DECARBONISING ROAD FREIGHT
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Executive Summary

In 2019 a collaboration between the Energy Systems Catapult (ESC), who predominantly have an interest in ensuring the UK’s energy system is sustainable and resilient in the future, and the Advanced Propulsion Centre (APC), who are supporting the transition of the UK’s automotive sector into a low carbon one, was formed. Under the UKERC Whole Systems Networking Fund a project was developed to provide insight and knowledge to define a cost-effective pathway to decarbonise road freight across the UK’s transport and energy systems.

The aim of the Decarbonising Road Freight project was to explore pathways for reducing emissions from the freight sector with a focus on heavy goods vehicles (HGVs). The objective of the work was to improve the understanding on the different options for reducing emissions and to collect input data for the modelling activities. Two workshops were organised with representatives from industry and academia from both the ESC and APC networks. The workshops provided a qualitative view on the problem of decarbonising HGVs which were converted by the project team into modelling scenarios.

Following alongside the workshops, a literature review was conducted to collect data on vehicle technologies and the required infrastructure that could be used from today to 2050. The literature review identified the lack of data across many of the areas explored by the project. Most of the literature was focussed on passenger vehicles, vans and in some cases buses. While some information was available for conventional powertrain technologies, data on new technologies such as fuel cell technologies, data on new technologies such as fuel cell information was available for conventional powertrain vehicles, vans and in some cases buses. While some project. Most of the literature was focussed on passenger lack of data across many of the areas explored by the

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Based on the workshop and literature review findings the modelling approach was adapted to reflect the objectives of the project. It was identified by the project team that a more detailed model of the HGV sector would need to be developed to reflect the operators’ choice when selecting fleet vehicles as a pure techno economic approach would not capture many factors affecting the decision and represent the diversity within the sector.

The energy system modelling environment (ESME) model was used to interpret the formulated scenarios and to show the impact that decisions within the freight sector would have on the energy system. In addition to this, the Energy Technologies Institute (ETI’s) Gas Well to Motion (WtM) model was used as the basis for developing a prototype Freight model. The Freight model used the choice model and total cost of ownership (TCO) objective function from the Gas WtM model to simulate HGV vehicle parc. New powertrains and infrastructure were added to capture a wider range of technologies.

The ESME results gave a whole energy system view of the effect of the different scenarios whereas the Freight model provided a detailed look into the vehicle parc. The results were able to illustrate the impact that decisions on the different options for reducing emissions had on the freight sector and the UK energy system.

The following key points were observed:

- Business models: The shift demand scenario reduced emissions not only from the HGV sector, but the road freight sector overall by about 10% without the need for additional policies. This shows that new business models could have a role to play in the decarbonisation of the transport sector, but the additional infrastructure to support the increased number of medium goods vehicles (MGVs) and light goods vehicles (LGVs) will have to be further explored.
- Powertrains: The introduction of new powertrains and vehicle categories optimised to operators’ usage and the updated techno-economic data affected the ESME modelling results. Quantification of these impacts will need further investigation. Electric vehicles are more cost competitive compared to hydrogen powertrains. To support uptake of hydrogen vehicles in the HGV sector efforts should be made to reduce technology costs. Further to cost reductions, other factors related to the operation of vehicles should be considered. Diesel fuelled vehicles with improved emissions could be used as transition vehicles.
- Infrastructure: As with the vehicle costs, higher infrastructure costs for hydrogen resulted in higher operator costs. Based on a mix of generation technologies, the commodity price of hydrogen was comparable to the electricity price. High CAPEX costs for the refuelling stations increased the fuel price the operators will see resulting in lower uptake of hydrogen vehicles. Similarly, catenary vehicles were not cost competitive because of high infrastructure costs.
- Policy: Enforcing stricter regulations on emissions could facilitate the quickest transition to a zero emission HGV fleet, leading to a zero emission vehicle parc by 2050. The methods by which policy can support operators in the transition to zero emission powertrains and mechanisms to ensure infrastructure is in place need consideration.

