chargers at service stations for passenger cars and supply power to pantographs.

However, if there is a breakthrough in battery technology, it may be better to simply charge the truck batteries in the same way as cars and forego the infrastructure cost and disruption associated with pantograph systems. Another example would be to tank hydrogen around the UK until such time as sufficient demand materialises in other sectors, e.g. heating homes and/or passenger cars, at which point the economics allow the development of a pipeline distribution network.

Another consideration for any UK transition is the integration of the road freight system with Europe. If the cost barriers to the development of GVs reduce due to the use of modular electronic components, it is conceivable that the UK market could support bespoke vehicles. However, any solution will need to maintain the current flow of goods into and out of Europe.

Bringing it all together

At the outset of this work, the ETI created three streams of work to consider four key questions. Table 8 summarises the questions and related workstreams.

The conclusions, narratives and proposed next steps have been split into three main sections, one representing off-highway, one for MGVs/ buses and another for HGVs.

Table 8
Key questions and the corresponding workstreams

Approximate Time frame	Timeframe Description	Key Questions	Workstream
2020+	Step 1, be as efficient as possible whilst using fossil fuels	How efficient can HDVs be where the adoption of technology is market-driven? I.e. any increase in up-front costs are offset by fuel savings within 2 years.	Stream 1: HDV efficiency technology demonstration programme targeting a 30% improvement in fuel consumption
2025 – 2040	Step 2, consider lower carbon fuels as an alternative to diesel	Can natural gas deliver a benefit over diesel engines considering a full well-to-motion pathway assessment?	Stream 2: A paper study to consider the well-to-motion implications of natural gas as an HDV fuel.
2040 - 2050	Step 3, consider VL-GHG emission HGVs	Can natural gas deliver the UKs 2050 GHG ambitions or are VL-GHG emission HDVs needed?	
		If VL-GHG trucks were to be implemented in the UK, what would they need to cost and what impact would they have on the UK's energy system?	Stream 3: An energy systems analysis of various zero (or near zero) CO_2 emission HGV energy vectors. Including an assessment of a target cost (on a carbon price basis) and the resulting impact on the energy system (e.g. electricity generation)

Off-highway HDVs

Much of the ETI's R&D investment has focussed on delivering an increase in efficiency as described in the Stream 1 section of this report. In the off-highway vehicle archetypes, the results of this work have been very positive with a demonstrated pathway to a ~30% improvement in fuel efficiency across this the wide range of off-highway machine types tested and simulated (Table 3). Rapid deployment of these technologies is therefore an important opportunity for the UK to achieve its climate objectives.

The off-highway sector represents an extremely diverse set of machines and uses. Some carry dirt from A to B; some excavate the dirt; some plough; some harvest; and some crush rock. In each case, the definition of the work done is different and therefore creating efficiency-based legislation, analogous to the on-highway VECTO process, is extremely challenging without considering each of the many sub-markets. At the time of writing, there are no proposals within the EU to legislate for off-highway vehicle efficiency.

In the short term, without a legislative imperative, the uptake of efficiency technologies will most likely be driven by the market. The ETI work has shown that the ~30% fuel efficiency improvements can be delivered with payback times of less than 24 months and are therefore viable for the first purchaser of the vehicle. The combination of market viability and competitive forces should then drive widespread market uptake.

When considering the next step beyond efficiency, the diverse sub-sectors and uses within the off-highway sector represent a further set of challenges. For example, safety concerns over the storage of CNG on construction sites may represent a barrier to uptake of this as an intermediary fuel in some instances. Whereas, in the agricultural industry, it may be acceptable to produce and store biogas on large farms for use in tractors and combine harvesters. When considering zero (or near zero) GHG solutions for off-highway a diversification of solutions appears likely. The actual set of 2050 solutions being a function of what technologies and infrastructures are available from the automotive sectors, zero-emission (including NOx and particulate matter) requirements for city construction sites, along with the energy density and power requirements of the myriad of machine types.

Battery electric machine/vehicles are likely at the small end of the market and are starting to become available through several OEMs. Some OEMs have proposed tethered excavators (i.e. permanently connected to a source of electricity) where the machine doesn't move often but has a large power and energy demand. For those vehicles which cannot be powered directly via electricity, fuel cell power or ammonia combustion engines (as proposed for marine vessels) may become the preferred solution.

The complexity of this sector means that more work is needed. This report, therefore, recommends that this is a future research topic requiring an in-depth analysis.

Rapid deployment of these technologies is an important opportunity for the UK to achieve its climate objectives.

[15] See "HGVs and their role in a future Energy System" insight

On Highway – MGV & Bus

A clearer pathway is present for MGVs and buses where electric vehicles already have some momentum. Supported by VECTO legislation, clean air zones and grant schemes in the case of buses, this sector is the most advanced in its transition to zero (or near zero) GHG emissions. Technically, this sector should be able to decarbonise sooner due to the lower vehicle weights, lower average spends and return to base operation. This sector is better suited to battery electrification and MGVs and buses are less likely to use hydrogen fuel cells as their main source of power due to the currently relatively high cost of a fuel cell powertrain and the ability of batteries to be topped up at bus stops by adding the necessary infrastructure. Indeed, electric buses are already commercially available and electric MGVs are under development through the major truck OEMs as well as new market entrants. A rapid adoption of battery electrification in this sector would limit the need for a transition via natural gas.

