An ETI Insights Report

LAND BASED HEAVY DUTY VEHICLE EFFICIENCY AT THE ETI

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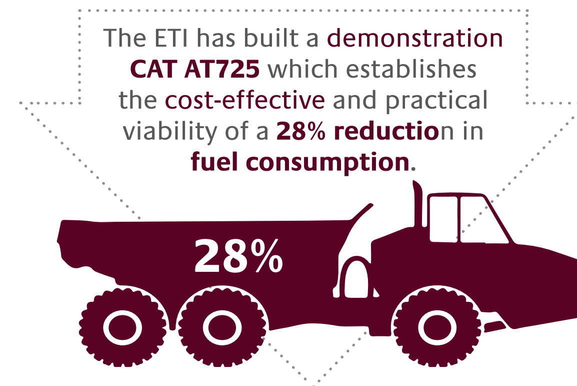
The **ETI land Heavy Duty Vehicle (HDV) efficiency** programme has modelled a range of technologies to achieve an average **18%** energy efficiency across **7 land HDVs archetypes.**

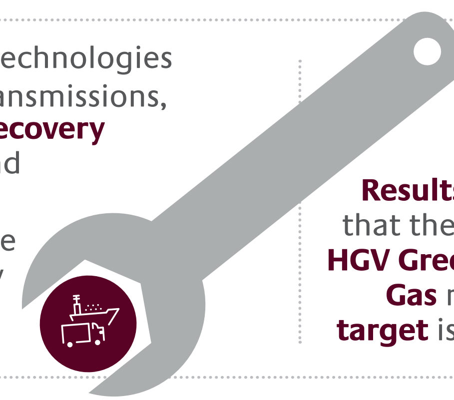
HDVs contribute around **8%** of the UK's Greenhouse Gas emissions, due to the **large quantities** of energy and power needed for **commercial operation.**

The ETI has built a demonstration **CAT AT725** which establishes the cost-effective and practical viability of a **28% reduction** in **fuel consumption.**

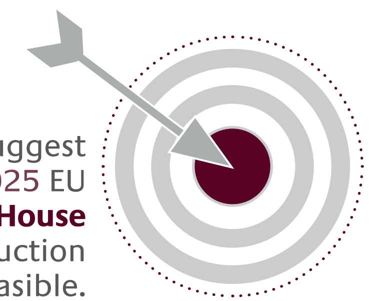


LAND BASED HEAVY DUTY VEHICLE EFFICIENCY AT THE ETI

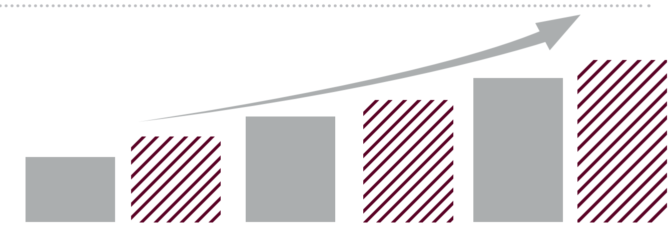
Development of technologies including CVT transmissions, **Kinetic energy recovery system (KERS)** and High Efficiency Axles can increase energy efficiency across a range of **HDVs.**



Results suggest that the 2025 EU **HGV Green House Gas** reduction **target** is feasible.



It is hoped that the research will continue to **influence** the powertrain strategy of off-highway equipment **manufacturers** like Caterpillar.



CONTEXT

At the Energy Technologies Institute (ETI), Heavy Duty Vehicles (HDVs) are defined as Goods Vehicles (GV) (both Heavy Goods Vehicles 'HGVs'[1] and Medium Goods Vehicles 'MGVs'[2]), buses, marine vessels, rail locomotives, quarry machinery, construction machinery and agricultural tractors. Traditionally, these vehicles and machines all use a diesel engine to generate the power needed to perform their myriad of functions. These HDVs are the backbone of our modern economy but represent a significant challenge when considering the UK's 2050 decarbonisation target. This challenge is due to the large quantities of both energy and power needed for the commercial operation of these HDV fleets. Such demands often exceed the capability or cost effectiveness of currently known zero tailpipe carbon technologies such as battery electric power. This 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. Whilst 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].

The first step was to create a coherent programme of interrelated technology development and demonstration projects that, when combined, targeted a 30% improvement in the efficiency of the UK's HDV fleet. The programme is subdivided into a land vehicle programme and a corresponding marine vessel programme. This insight report discusses the land vehicle portion of the HDV efficiency programme only. This encompasses GVs, buses, rail locomotives, quarry machinery, construction machinery and agricultural tractors. The land programme is largely complete with the remaining activities due to complete in quarter four of 2019.

The purpose of this insight report is to provide a narrative for both the programme approach and the high-level outcomes.

[1] Maximum Gross Vehicle Weight 17 tonnes to 44 tonnes
[2] Maximum Gross Vehicle Weight 7 tonnes to 17 tonnes
[3] As per the Climate Change Act 2008

HDV EFFICIENCY TECHNOLOGY DEMONSTRATION PROGRAMME

The land HDV efficiency programme is a £30m programme of work that targets a fuel efficiency improvement of 30% or more. This weighted average target 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 will be on sale by 2022 and that the full efficiency benefit will be delivered into the market from 2030 onwards. It is intended that these vehicles will be competitively superior products and will be purchased preferentially due to their superior economics and mission performance in use.

The programme invested in projects that were designed to accelerate key technologies into the market. The projects encouraged collaboration between academia, Tier 1 suppliers and Original Equipment Manufacturer (OEMs), thus engaging the UK's knowledge base and the HDV industry supply chain. A range of innovation barriers were considered in the design of the programme so that their effects could be minimised.

Innovation barriers

Over the past 30 years, the HDV industry has been driven by both market demands and, more significantly, criteria emissions legislation. This legislation does not focus on GHG emissions but deals with pollutants that affect human health such as oxides of nitrogen (NO_x) and particulate matter, often referred to as 'noxious emissions'. The cost associated with complying with ever more stringent noxious emission legislation has absorbed much of the development resources and budgets of many HDV research and development (R&D) departments over that period. This has led to a reduction in the capacity of these departments to innovate in other areas of performance such as fuel economy. In addition, it is worth noting that the economics of heavy-duty vehicle development and supply are also challenging given the relatively small volumes of HDVs when compared to light duty vehicles. Therefore, to overcome this lack of resources, the programme provided targeted investments to accelerate key technologies from lab proven to full scale demonstrations in their intended operating environment.

However, even the substantial funds allocated were potentially insufficient to impact all the HDV fleet. To maximise the yield from the programme it was decided that the programme would invest in key 'platform technologies'. A platform technology is defined as a technology (and its associated interfaces) that can be efficiently implemented into a wide range of products (in this case a vehicle or its powertrain). Platform technologies scale efficiently and are robust to a wide range of noise factors. This approach focussed the programme on powertrain technologies, rather than vehicle specific approaches such as aerodynamic treatments.

Another advantage of the platform technology approach was that it helped with the economies of scale. Often there are challenges within the HDV market where no single OEM or market sector has enough volume to get to the lower regions of a technology's cost curve (i.e. the theoretical cost vs volume manufactured). This creates a dichotomy where the technology is too expensive for a first mover to implement and hence it never reaches its cost potential, even though its mature volume cost would be acceptable to the market. The platform approach either allows technologies to mature in less cost sensitive market niches or allows coordination across non-competing OEMs who operate in different markets, thus, attempting to facilitate the market to overcome this barrier.

Another perceived barrier to the adoption of innovative fuel-efficient technologies was 'market risk'. HDV markets are often conservative and brand sensitive. Reliability, durability and operability are vital characteristics. To overcome this conservatism and to build confidence in all stakeholders, the ETI programme featured a large-scale demonstration of the key technologies integrated into a single vehicle application.

In summary, the HDV market is characterised by tight R&D budgets, challenging sales volumes and conservative markets. The ETI programme was designed to overcome these challenges by providing investment, engaging the supply chain, using platform technologies and demonstrating these technologies at scale. The following section details the programme structure in more detail.