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# Contents

1 Introduction 10
  1.1 Background 10
  1.2 Scope of the project 11

2 Workshops 12
  2.1 Vehicle life 13
  2.2 Suitable technologies for Heavy Goods Vehicles 14
  2.3 Infrastructure and air quality 14
  2.4 Energy system decarbonisation 15

3 Literature Review 16
  3.1 Battery electric vehicles 16
    Battery costs
    Powertrain efficiency
    Battery size
  3.2 Catenary electric vehicles 18
    Battery size
    Infrastructure
  3.3 Fuel cell vehicles 18
  3.4 Future internal combustion engines 19
    Diesel fuelled engines
    Methane fuelled engines
    Powertrain cost
    Aftertreatment
    Commodity prices
  3.5 Challenges 20

4 Modelling 22
  4.1 Methodology and Modelling tools 22
    Methodology
    Energy Systems Modelling Environment (ESME)
    Gas Well to Motion model (WtM) and Freight model
    Vehicle cost model
  4.2 Assumptions 28
  4.3 Scenarios 30
  4.4 ESME results 31
  4.5 Freight Model results 35
  4.6 Discussion of results 44

5 Conclusions 46
  5.1 Key learnings 46
  5.2 Limitations and barriers 49

6 Future research opportunities 50

7 Future Collaborations 52

8 UKERC Whole System Network Funding 54
  8.1 Gender balance 54
  8.2 Impact for whole systems energy research 55
  8.3 New voices 55
  8.4 Not business as usual 56
  8.5 Measures of success 56
  8.6 Authors 57

9 Appendix 58
  References 58
  Glossary 61
  Catenary vehicles 62
  Workshop participation 63
Figures and tables

Figures

Figure 1  Overview of the WIM model (Element Energy, 2016)  23
Figure 2  Price of dispensed gas seen by fleet operators (Element Energy, 2016 b)  24
Figure 3  Vehicle parc – ESME standard, ESME new vehicles and ESME freight model cases  32
Figure 4  Base case and zero emission vehicles from 2040 case – HGVs per year for each fuel type  33
Figure 5  Shift demand and base case scenarios – MGV zero emission powertrains  33
Figure 6  Shift demand and base case scenarios – emissions in 2050  34
Figure 7  Base case and CCS cases – hydrogen generation  34
Figure 8  Base case and CC cases – net emissions in 2050  35
Figure 9  Liquid haulage 3 axle artic TCO  36
Figure 10  Powertrain sales for all freight categories  37
Figure 11  Powertrains across the fleet  37
Figure 12  Comparison of TCO between base case and stricter legislation scenarios  38
Figure 13  Powertrain sales for all freight categories – stricter legislation  39
Figure 14  Powertrains across the fleet – stricter legislation  39
Figure 15  Powertrains across the fleet – shift demand  40
Figure 16  Number of gas refuelling stations in each scenario in 2040 and 2050  41
Figure 17  Number of hydrogen refuelling stations in each scenario in 2040 and 2050  41
Figure 18  Number of electric chargers in each scenario in 2040 and 2050  42
Figure 19  Fuel price in base case scenario  43

Tables

Table 1  Reported battery pack costs  16
Table 2  Powertrain efficiency  Source: Transport and Environment, 2018  17
Table 3  Properties of announced electric HGVs  Source: CCC Nikolas Hill, 2019  17
Table 4  Properties of announced catenary electric HGVs  Source: CCC Nikolas Hill, 2019  18
Table 5  Powertrain types and fuel sources  24
Table 6  Vehicle wheel plan for each operation type – vehicle categories  25
Table 7  Modelling assumptions  28
Table 8  Modelling cases  31
Table 9  Future research  50
Table 10  Future collaborations  54
Table 11  Catenary deployment phases  64
Table 12  Catenary powertrains  64
1. Introduction

1.1 Background

Road freight is expected to become one of the most significant energy users from 2030 onwards as the UK economy evolves. In 2017 carbon emissions from road freight accounted for about 17% of the UK’s emissions and are projected to increase in the next 30 years (DfT, 2017). Other countries like the United States, China, Japan and Canada have already made provisions and set targets to reduce emissions from road freight. The European Commission has recently proposed an interim CO2 reduction target of 15% by 2025 for all large trucks compared to 2019 levels. By 2030 trucks will have to emit at least 30% less CO2 than in 2019 (European Commission, 2019). Large trucks account for around 65–70% of all CO2 emissions from heavy-duty vehicles in the EU, which also include smaller trucks, buses and coaches. The expectation is that these targets will save around 54 million tonnes of CO2 from 2020 to 2030, equivalent to the total annual emissions of Sweden.