On-Highway – HGV

Figure 1 shows the importance of on-highway HGVs in the UK, both from energy consumption and GHG emissions perspectives. The ETI selected the heaviest on-highway HGVs (> 33 tonnes) as an area for further work within the Stream 3 activities. This additional work allows a more detailed narrative to be created for HGVs.

Zero (or near zero) emission vehicles will certainly be required by 2050, but the characteristics of today's available technologies make the transition from today's diesel powertrains difficult while at the same time meeting performance constraints. A continued focus on improved efficiency is therefore required while developments in vehicle electrification and hydrogen supply and powertrains continue. Given the challenges ahead, there is likely to be an opportunity for a gas or gas-electric hybrid drive train[15] to emerge as a stepping stone to fully decarbonised solutions. The more detailed HGV narrative is described across three periods in Table 9.

Table 9
Pathway period 1 (2020 – 2030)

Title	Period 1: The drive for efficiency
Approx. Timeframe	2020 – 2030
Proposed Actions	To be as efficient as possible: › Optimising all levels of the system (not just those parts of the system covered by EU VECTO legislation) › Systemic improvements, aerodynamics and rolling resistance being of particular importance
Rationale	› Reduces the emissions from the combustion of hydrocarbons › Eases the transition to alternative, low GHG energy vectors in the future
Energy Vector/Powertrain Technology	Diesel via an internal combustion engine
Recommended Work	Start work on flexible, full-scale implementation plans for new low carbon energy vectors and distribution systems for on-road HDVs. This work needs to consider both public and private energy onboarding sites. Furthermore, the work must co-optimise with efforts to improve the freight efficiency of the logistics system. This will require an end-to-end appreciation and system modelling capability. The ETI has supported the CSRF to ensure that there is an organisation with this capability. See www.csrf.ac.uk. Based upon the work above, run large scale pilot projects to trial viable zero (or near zero) emission HGV options. These large scale trials are essential to determine the true impacts of particular energy vector choices, thus de-risking the large investments needed to implement full-scale infrastructures and vehicle fleets.

Table 10
Pathway period 2 (2025 – 2040)

Title	Period 2: Natural Gas and the start of the electrification journey	
Approx. Timeframe	2025 – 2040	
Proposed Action 1	Continue to improve freight efficiency	
Rationale 1	› Reduces the emissions from the combustion of hydrocarbons › Eases the transition to alternative, low GHG energy vectors in the future	
Proposed Action 2	Implement cost-effective NG vehicles and infrastructure: › Consider achieving investment payback by circa 2035. › Consider policy options to accelerate the deployment of 'best case' gas trucks and upstream infrastructure	
Rationale 2	› Provides double-digit GHG savings in a sector where fuel efficiency savings of the same magnitude are rare. › The EU VECTO target of a 30% reduction in GHG by 2030 could be achieved by combining ETI efficiency technologies, aerodynamic treatments and NG. › HGV drive cycles are more conducive to the efficient use of NG.	
Proposed Action 3	Transfer passenger car electrification technology to HDVs › Increasing vehicle electrification as costs and battery embedded GHGs reduce. Also, further decarbonisation of the electricity grid supports plug-in hybrid systems. Think about flexibility in the design of vehicles and powertrains to adapt to market and technology changes.	
Rationale 3	› These investments will be 'no-regret' because some form of electrification exists in all the 2050 scenarios. › HDVs can leverage huge investments being made in the passenger car market by using modular motors in multiples to provide the required power and torque. › In any case, investments in electrification are likely to be needed in on-highway HDVs to meet the EU VECTO targets in 2030. › Zero-emission (NOx, particulate matter, etc.) kilometres will be important in urban clean air zones. Hybrid operation supports this.	
Energy Vector/Powertrain Technology	NG and, where suitable, an NG hybrid (either mechanical flywheel, hydraulic or electric)	NG hybrid with increasing levels of electrification and battery storage within the powertrain system
Recommended Work	Continue to demonstrate key aspects of the proposed low carbon HGV systems and mature the technology. Use this information to select a system or systems for full deployment. Use the information from the pilot schemes to design and implement the necessary policies and business models. Start the process of facilitating the necessary large scale investments.	