PROGRAMME STRUCTURE

Background

An important input to the programme was an understanding of the GHG emissions from each of the HDV sectors. This breakdown of emissions is shown in Figure 1.

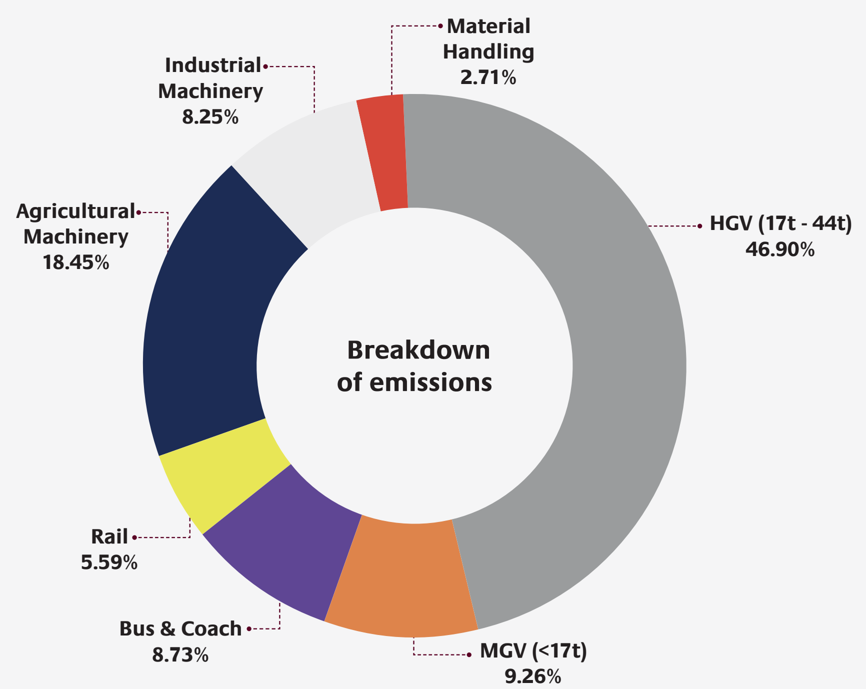
Several conclusions were drawn from this data:

- Whilst 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 was sound.
- The programme should consider technologies and integrated solutions to a range of vehicle types and usage cycles.
- Rail's contribution was small and was neglected due to other on-going initiatives, such as electrification.
- Material handling also had a small contribution and hence was not a focus of the programme.

Another consideration for the programme was how to foster innovation whilst also delivering impact. In addition to the collaborative nature of the project investment mechanism, the ETI decided to allow innovation at all 'system levels'. In other words, the programme allowed work on both new vehicle concepts as well as new component technologies.

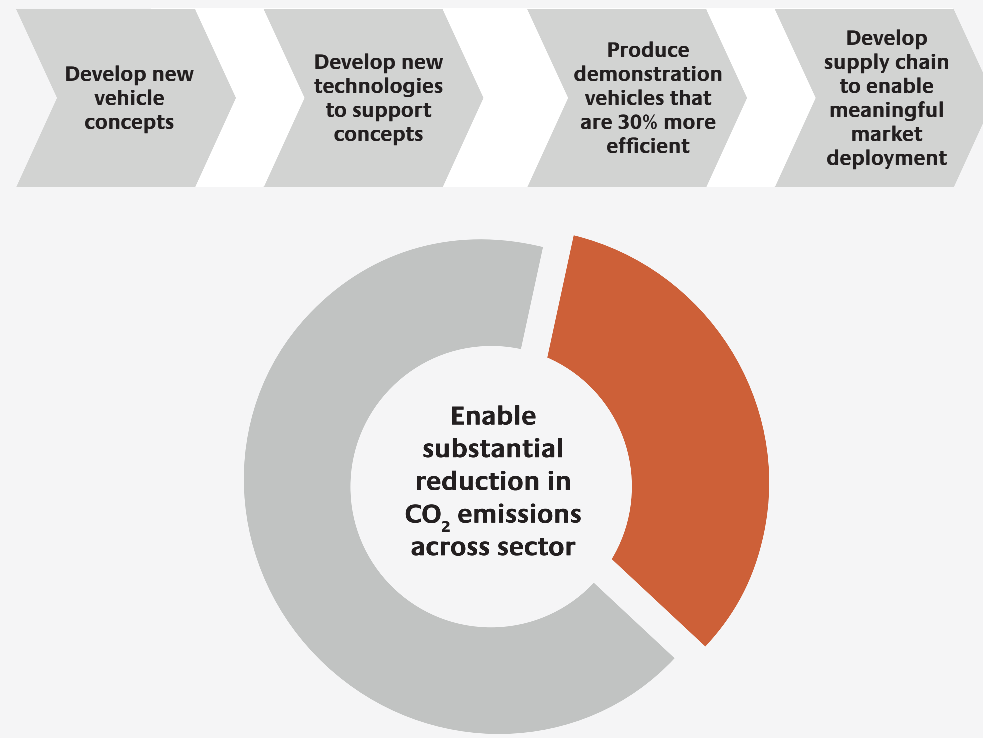
To do this the programme implemented a V-model approach where model-based system engineering (MBSE) was used to drive the engineering decision making process. Figure 2 shows a high-level view of this approach.

Figure 1
Breakdown of UK HDV emissions



Source: Ricardo Project Data (DfT & NAEI Data), CAT Phase 1 Project Data, ETI Analysis.