In this context, the aim of this project was to define a cost-effective pathway to decarbonise road freight across the UK’s transport and energy systems. A series of workshops brought together new sets of stakeholders to generate ideas, with discussions informed by insights by the Energy System Catapult’s whole energy system model ESME, and a literature survey.

From these varied sources – model, analysis, and discussions – decarbonisation pathways and the appetite amongst stakeholders to undertake actions to promote them was explored. Topics considered included: research and development (R&D), technology challenges, legislation, investment (volume and direction), and initiatives from firms, government, and other sectors – the aim being to understand the major themes in a collaborative way.

The ambition of this research was to provide additional granularity for both the future propulsion systems in road freight vehicles, and the energy systems capability of the ESME model. The findings will provide direction for further research on mixes of technology solutions and energy vectors that could be used for future propulsion technologies which will be vital to support the integration and decarbonisation of future transport and energy systems. This will allow future research to understand more about the impact that transport (heavy goods) vehicles will have on the total energy system and potentially influence where the investment priorities should lie to ensure delivery on current CO2 targets.

By working this way, a more robust understanding of the influence that the propulsion systems of heavy-duty vehicles will have on the whole energy system will be developed.

1.2 Scope of the project

This project provided more informed, holistic understanding of the challenges for the heavy-duty market. This was done by working with experts within industry and academia who have in depth knowledge of both vehicle propulsion technology (APC and APC Spoke for Thermal Efficiency) and the energy system as a whole (ESC). The findings from the research have the ambition to inform all aspects of the community interested in this area from academia to industrial players and will form an evidence base to inform policy development. The focus that the research brings will support the inception of new, targeted R&D programmes in both vehicle technology and energy system domains.

This activity provided five important outcomes:

- A set of scenarios in terms of future energy options informed by the understanding of upcoming needs for heavy goods and off-highway vehicles.
- ESME analysis of these scenarios to enable examination of the impact of different heavy-good propulsion technologies on the wider energy system.
- Close connections between modelling and the ‘real world’ such as the thoughts and beliefs of key stakeholders developed through collaboration and co-creation.
- Articulating industry needs in R&D and innovation to a broad range of academics across the energy system outside the directly automotive tech sector and encourage dialogue on these (‘ideas from the ground-up’).
- Bringing together new combinations of stakeholders across both the automotive and energy systems sectors who are engaged in the problem of freight decarbonisation and are more likely to collaborate on further projects.
2. Workshops

The ambition of the workshops was to spark discussion, to complement results from the project team’s analysis and literature surveys. The workshops were structured to encourage creative thinking on the problem – as well as to clarify organisations understanding and gaps in knowledge, and explore differences of opinion. Workshop participants (listed in the appendix) worked with the project team to inform thinking, analysis and modelling, in a collaborative way. From these varied sources – model, analysis and discussions – decarbonisation pathways and the appetite among stakeholders to undertake actions to promote them were explored. Topics considered included, required R&D, and technology development, legislation, investment (volume and direction), and initiatives from firms, government, and other sectors.

Two workshops were organised bringing together representatives from industry and academia. These workshops brought new sets of stakeholders together to explore decarbonisation pathways for the road freight sector. The workshops were divided into four sessions that investigated specific challenge areas.

2.1 Vehicle life

The vehicle life session addressed the key needs, challenges and opportunities from the operators, manufacturers and customers. These sessions discussed a range of topics, from vehicle selection, typical mileages and running costs, refreshing of fleets including upgrading and retrofitting new low-carbon technologies.

Key themes that emerged from the discussion were:

- **Policy challenges** – it was felt that there was a lack of long-term vision which is leading to delays and postponement in investment decisions. Solutions could include applying a carbon tax to support the uptake of low-carbon fuels as this could be the easiest and quickest way to achieve carbon reduction across the existing fleet. Examples were tabled of other European countries taking this approach to supporting the uptake of low-carbon fuels e.g. HVO. Scandinavia has fiscal benefits for the introduction of paraffinic fuels; Finland and France were cited as creating a differential taxation on alternative fuels such as e10.