Table 11
Pathway period 3 (2035 – 2050)

Title	Period 3: Zero (or near zero) emission HGVs
Approx. Timeframe	2035 – 2050
Proposed Action 1	Continue to improve freight efficiency
Rationale 1	› Reduces the consumption of higher cost fuels, such as electricity/hydrogen
Proposed Action 2	Transition to very low GHG emissions: › There are a number of viable vehicle and energy distribution technologies that can decarbonise the HGV fleet. The 'best' fuel vector and powertrain technology cannot be identified at this point, but all stakeholders should plan for this transition. › These very low emission vehicles will contain some degree of electrification irrespective of the end powertrain technology. This will allow some flexibility in the exact configuration of the new HGVs. › Any fuel and powertrain solutions need to be co-designed with any systemic improvements within the logistics system, i.e. a systems approach. Ensure compatibility with any pan-European approaches.
Rationale 2	› Very low GHG emission HGVs are an important and cost-effective component in the UK achieving its climate goals. › The solutions shown below all contain some form of electrification. › The UK's electricity system will likely be decarbonised in this timeframe › The logistics design affects the mass of freight hauled, vehicle speed and distances travelled. These are all fundamental inputs to the design of HGV powertrains.
Energy Vector/Powertrain Technology	Plug-in Series hybrid with NG powered range extender?
	Electricity (battery)?
	Electricity (pantograph with battery)?
	Hydrogen fuel cell with battery?
Recommended Work	Implement the full-scale roll-out plans.

Large and cost-effective efficiency gains are achievable across a wide range of HDV types.

INSIGHT SUMMARY

This insight report summarises and integrates the ETI's extensive portfolio of HDV decarbonisation projects. The decarbonisation narrative provided is intended to guide further work and drive action towards zero (or near zero) HDVs.

This report has shown:

All vehicle types

- Large and cost-effective efficiency gains are achievable across a wide range of HDV types.
- Natural gas (as delivered to the UK) can provide significant well-to-motion GHG benefits when used to power HDVs. This could be useful in the transition, but is not an end goal.
- Efficiencies and natural gas aren't enough for the UK to meet its ambitious net-zero targets in 2050. Therefore, a new, low carbon energy source is needed.
- All paths lead to some form of electrification in the powertrain. Either as a hybrid, as an electric vehicle or powered from a fuel cell.
- Hybrid powertrains will be important during the transition from fossil fuel power to a zero-carbon energy vector. Hybrid powertrains will allow time for the roll-out of any necessary infrastructure.
- Modular and cost-effective electrification components are likely to have a disruptive and positive effect on HDV design and manufacture in the future.

Heavy Goods Vehicles (HGVs)

- The EU's HGV GHG targets of 15% and 30% are plausible; this is especially true if the benefits of natural gas are permitted.
- Any NG infrastructure and vehicle investments mustn't become a barrier to a transition to zero (or near zero) GHG emission HGVs.
- Zero (or near-zero) HGVs make sense in 2050 on a carbon price basis. This is true with an 80%, UK wide, GHG reduction target (vs 1990 levels); with a net-zero GHG target, zero (or near-zero) HGVs become an imperative.
- When considering HGVs, logistics system efficiencies are important as they represent some of the largest and most cost-effective efficiency gains within the freight system. However, on their own, these actions aren't enough and must be coupled with zero (or near zero) GHG emission HGVs to achieve the UK's climate change objectives.
- The impact on the required electricity generating system capacity, whether to produce hydrogen or supply electricity directly for battery electric HGVs is relatively small, i.e. neither energy vectors require major changes to the generating system to enable them. Therefore, from an electricity generation perspective, this decarbonisation option can be invoked relatively late in the journey to meeting the UK's 2050 objectives.
- The use of hydrogen for HGVs approximately doubles the amount of hydrogen generation required compared to that used in the decarbonisation of heavy industry.
- The deciding factor for the energy vector (or vector mix), is likely to be in the cost, efficiency and roll out timeframe of the local distribution systems needed to link the national level assets to the vehicle refuelling/recharging points.
- Large-scale pilot schemes are needed as soon as possible to demonstrate and de-risk zero (or near zero) GHG emission vehicles and their associated infrastructure, including local distribution and dispensing systems. The knowledge from these pilots will be vital in developing the technologies, supply chains, business models and policies such that the UK can implement a zero (or near zero) GHG emission HGVs at a minimised cost.

Medium Goods Vehicles and buses

- Buses are already on the journey to zero tailpipe emissions (including carbon) due to concerns over urban air quality.

- The UK has trialled both battery-electric and hydrogen fuel cell buses. However, battery-electric buses are already commercial products and are more widely deployed. This trend is expected to continue with a buyer preference for battery-electric buses due to lower costs and the ability to opportunity charge their batteries on the fixed routes.
- Zero-emission bus technologies can be applied directly to medium goods vehicles; indeed, electric MGVs are under development through the major truck OEMs as well as new market entrants.

Off-Highway

- The off-highway vehicle category contains the highest variation in vehicle types and usage profiles. Therefore, it will likely have a highly stratified set of solutions. With some vehicles converting to an electric/hydrogen power source and others remaining on an internal combustion engine out to 2050.
- Continued focus on efficiency improvements, especially for those segments remaining on an internal combustion engine, is therefore essential.
- Large-scale pilot schemes are needed as soon as possible to demonstrate and de-risk zero (or near zero) GHG emission vehicles and their associated infrastructure.

ABOUT THE AUTHOR

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