Figure 2
Land HDV efficiency programme approach



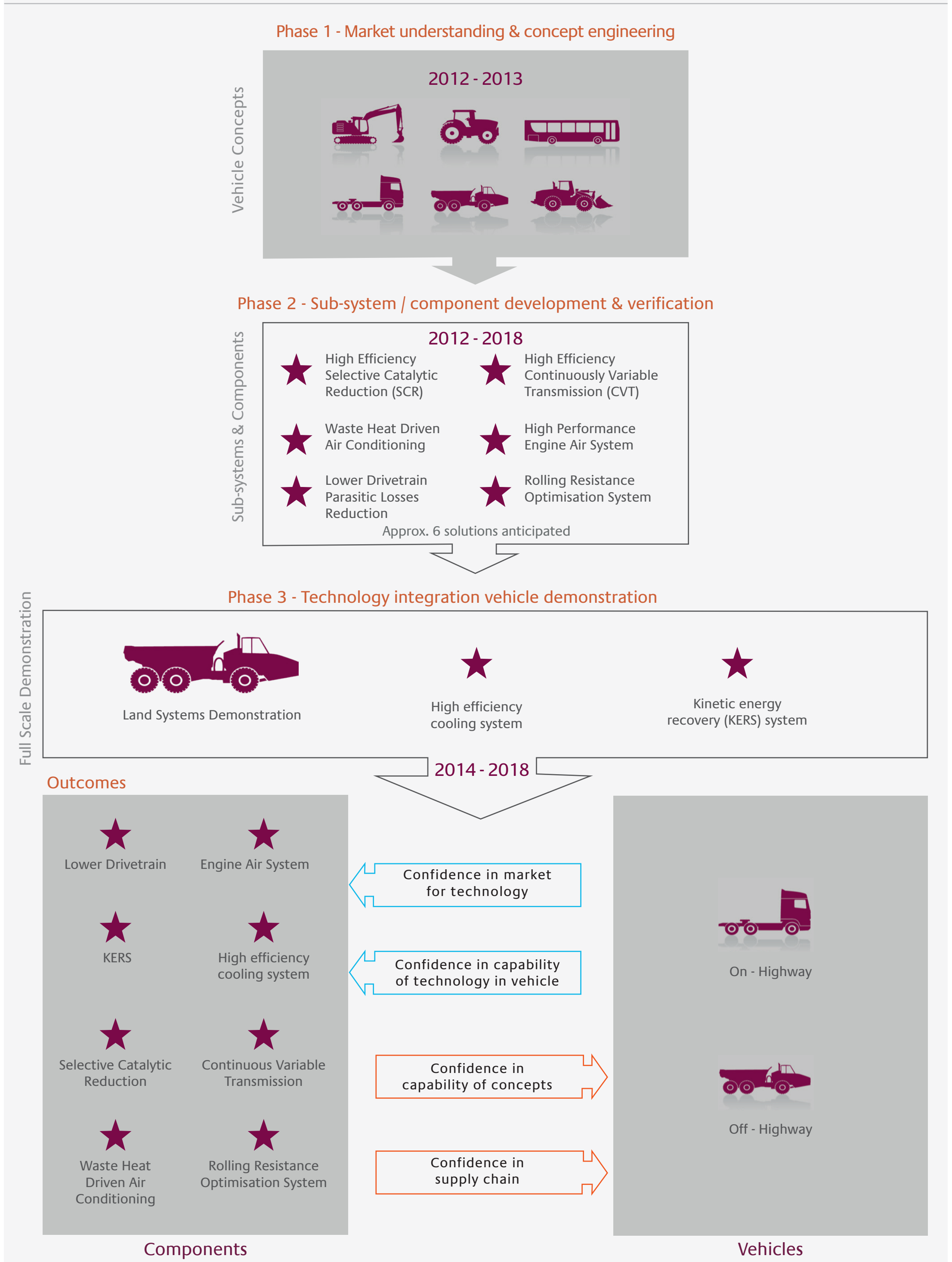
Programme in detail

The programme was split into 3 phases:

- Phase 1
  Understand the requirements of each land HDV sector (drive cycles, legislation, customer needs, etc.), whilst determining and optimising technology combinations for GHG reduction with wide market applicability using a MBSE approach.
- Phase 2
  Understand, develop, produce and verify the proposed GHG reduction technologies identified in Phase 1 at the sub system or component level.
- Phase 3
  Integrate and optimise technologies into major and whole vehicle systems. Thus, validating the true benefit of the suite of technologies.

Phase 2 was further sub-divided into six individual technology projects. See Figure 3. In addition to the technologies shown under Phase 2, several key technologies were also employed in Phase 3 and these were purchased as working prototypes or developed in Phase 3 as part of the vehicle systems integration. These included a flywheel based kinetic energy recovery unit and a hydraulic kinetic energy recovery unit.

Figure 3
Programme structure – see Appendix A for a timeline of the projects, the project participants and the amounts invested



An important first step of the Phase 1 project was to select a set of vehicles that were a proxy for the UK fleet (see Figure 4). These vehicles formed the baseline for any improvements due to the programme and a bar against which to judge the 30% improvement target. Therefore, it was vital to select both fuel efficient and popular vehicles to ensure the baseline was representative of the ‘best in class’. The selected vehicles were often worldwide or European products, and therefore, any realised fuel savings would yield GHG benefits way beyond the UK.

Each of the six vehicles were represented by a high-fidelity computer model of their longitudinal dynamics. The models included a 1-dimensional gas dynamic model of the engine and true representations of the transmission system and their respective electronic control software. These models were then compared to data, where available, to ensure they represented the selected vehicle’s performance. In the case of the DAF XF105, an HGV was purchased, instrumented and tested to provide the necessary data. This reflected the importance of the HGV sector on the UK HDV emissions (Figure 1).

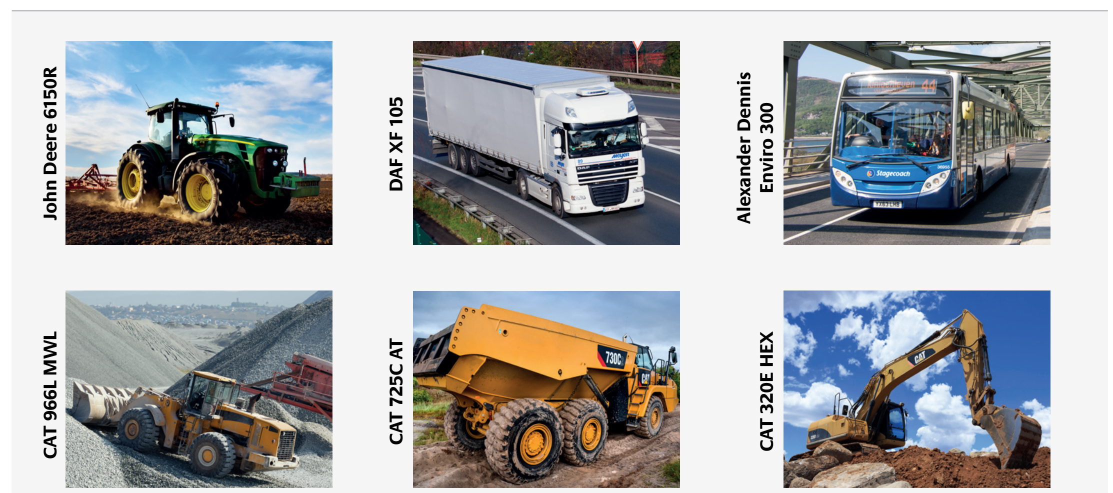
Due to similarities in the powertrain, both the bus model and the HGV model were also used to calculate a fuel efficiency benefit for the MGV sector. This was performed by using different drive cycles to better represent the MGV’s use. This resulted in a seventh, but sector generic, archetype and associated models.

The seven vehicle models were then used to perform the technology selection in Phase 1 and the sub-system / component engineering of Phase 2. In Phase 1, the baseline models were adapted to include new technologies and vehicle architectures. At each iteration the results were compared to the 30% fuel efficiency target as well as the market requirements (e.g. cost, productivity, emissions, etc.) until an optimum set of architectures and technologies were identified.

In Phase 3, only the Caterpillar AT 725 articulated truck was built as a full physical demonstration. This was due to the costs associated with purchasing the various technologies and integrating them onto a vehicle. The Caterpillar AT 725 was selected because it represented the most challenging application of the vehicle architecture, sub-systems and components, thus providing the most rigorous technology verification platform. However, lessons learnt from the real demonstration of the AT 725 have been fed back into the models of the other six vehicle types.

The resulting programme was unique in its ambition, depth and breadth.