- **Understanding the user case** – this impacts not only selection of vehicles but also understanding of the ancillary technology that can support vehicles e.g. telematics / autonomous functionality / geo-fencing to limit emissions of vehicles. In addition to the in-use phase, the importance of a range of other costs was highlighted: maintenance and servicing costs of the new vehicle powertrain solutions along with additional costs for infrastructure e.g. installing charging points and retention/retraining of in-house maintenance teams.

- **Operating models** – many larger organisations in the HGV sector now operate on a leasing model. Currently electric vans that are being trialled are being given a longer lease compared to their diesel counterparts to ensure that the TCO is comparable. There is an expectation that fleet transport managers and companies will need to reduce carbon emissions to meet corporate social responsibility initiatives. This need could provide an opportunity to look at the whole carbon cost of logistics, taking into account multi-modal and distribution networks where modular solutions could offer low carbon alternatives. When adopting new solutions there is the challenge of having the right infrastructure to support these technologies e.g. charging infrastructure, re-fuelling infrastructure to support alternative e.g. CNG, LNG and Hydrogen.

- **Retrofit solutions** – within the off-highway and HGV segment were not deemed appropriate due to high vehicle refresh rate and lack of incentives (currently vehicle second life is minimal as older vehicles are exported). However, smaller hauliers were in favour of retrofit as they may retain their vehicles for a period of 9–10 years.
2.2 Suitable technologies for Heavy Goods Vehicles

The technology session addressed the suitability of a range of technologies for different vehicle types. The session discussed diesel and low carbon replacements, electrical technologies (hybrid, BEV and catenary vehicles), hydrogen (fuel cells and combustion engine) and natural gas vehicles across medium and HGV categories currently in use in ESME.

Key themes that emerged from the discussion were:
- **Duty cycle (engine and vehicle load and speed, transience of driving)** affects technology suitability and benefits, with geographical context increasingly important e.g. ZEV capability is expected to be key in cities.
- **Infrastructure** was seen as a big challenge for hydrogen-fuelled transport, although back to base fuelling can alleviate this issue for some applications.
- **Technology suitability varies by vehicle size** - BEVs were recognised as being suitable options for smaller vehicles but were not thought to be suitable for those with long distance duty cycles due to the trade-off between battery size (vehicle range) and mass, with payload, cost and charging time.
- **ESME vehicle categories** (vehicles are categorised based on their weight, more details can be found in the Modelling section) were not recognised by industrial stakeholders, further discussion between Volvo and the team was proposed to investigate alternatives.
- **Economics** are key to the introduction of natural gas powertrains, with emissions and CO2 benefits of CNG vs Euro VI diesel baseline depending on duty cycle. There was also uncertainty around future availability of biomethane in the transport sector due to the prioritisation of its use in other sectors e.g. power generation.

2.3 Infrastructure and air quality

The infrastructure session revealed a variety of attitudes towards technologies and policies. Infrastructure requirements for new powertrain options were discussed.

Key themes that emerged from the discussion were:
- **The additional energy demand and impact on the electricity grid**, were seen as a challenge for electric HGVs. Furthermore, there were concerns that large battery packs will make freight less efficient and therefore less economic by reducing the load that can be carried in a vehicle of a given size. Scepticism was expressed regarding the willingness of operators to make any operational changes required to accommodate electrification. It was noted that HGVs and buses could potentially share infrastructure.
- **Electric roads were seen to have the advantages of reducing required battery size and alleviating the load reduction concern identified above.**
- **The participants considered the advantages of hydrogen, gas and synthetic liquid fuels to be use of existing infrastructure and the existing refuelling model.** Participants were concerned about hydrogen purity if the gas network was converted for hydrogen use but other options for H2 distribution were considered.
- **It was generally considered that public funding is needed for infrastructure, including grid reinforcement.** It was also mentioned that fleet operators and bus operators, particularly in the near term, might build their own infrastructure, which could be shared if reliable billing mechanisms were to exist, although this would be a tertiary role.

2.4 Energy system decarbonisation

In this session the different ways of reducing emissions from the freight sector and improving air quality in urban areas were explored.

The key messages that emerged from the energy system decarbonisation session were:
- **Central policy for freight decarbonisation is needed** for zero emission vehicles to be adopted by operators.
- **The operator’s choice and needs will have to be accounted for.** For example, the vehicle size, fuel cost and infrastructure requirements and TCO.
- **Participants thought that a mix of technologies will be used in the future.** Not all powertrain options were seen as suitable for all vehicle types and not all vehicle types were seen as an option for all types of operation.
- **Big data and technology that will allow monitoring and operation optimisation will enable emission reduction from road freight.**
- **Consumer behaviour will affect future freight demand.**

- **Alternative operation strategies like portable distribution centres, consolidation of services and freight also have the potential to reduce emissions.**
- **Moving freight demand from HGVs to electric medium and light goods vehicles with an increase in the number of distribution centres around cities was seen as an option to reduce emissions.**
- **Hybrid vehicles that can operate on electric mode when in zero emission zones were discussed as a potential solution.** Furthermore, it was stated that further improvements to diesel engines will have a positive impact on reducing emissions from HGVs.
- **Large rapid charging stations and charging super-hubs were seen as an enabler for battery electric vehicles, with participants expressing the opinion that the infrastructure should be ready for vehicles to be adopted.**
- **Deployment of Carbon Capture and Storage (CCS) was considered to be directly linked to the availability of hydrogen and participants were sceptical about assumptions for CCS deployment timescales included in the current ESME model.**
3. Literature Review

A literature review was included in the project scope of work to update existing model parameters, provide information for new powertrain types in the ESME model (ETI, 2014) and provide data for the Gas WtM model for all powertrain types. Information was gathered from a combination of sources: scientific literature, public domain reports, APC roadmaps and project workshops. Key references and data are described in this section for each powertrain type.

3.1 Battery electric vehicles

Battery costs

A range of literature was reviewed to understand the expectations for future battery costs, as summarised in Table 1 below. Battery costs in the zero-emission database from the ETI knowledge zone (ETI, 2017) were found to be within the range detailed in the literature reviewed.

Table 1: Reported battery pack costs

<table>
<thead>
<tr>
<th>Pack cost £/kWh</th>
<th>2015</th>
<th>2017</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC roadmap</td>
<td>218</td>
<td>117</td>
<td>78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge Econometrics Report – min</td>
<td>262</td>
<td>121</td>
<td>101</td>
<td>80</td>
<td>73</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge Econometrics Report – max</td>
<td>262</td>
<td>182</td>
<td>151</td>
<td>120</td>
<td>89</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre for sustainable freight</td>
<td>107 (2019)</td>
<td>70 (2021)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETI WtM model data set</td>
<td>253</td>
<td>154</td>
<td>122</td>
<td>101</td>
<td>91</td>
<td>83</td>
<td>75</td>
<td>68</td>
</tr>
</tbody>
</table>

Powertrain efficiency

Efficiency of battery electric vehicle powertrains was derived from a report by Transport and Environment (Transport and Environment, 2018).

Battery size

Modelled battery size was based on information from Ricardo’s Zero Emission HGV Infrastructure Requirements report for Committee for Climate Change (CCC) (Hill, 2019) which includes evidence of battery size of currently announced Heavy Good–BEVs (as shown in Table 3).

Table 2: Powertrain Efficiency, Source: Transport and Environment, 2018

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Diesel ICE</th>
<th>BETs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACDC Rectification*</td>
<td>–</td>
<td>95%</td>
</tr>
<tr>
<td>Battery charging/running</td>
<td>–</td>
<td>95%</td>
</tr>
<tr>
<td>DCAC inversion</td>
<td>–</td>
<td>95%</td>
</tr>
<tr>
<td>Engine operation: Fleet (best in class)</td>
<td>39%; 46%</td>
<td>95%</td>
</tr>
<tr>
<td>Transmission</td>
<td>95%</td>
<td>99%</td>
</tr>
<tr>
<td>Total drivetrain</td>
<td>40%</td>
<td>85%</td>
</tr>
</tbody>
</table>