Figure 4
Vehicles selected to represent the UK HDV fleet



PROGRAMME RESULTS

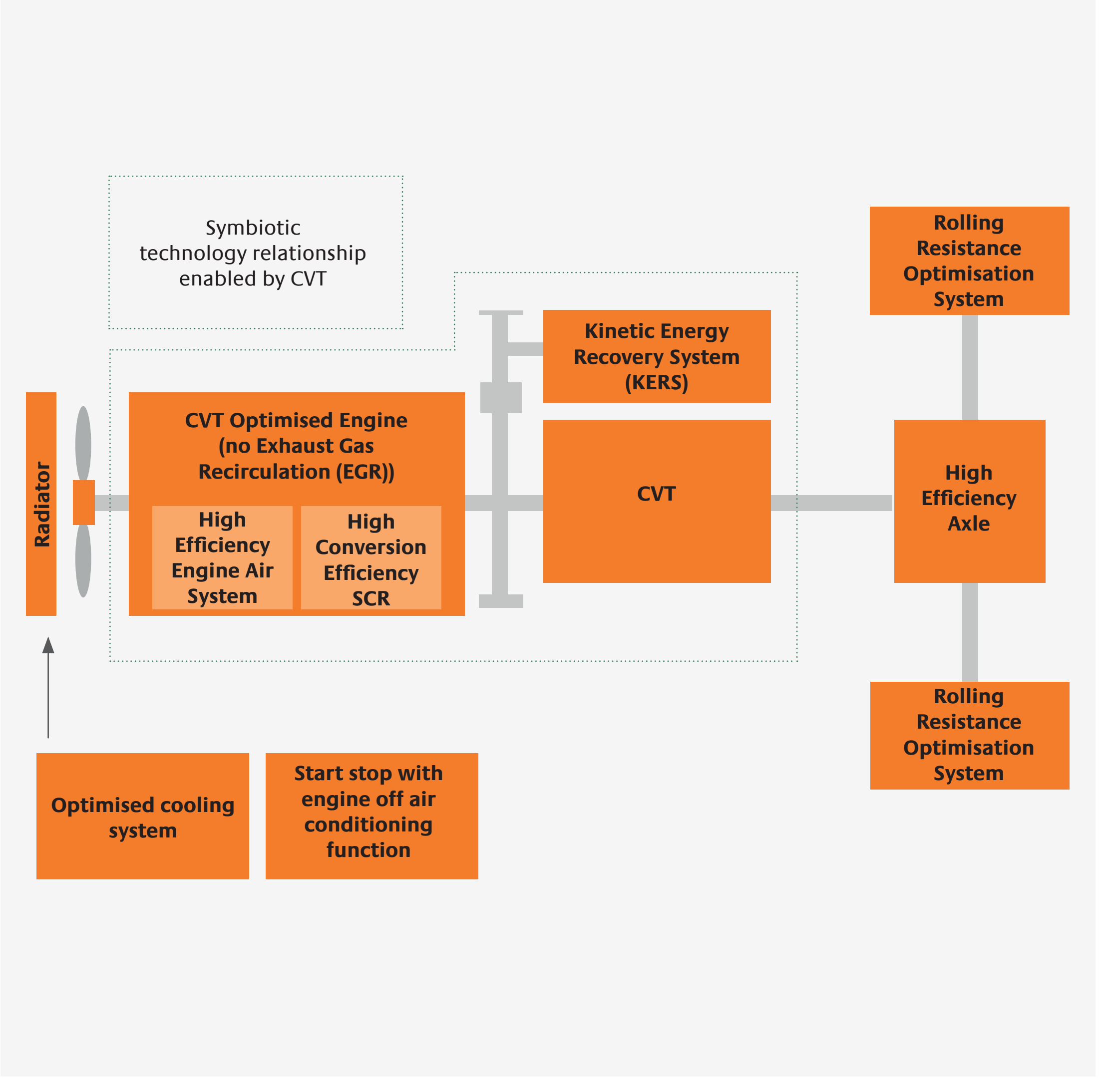
Phase 1

The output of Phase 1 was seven vehicle powertrain architectures and a corresponding list of key platform technologies. Not all the technologies were deployed in all the seven vehicles, however, there was a high degree of commonality.

Figure 5 shows a schematic of the proposed DAF XF105 HGV powertrain architecture (i.e. the 'New Concept HGV' or NC-HGV) and Table 1 provides a complete list of the technologies deployed on each of the seven vehicle architypes.

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

Figure 5
NC-HGV powertrain architecture



This architecture has several symbiotic benefits such as:

- The engine is operated at its most fuel efficient point irrespective of vehicle speed (also known as the most efficient 'running line').
- The resultant running line also provides a better match between engine and turbomachinery characteristics.
- The air flow through the engine is better matched to power demand which results in higher average exhaust temperatures. Higher exhaust temperatures are good for the real world performance of the Selective Catalytic Reduction (SCR) system (a key component in managing the NO_x emissions from the powertrain).
- Smaller speed range at the KERS connection point, resulting in a cheaper KERS system and higher KERS round trip efficiency.
- No torque interrupts during gear changes due to the CVT, thus allowing KERS charging/discharging at any time, maximising yield of the KERS.
- Smaller engine speed range resulting in lower ancillary parasitic losses.

The downside of the proposed architectures was the inefficiency of the CVT. Hence, the challenge was to derive more benefit from the system effects of the CVT whilst attempting to maximise the efficiency of the CVT used. The balance of these effects was dependent on the vehicle usage cycle. Whilst transient cycles such as off-highway vehicles or buses yielded excellent results, the HGV vehicle was more of a challenge, especially when cruising at constant speed on the motorway.

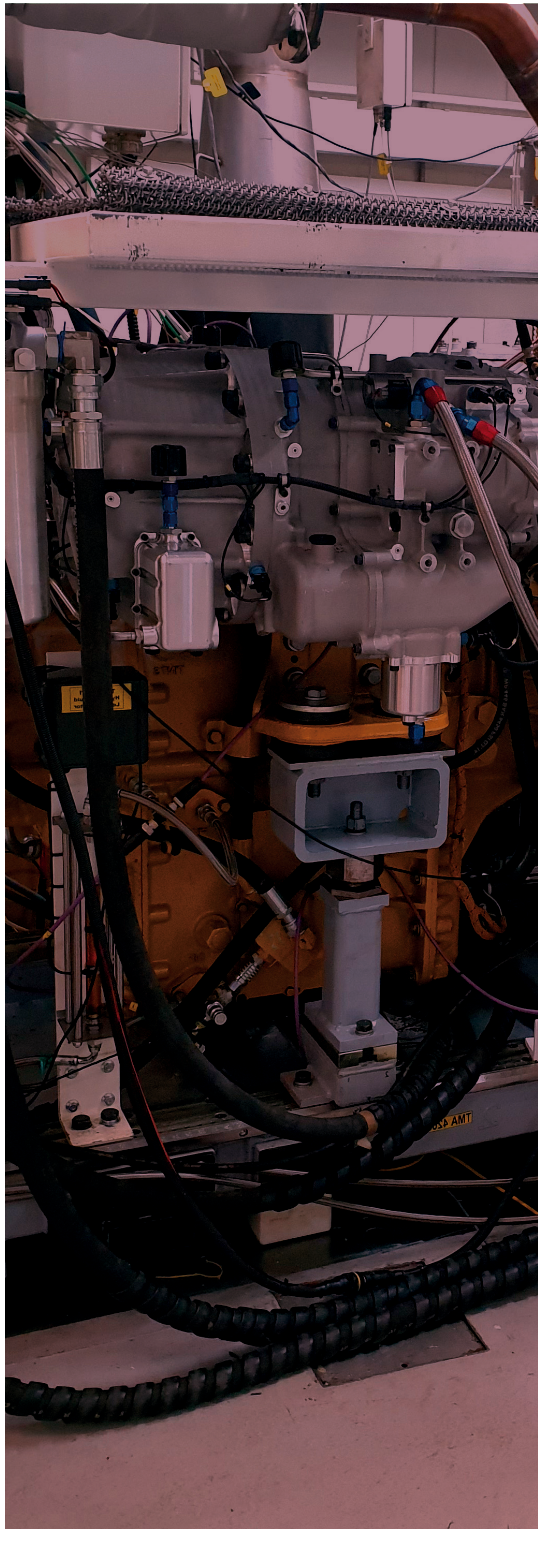


Table 1

Vehicle	Key Platform Technologies								
	Engine (with no exhaust gas recirculation): High Efficiency Selective Catalytic Reduction (SCR) (circa 98% conversion efficiency); High Efficiency Engine Air System (EAS)	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

As can be seen in both Figure 5 and Table1, the vehicle concepts do not contain any electrification technologies or components. Over the period of the Phase 1 work (2012 – 2013), electric storage of recovered kinetic energy was carefully considered as a potential technology but, over the 2022 – 2030 timeframe, was predicted to suffer from high costs, low power density, lower life (than the vehicle) and poor performance in low temperature conditions (< -20°C). The ETI concept, therefore, attempts to maintain as much of its energy in a mechanical form to minimise the inefficiency of repeated conversions of energy from one type to another.

Whilst many of the challenges of electrifying HDVs remain, huge gains have been made in the last six years in the cost and power density of the necessary electric components. As volumes increase and significant passenger car R&D funds are spent, the view on electrification continues to improve. The ETI's latest assessment on the cost of batteries and motors can be found on the ETI Knowledge Zone.

In September 2015 the Volkswagen diesel-gate scandal became public. For the passenger car sector this resulted in an acceleration in the implementation of policies to enforce low emissions and hence accelerated investment in the electrification of vehicle powertrains. This scandal also accelerated and strengthened the ambition of EU policy on regulating GV GHG emissions in Europe. 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. The legislation also promotes zero tailpipe emission trucks through a temporary credit system.

Phase 2

As mentioned previously, Phase 2 consisted of six technology development projects. The technologies and their specifications were derived from the Phase 1 work. Of the six projects contracted, four were completed successfully. These successful projects included High Efficiency Selective Catalytic Reduction (SCR), High Efficiency Engine Air System (EAS), CVT transmission and High Efficiency Axle. The unsuccessful projects included Rolling Resistance Optimisation System (RROS) and Waste Heat Driven Air Conditioning.