Table 3: Properties of announced electric HGVs, Source: CCC Nikolas Hill, 2019

<table>
<thead>
<tr>
<th>Manufacturer / Model</th>
<th>Vehicle Class</th>
<th>Battery Capacity (KWh)</th>
<th>Range (miles)</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEVs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tesla Semi Artic</td>
<td>1000*</td>
<td>300–500</td>
<td></td>
<td>Tesla, 2018</td>
</tr>
<tr>
<td>Renault Trucks</td>
<td>Common base platform shared amongst models 16–26 tonnes</td>
<td>300</td>
<td>190</td>
<td>Renault Trucks, 2018</td>
</tr>
<tr>
<td>Mercedes-Benz Electric Truck</td>
<td>261 Large Rigid</td>
<td>200</td>
<td>124</td>
<td>Daimler, 2019</td>
</tr>
<tr>
<td>BYDT7 Small Rigid</td>
<td>145</td>
<td>135 (half-load)</td>
<td></td>
<td>BYD, 2019</td>
</tr>
<tr>
<td>BYDT7 Large Rigid</td>
<td>221</td>
<td>124 (full load)</td>
<td></td>
<td>BYD, 2019</td>
</tr>
<tr>
<td>BYDT9 Artic</td>
<td>435</td>
<td>124 (full load)</td>
<td></td>
<td>BYD, 2019</td>
</tr>
<tr>
<td>Volvo FL Electric Truck</td>
<td>Small Rigid</td>
<td>100–300</td>
<td>Up to 186</td>
<td>Volvo Group, 2018a</td>
</tr>
<tr>
<td>Volvo FE Electric Large Rigid</td>
<td>200–300</td>
<td>124</td>
<td></td>
<td>Volvo Group, 2018b</td>
</tr>
<tr>
<td>VW e-Delivery Small Rigid</td>
<td>–</td>
<td>124</td>
<td>Volkswagen, 2018</td>
<td></td>
</tr>
<tr>
<td>Peterbilt 220EV Small Rigid</td>
<td>148</td>
<td>100</td>
<td>Peterbilt, 2019</td>
<td></td>
</tr>
<tr>
<td>Peterbilt 579EV Artic</td>
<td>350–440</td>
<td>150–250</td>
<td>Fleet Equipment Mag, 2018</td>
<td></td>
</tr>
<tr>
<td>Arrival Royal Mail/UPS Small Rigid</td>
<td>–</td>
<td>100–150</td>
<td>Arrival, 2019</td>
<td></td>
</tr>
<tr>
<td>D-REEVs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tevva Motors RoX</td>
<td>Small Rigid</td>
<td>–</td>
<td>100 electric, 250 total</td>
<td>Tevva, 2019</td>
</tr>
<tr>
<td>Calor/EMOS1 Small Rigid</td>
<td>–</td>
<td>40 electric, 250 total</td>
<td>SMHT, 2017</td>
<td></td>
</tr>
</tbody>
</table>

*calculated based on range and assumptions. Hyphens indicate that no information is available.
3.2 Catenary electric vehicles

Battery size
To include the new category of catenary vehicles, information was required on likely battery size. At the time the project was carried out there was limited evidence available on expected battery size for catenary vehicles. Ricardo’s Zero Emission HGV Infrastructure Requirements report for the CCC (Hill, 2019) details of battery size of catenary vehicles, as shown in Table 4.

Table 4: Properties of announced catenary electric HGVs, Source: Hill, 2019

<table>
<thead>
<tr>
<th>Base vehicle</th>
<th>Modified by</th>
<th>Drivetrain</th>
<th>Electric drive power (kW)</th>
<th>Energy storage capacity (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mack Pinnacle</td>
<td>Volvo Group</td>
<td>Hybrid</td>
<td>120</td>
<td>1.2</td>
</tr>
<tr>
<td>Navistar International Prostar</td>
<td>Transportation Power Inc.</td>
<td>Hybrid</td>
<td>300</td>
<td>115</td>
</tr>
<tr>
<td>Navistar International Prostar</td>
<td>Transportation Power Inc.</td>
<td>BEV</td>
<td>300</td>
<td>115</td>
</tr>
<tr>
<td>Scania S-series</td>
<td>Siemens/Scania</td>
<td>Hybrid</td>
<td>-</td>
<td>15</td>
</tr>
</tbody>
</table>

3.3 Fuel cell vehicles

Fuel cell cost
Evidence for fuel cell cost in HD trucks is relatively limited, with more focus in the literature on fuel cell buses, as detailed in the following references:

- Cambridge Econometrics Report, Trucking into a Greener Future: the economic impact of decarbonizing goods vehicles in Europe (Cambridge Econometrics, 2018) presents analysis for fuel cell articulated vehicles, although fuel cell costs are based on a cost model for passenger cars and therefore, may not be valid for Heavy duty vehicles due to their more severe duty cycle
- Strategic Analysis worked with Argonne National Labs (James, 2016) to produce forecasts for fuel cell costs at volume production (total system cost $52/kW)
- US DoE analysis (Thompson, 2018) also estimated costs of the fuel cell system at ~$50/kW
- NREL (Saur, 2018) forecast very high costs per kW for HD applications ($3M total for a bus system)
- Feurholter (Gnann, 2017) present costs for fuel cell vehicles in 2015 and 2030 (174, 600 Euros for an articulated truck in 2030)

3.4 Future internal combustion engines

Information was gathered for future internal combustion engines fuelled by diesel and methane. Current fuel consumption and vehicle cost data for rigid and articulated vehicles is available from Motor Transport (Motor Transport, 2018).

Diesel fuelled engines
Three categories of diesel internal combustion engine (ICE) were included in the updated model: Euro VI baseline, ICE Diesel Hybrid (Euro VI Diesel engine with the addition of energy recovery) and Future Diesel, Revolutionary offering significant improvement in efficiency and emissions based on current R&D activities. A range of studies report changes in efficiency for future diesel powertrains:

- Ricardo Energy and Environment (Escher, 2017) suggests improvements of 5–10% in engine brake thermal efficiency (BTE) by 2030
- ICTC (Oscar Delgado, 2017) details a scenario to 2025 giving 3.1% vehicle fuel consumption reduction per year from 2015 to 2025, with a long term scenario suggesting 3.6% vehicle fuel consumption reduction per year between 2015 and 2030. This work assumes 55% BTE at 2030 in the long-term scenario
- Cambridge Econometrics (Cambridge Econometrics, 2018) report vehicle efficiency improvements to 2050 at 42% for HGV
- APC roadmaps (Advanced Propulsion Centre, 2018) present targets for engine BTE of 60% by 2035

Brake Thermal Efficiencies for diesel powertrains included in the model were:

- Diesel Euro VI Baseline – Cycle average BTE data for Euro VI diesel of 42% is presented by ICTC (Manissa Moultar, 2017) over a representative truck duty cycle
- Diesel Revolution – Future technology developments could lead to a step change in diesel ICE efficiency. Examples of this type of technology are: Double Expansion compression ratio engine concept developed by Lund University and Volvo (Nhut Lam and Per Tunestal, 2019) Split cycle engine as developed by Ricardo and University of Brighton (Robert Morgan, 2019) APC roadmaps for Thermal Propulsion Systems (Advanced Propulsion Centre, 2018) target efficiency around 60% by 2035 with current research indicating potential for increases in efficiency of around 10% by 2025, and 30% by 2030 compared to Euro VI diesel.

Methane fuelled engines
Stoichiometric and high-pressure direct injection (HPOII) methane fuelled engines are included in the model. While the majority of current trucks are port fuel injected, HPOII technology is being introduced by Volvo due to improved BTE compared to stoichiometric engines.

Data on gas engine efficiency available from a range of sources Ricardo (Penny Atkins, 2013), Imperial Sustainable Gas Institute (Jamie Spears, 2019), AVL, Scania, Royal Institute of Technology Costgas project (Adlercreutz, 2018) and Gas WiM model (Element Energy, 2016).

Two tank types were included in the model: steel and composite. Data for these tanks was derived from zero emission database from the ETI knowledge zone (ETI, 2017). Improvement in methane engine efficiency over time included in the model was derived from the Gas WiM model (Element Energy, 2016).

Powertrain cost
Methane powered trucks are on the market, so the current price differential to diesel trucks can give an indication of additional powertrain cost. Additionally, Imperial Sustainable Gas Institute (Jamie Spears, 2019), collates evidence on methane truck price, compared to diesel and BEV.