The RROS project originated as a concept from Phase 1 and was patented. The cost-effective concept allowed the tyre pressures of an HDV to be modulated and thus optimised whilst the vehicle was in operation, resulting in lower rolling resistances. The RROS project halted at the concept development stage due to a lack of industry engagement. However, the benefits of the concept are still included in the fuel efficiency calculations despite the lack of a physical embodiment.

The Waste Heat Driven Air Conditioning project utilised an absorption process to store energy and provide cooling from the low-grade waste heat in the exhaust system post the engine after treatment. This project was stopped as the technology could not be made small enough to be viable and was replaced with an alternative approach that utilised a cold store to provide cold air during periods when the engine was shut off by the stop / start system. This alternative approach was delivered as part of the Phase 3 project.

Any project that had the potential to impact on the legislated emissions of the engine (noting that HDV emissions are measured over an engine cycle not on a vehicle basis) was mandated to meet the EU6/Stage IV standards over the legislated cycles and to exceed the standards over real-world cycles[4]. This correct decision was taken pre the Volkswagen scandal and prior to more recent legislative proposals. The project also monitored N_2O to ensure that this powerful GHG did not eradicate any fuel efficiency benefits.

[4] This was achieved by lowering the Work Based Window (WBW) threshold from 20% to 10% of the rated power whilst reducing the allowable emissions factor from 1.5 to 1

Phase 3

During Phase 3 the computer models of the seven vehicle types were maintained and used to develop and debug software using a Software-in-the-Loop (SiL) process. In addition to these computer models, two main testing platforms were used to mature the technologies and drive their integration.

Firstly, a drivetrain simulator (DTS) rig was built and commissioned. This rig is based at Caterpillar's facility in Peterborough, UK and consists of a 4-quadrant electrical dynamometer. This rig has the capacity to mimic the vehicle dynamics and lower drivetrain of any number of HDVs in a Hardware-in-the-Loop (HiL) environment. The engine, CVT transmission and KERS system are all present within the test cell, whilst the lower drivetrain, axles, wheels and vehicle dynamics are simulated by the electrical machine and a real time model. Figure 6 shows the engine, transmission and hydraulic KERS in yellow and the electrical dynamometer in white.

Secondly, a range of Caterpillar AT725 vehicles were modified in stages to add and integrate the technologies in a stepwise manner. This allowed any issues to be identified and rectified prior to the addition of further technologies. Cooling system and oil specification changes were verified in Malaga, Spain and vehicle performance testing was conducted at various sites in the UK. Figure 8 shows a prototype AT 725 under test in a quarry near Peterlee, UK.

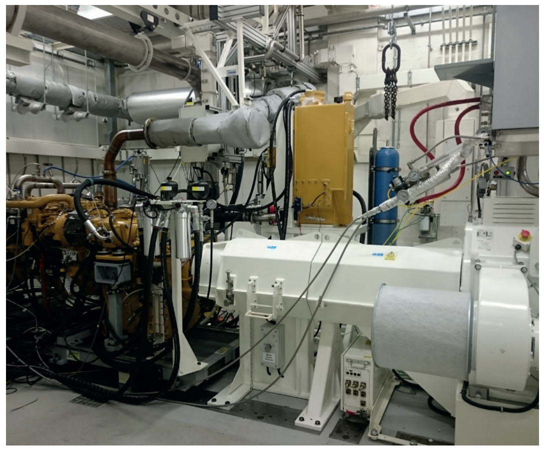
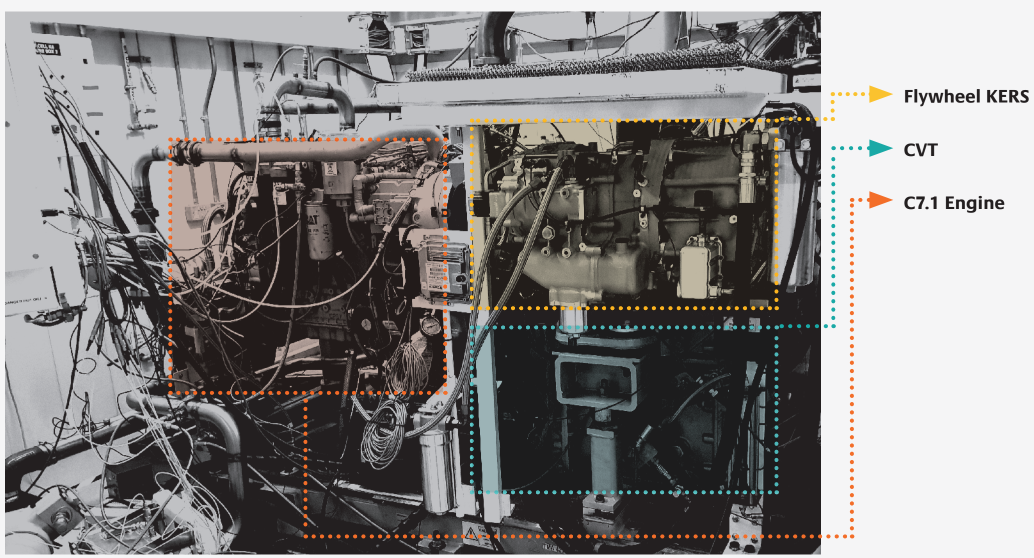


Figure 6
Drivetrain simulator (DTS) Rig, Peterborough, UK. The same DTS rig set-up was also used to test the flywheel KERS, see Figure 7

Figure 7
DTS rig with flywheel KERS fitted alongside Caterpillar C7.1 engine and CVT transmission



HGV due diligence and simulation support

During Phase 3, it became apparent that the fuel efficiency benefit of the NC-HGV was particularly sensitive to its use. This was because the benefit of the platform concept during steady state motorway operation was marginal. Therefore, two additional pieces of work were commissioned. Firstly, Element Energy were contracted to quantify how GVs are actually used in the UK by using anonymised telematics data from thousands of GVs.

Secondly, AVL UK worked to re-create computer models of both the baseline HGV vehicle as well as the NC-HGV. AVL has a wealth of expertise and experience in HGV vehicle engineering and could therefore verify that the fuel efficiency of the project baseline was both representative and competitive. These models in combination with the Element Energy project were then used to provide a second opinion on the benefit of the technologies proposed. These verified results are shown in the results section below.

Results - Overall Fuel Efficiency Benefit

The target for the programme was to deliver a 30% reduction in fuel consumption. Table 2 shows the actual performance achieved. 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 also shown in Table 2.

Figure 8
Prototype AT 725 test truck under test in Peterlee, UK

Table 2
Results table for 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, whilst significant, was lower than targeted. This results in a circa 18% improvement across the fleet when weighted by the current emission contribution of each vehicle archetype. This is less than the programme target and is largely due to the lower than desired results in the highly weighted HGV sector. Therefore, the HGV sector warrants further discussion.

HGV results in more detail

As mentioned previously, early work had shown that the fuel efficiency benefits of the NC-HGV proposed for the HGV were very sensitive to its use. The main parameters of concern included the payload carried, the aerodynamic drag and the type of roads travelled (e.g. motorway vs rural vs urban). The following section considers the roads travelled.

HGV use in the UK

In 2013, and in the absence of publicly available data, two routes were selected as typical of UK HGV driving. These routes were then used to collect data from an instrumented DAF XF105 HGV over a period of two weeks. Figure 9 and Figure 10 show the routes selected. A 26-minute 'ETI' cycle was then generated that best represented the two weeks of data with respect to speed, acceleration and gradient. It was recognised that this cycle wasn't statistically representative of UK use and was potentially biased to motorway and hence high-speed driving. This cycle predates the EU VECTO long haul cycle, which wasn't available at the outset of the programme.

To address the concern of a lack of statistical validity, Element Energy were commissioned to conduct a study to determine how GVs are used in the UK using pre-existing telematics infrastructure and data. The details of this work can be found in the ETI's 'HGV Use in the UK' report.

Despite significant efforts, it wasn't possible to obtain a sample of telematics data that accurately represented the population of HGVs within the UK fleet. However, data from around 4,500 GVs was used to provide statistics on daily distances, speed distributions and fuel consumption. The data was grouped into differing wheel plans and types of operation. Figure 11 shows the median of all three axle articulated HGVs, that is the heavier trucks that contribute most to GHG emissions, and speed histograms for the World Harmonised Vehicle Cycle (WHVC), the FIGE cycle (FIGE Institute

Figure 9

Route 1: Ashford to Northampton (and back)

Figure 10

Route 2: Newcastle to Sheffield (and back)

Aachen), the EU Vehicle Energy Consumption Calculation Tool (VECTO) long-haul cycle (as of 2016)[5] and the ETI cycle.

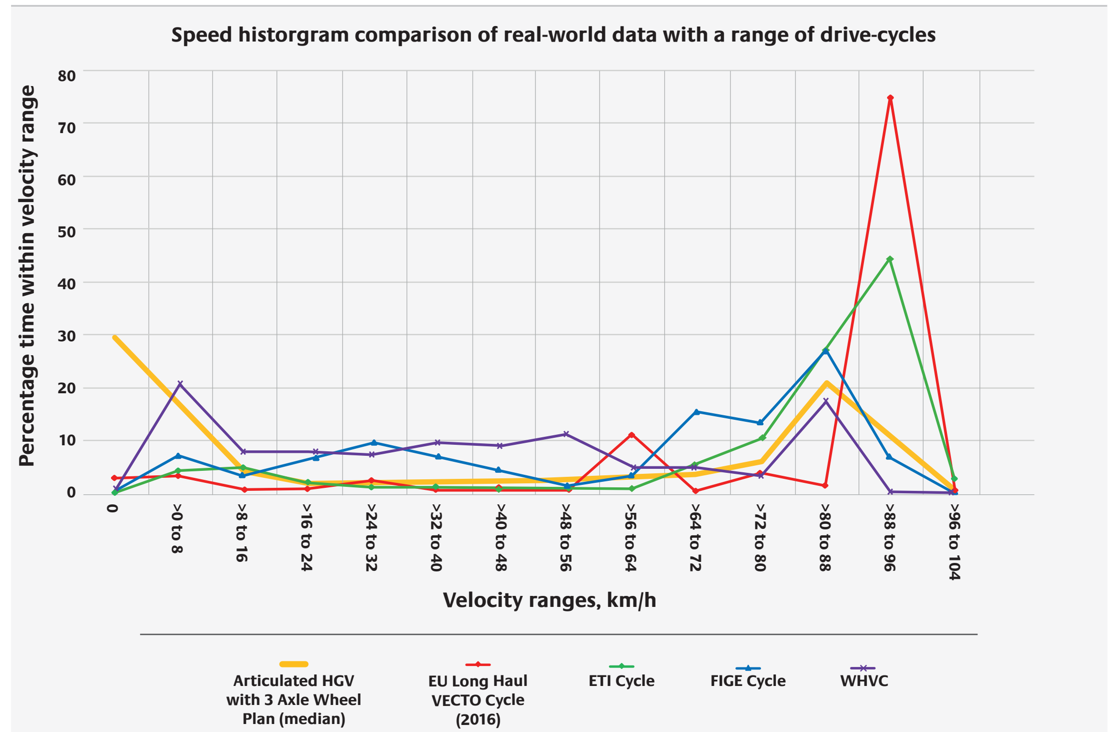
Several conclusions can be drawn from Figure 11, firstly the telematics data contains a high proportion of stationary and very low speed operation. This was not expected at the outset of the work and the data available could not be used to determine the reasons for this stationary and slow speed operation. Therefore, further work by others is needed to determine the cause and its significance with respect to GHG emissions. Secondly, other than the slow speed operation, the ETI and VECTO cycles represent the mix of speeds seen within the real-world data and therefore cannot be discounted for assessing the fuel efficiency of the NC-HGV. Given that the histograms all add up to 100%, the differing slow part of the histogram results in an increase in the difference between the histograms elsewhere. In the case of the ETI cycle and VECTO cycle, these results in those cycles having a higher proportion of time at high speed, this is directionally correct because most of the fuel is consumed at higher speed so weighting the cycle towards this area of operation drives the correct technology choices and optimisations. However, should the GV be used in a mix of urban, rural and motorway environments then the FIGE and WHVC should be considered.

Therefore, the results shown in Table 2 use the ETI and the FIGE cycles to show the likely range of performance to be achieved during real-world use.

Element Energy's work has shown the value of using telematics data to better understand the real-world use of HGVs. This work was limited by the frequency of data available via current telematic systems. However, data rates will improve in the near future and this will allow a more detailed analysis of GV usage.

Figure 11

Comparison of real-world HGV usage with the cycles used within AVL-CRUISETM to assess the benefit of the NC-HGV vehicle



[5] The 2016 VECTO long-haul cycle was used and is shown in Appendix B for completeness

HGV fuel economy results

As mentioned previously, the results shown in Table 3 were generated by AVL using AVL-CRUISE[M] models. The baseline HGV model was calibrated to publicly available data and measurements taken from a DAF XF105 HGV and the NC-HGV model to test results from the new technology projects. The modelling work also considered all the aforementioned drive-cycles as this work was conducted in parallel with that of Element Energy. 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+ timeframe.

Table 3
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

As can be seen from Table 3, the results vary across the cycles, but to a lesser degree with vehicle mass and aerodynamic drag. The cycles that contain more transient use yielding larger benefits than those which contain lots of constant speed driving. It is also worth noting that if the benefits of the 25% aerodynamic drag improvement are included with the other changes then the concept achieves between 13.7% and 15.8% over the EU VECTO long haul cycle (2016). Thus, 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.

Table 4
Technology benefit analysis, figures only valid in left to right sequence shown

		Technology, Percentage Benefit							
		25% drag reduction	RROS	CVT	Engine (SCR & EAS)	High Efficiency Axle	Optimised Cooling and Engine Off HVAC	Flywheel KERS	Start/Stop
Drive Cycle	ETI Cycle (Motorway)	6.9	2.5	-4.1	4.7	1.2	0.9	1.2	0.0
	VECTO Long Haul (2016)	7.5	2.7	-2.8	4.0	1.1	0.8	0.8	0.0
	FIGE	6.5	2.9	-1.2	6.4	0.9	0.9	1.0	0.3
	WHVC	3.5	2.1	-0.2	4.3	0.7	1.2	6.1	0.8

As stated previously, the NC-HGV contains several symbiotic system interactions, therefore, determining the value of individual technologies is difficult and needs to be considered carefully. The percentage benefits in Table 4 are only valid for the left-to-right sequence shown and represent the results from a piecewise modelling study whereby the individual technologies are added to the model one-by-one. For example, the CVT benefit shown is in the context of lower aerodynamic drag and tyre rolling resistance, but with the standard engine, axle, cooling, without a KERS and no start/stop functionality. The numbers can only be used in this context.

Table 4 shows that in the drive cycles with lots of high-speed cruising the CVT results in worse fuel economy and whilst it does enable some of the subsequent engine benefit, it does not enable a huge fuel saving from the KERS system. The poor KERS performance was due to a lack of braking events that charge the KERS and energy was also lost maintaining the minimum speed of the flywheel (so that it can accept charge). These ‘spin-down’ losses could be better managed through integration with a truck’s Global Positioning System (GPS) and front radar whereby the flywheel is deactivated on long, flat and open roads. However, this wasn’t implemented within the modelling study. Across all the drive cycles the KERS achieved a round-trip efficiency ranging from 50% to 55%. The KERS becomes very beneficial during the WHVC due to the number of braking events and higher proportion of urban and rural driving.

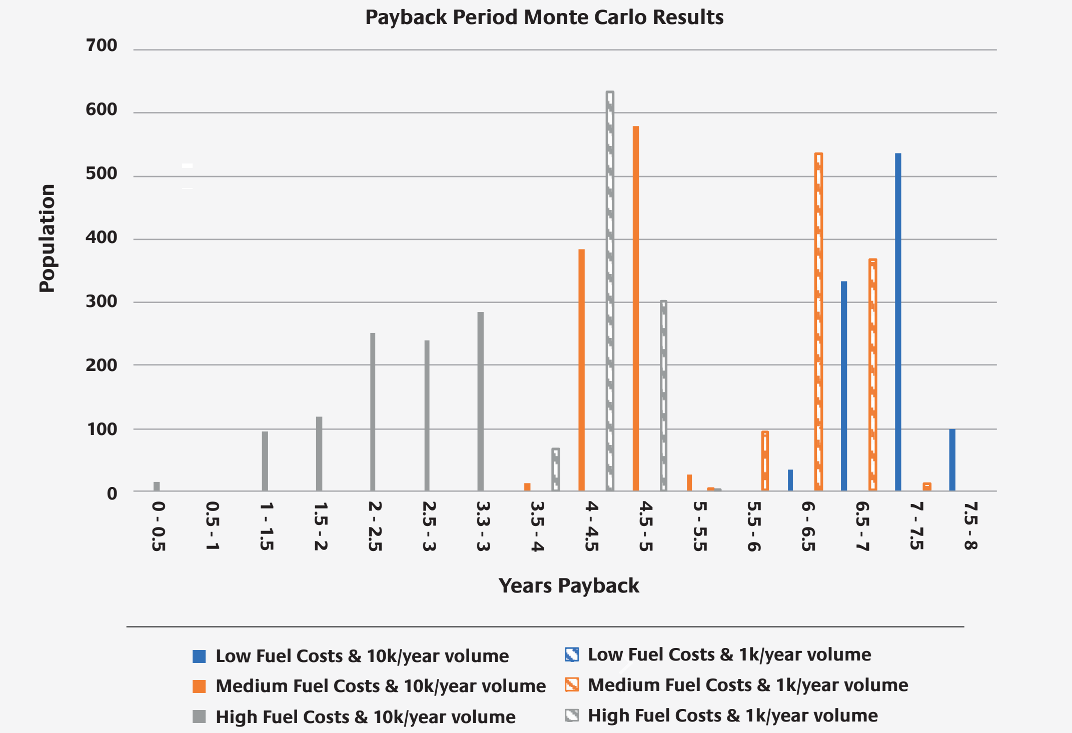
Table 4 also shows that the value of technologies and integrated systems is dependent on the usage assumptions. Therefore, the ETI is supporting on-going work at the Centre for Sustainable Road Freight (www.csrf.ac.uk) to better understand how GVs are used and will be used in the future.

Results – Payback Period

The results shown in Table 3 are lower than that required to achieve the 30% target set at the outset of the programme. However, back in 2010 and prior to the EU GHG legislation, the programme set a secondary objective whereby any fuel efficiency gains had to make economic sense to the vehicle purchaser. The intention was that economic superiority would drive uptake even in the absence of policy or legislation. The desired payback varied from market to market and was most challenging in the HGV sector where the target payback period was set at 2 years. This is no longer the case for on-highway vehicles as the EU has now implemented a GHG legislative framework. However, payback periods are still relevant as a measure of the success of the work and the economic impact of the EU legislation.

Given the uncertainty involved in a payback calculation, a Monte Carlo based study was used to calculate the likely payback period for a range of different scenarios. The calculation considers the purchasing price, financing costs, second-hand value, operating costs, and more, whilst comparing a ‘do nothing’ baseline case with an NC-HGV purchase. The costs for the NC-HGV technologies are based upon information provided by programme participants and their suppliers. Where possible costs were requested across a range of manufactured volumes (i.e. the unit cost when buying 10,000 units should be cheaper than when buying 1,000 units). The analysis considers the purchase in the 2022 timeframe. The results are shown in Figure 12.

Figure 12
Payback period estimates for the NC-HGV (as per Figure 5) across varying fuel costs, mileages and manufacturing volumes



	Low Fuel Costs	Medium Fuel Costs	High Fuel Costs
Fuel Price, p	114	123	128
Annual Mileage	70,000	85,000	100,000

The NC-HGV pays for itself within the desired two-year period for 23% of the Monte Carlo runs when:

- the fuel efficiency benefit is assumed to be the average of the ETI cycle and the FIGE cycle at a Cd of 0.53;
- the fuel efficiency results from each cycle are an average of the 25% and 75% payload results (i.e. 23.9 tonnes and 36.9 tonnes respectively);
- the technologies are manufactured in reasonable volumes; and
- the high fuel costs scenario is considered.

The payback starts to exceed the useful life of the vehicle only when fuel costs are low and technology volumes are also very low. Please note that Figure 12 shows the payback calculation for the NC-HGV without any optimisation.

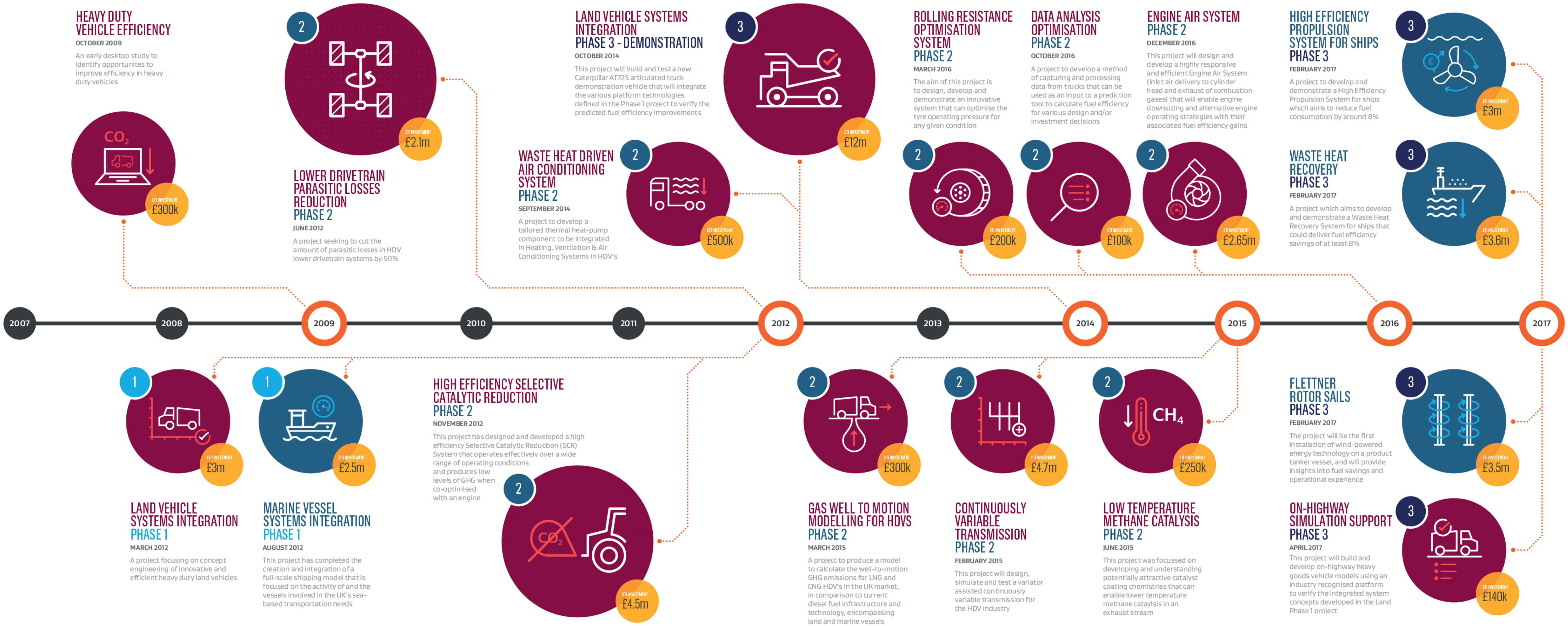
Table 4 shows that there is scope to significantly improve payback periods if a vehicle usage type and therefore, drive cycle is known. For example, removal of the KERS if the HGV operates solely on uncongested motorways.

SUMMARY

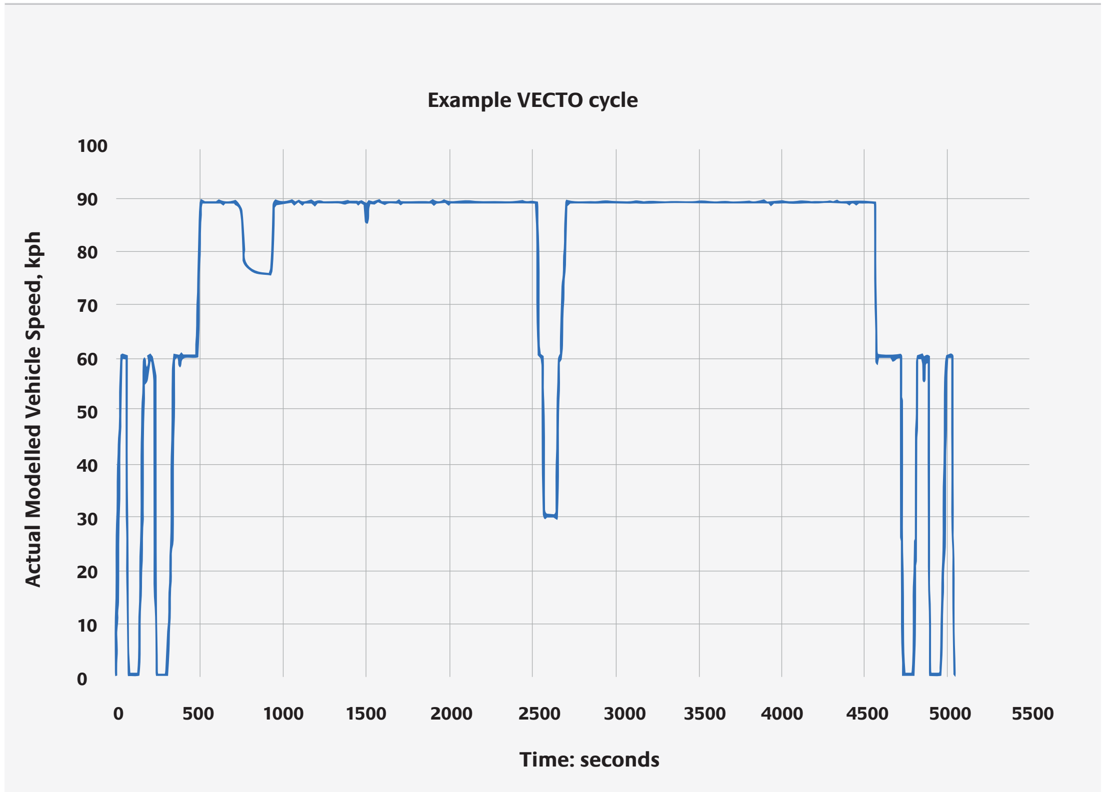
The ETI has conducted a programme, unique in its breadth and depth, that attempts to deliver a meaningful impact in the fuel efficiency of the HDV fleet in the UK. The ETI hopes that the programme has the following long-term impacts:

- It will continue to influence the powertrain strategy of Caterpillar, the world's largest off-highway equipment manufacturer.
- It shows the fuel efficiency gains that can be achieved across a range of vehicle types and that these gains can be financed by the fuel savings. In some instances, the payback period is acceptable to the first purchaser and, in those instances where they are not, the payback period is within the economic life of the vehicle.
- The results achieved suggest that the 2025 EU HGV GHG reduction target is feasible, thus supporting the stringency of this target.
- That more publicly available research is conducted on HGV movements and payloads to enable better research, technology developments and policies going forward (the ETI's support for the Centre for Sustainable Road Freight is an example of this).
- That the work shows the challenge of delivering double digit powertrain fuel savings on HGVs as their powertrains are already well optimised for the motorway use that they often see. Thus, accelerating the implementation of lower carbon fuels or energy carriers as the only practical way of delivering significant (i.e. in excess of 15%) GHG reductions in the mid to longer term.

APPENDIX A – HDV PROGRAMME TIMELINE



APPENDIX B – HGV LONG HAUL VELTO CYCLE USED



ABOUT THE AUTHOR

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Between 2016 and 2019, Chris has been the ETI's Chief Technology Officer for Heavy Duty Vehicles. Previously, Chris has been Heavy Duty Vehicle Strategy and Programme Manager at the ETI.

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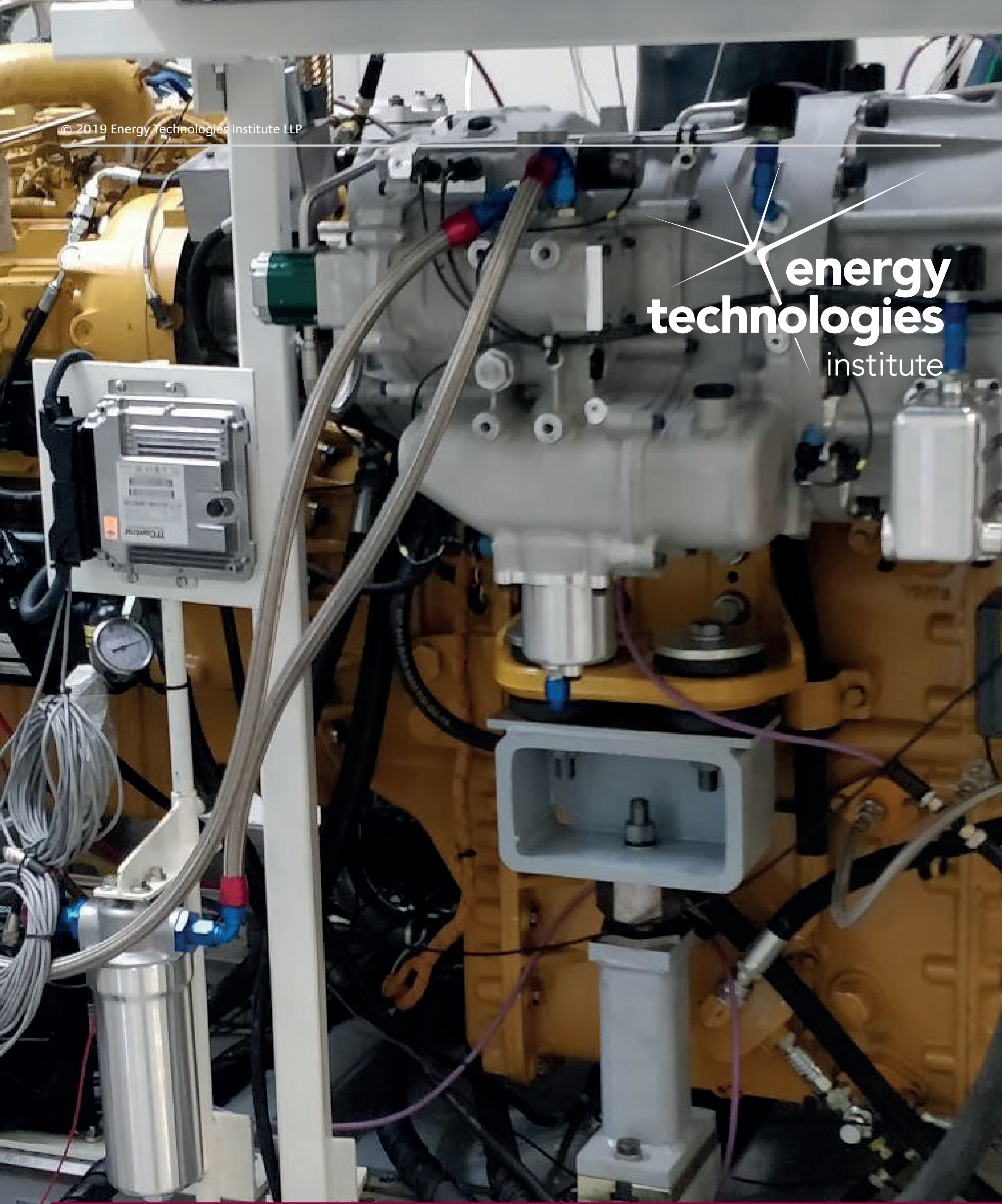

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