Aftertreatment
Aftertreatment costs included in the model were based on costs detailed in iCCt’s report ‘Cost of Emissions Reduction Technology for Heavy Duty Vehicles’ (Francisco Posada, 2016).
Commodity prices

Commodity prices were gathered from the following sources:

- Wholesale gas price (NBP): National Grid Future Energy Scenarios (National Grid, 2019) – High case, Two Degrees – this case was selected since it was the only one which meets the emission targets.
- Hydrogen: data not publicly available – data generated from ESME model with CCS deployment.

3.5 Challenges

A literature review to support model parameterisation presents a number of challenges to gathering representative data:

- A range of values for each parameter is often reported by different authors. There are a number of reasons for this: different baseline assumptions (vehicle type, duty cycle etc), different approaches to the estimation (model based, synthesis of values from literature, stakeholder engagement) and changes to technology and the understanding of technology over time.
- Data is often reported for different time points to those required for the model.
- It is generally not possible to gather data for all parameters needed due to a lack of public domain data. In this study, particular challenge areas were infrastructure, commodity/fuel prices, data on HGVs (powertrains and vehicles).

It is therefore important to recognise the limitations of a literature review of this type, and the importance of regular updating to maintain the relevance of the models. In this case, evaluation of model parameters could be improved through targeted vehicle modelling activities and focussed stakeholder consultation, including activities like stakeholder interviews to understand future fuel/commodity prices for example.
4. Modelling

4.1 Methodology and Modelling tools

Methodology

Based on the workshops and literature review findings, a modelling approach was adopted to reflect the complex questions posed. A combination of modelling tools was employed: in addition to modelling the whole energy system (optimising system costs) using the Energy Systems Modelling Environment (ESME), an operator choice model was developed (driven by operating costs which were generated by the vehicle cost model).

Many factors affect the operators’ decision and a techno-economic system approach, as provided by ESME, would not have been able to capture the diversity within the transport sector.

Energy Systems Modelling Environment (ESME)

The ESME model was developed by the ETI and is part of the ESC’s assets. ESME models the UK energy system with sufficient spatial and temporal detail to understand system engineering challenges, for example around building an electricity system that meets demand in different seasons: summer, winter and peak and at different times of the day.

ESME is a Monte Carlo model which considers the uncertainty in this problem, particularly the uncertainty in future energy prices and the future cost and performance of energy technologies. This functionality allows the user to explore system-level responses to user-specified uncertainty in the future values of key assumptions.

Its ‘whole system’ scope includes all the major flows of energy: electricity generation, fuel production, heating and energy use in buildings, energy use in industry, and transportation of people and freight. Various technology choices are available in each of these sectors, such as alternative power stations, vehicle types or heater types. ESME performs a high-level cost optimisation that analyses different combinations of technologies in each sector and selects the combinations which together minimise the total cost of the energy system while meeting specified targets and constraints (ETI, 2019).

Gas Well to Motion model (WtM) and Freight model

It was identified that a more detailed model is required to reflect HGV operators and their choices when selecting fleet vehicles. The WtM model is an existing model quantifying emissions and their costs for HGVs in the UK market. It was developed by the ETI and offers a more detailed look into the HGV sector as it considers several natural gas supply pathways and addresses their uncertainty.

The WtM model calculates the vehicle parc based on how attractive vehicles are to the operator (see Figure 1). The attractiveness is represented by the TCO over a time period. The operator/purchaser portion of the model is key to the deployment of vehicles and this portrays the ‘behaviour’ of the fleet purchaser. Furthermore, the model uses a logistic regression (logit) based choice model to estimate the future uptake of vehicles. The logit model generates probabilities or market shares of discrete choices to capture variations in fleet decision making. Market shares vary proportionally to their TCO. This provides a more realistic representation of the market compared to a ‘winner takes all’ approach where the technology with the lowest TCO receives 100% of the market share, eliminating other vehicle choices (Element Energy, 2016).

Figure 1: Overview of the WtM model (Element Energy, 2016)
Based on the WtM, the prototype ‘Freight model’ was derived including changes and additions reflecting the insights from the workshops.

New powertrain options were added to the Freight model and were tailored and optimised for each vehicle category based on daily mileages and duty cycles from publicly available data aiming to reduce battery pack size, hydrogen tank size, weight, etc, so these vehicles are optimised for their specific use. It is worth noting that this requires changes in operator ‘habits’ such as charging every day.

Electricity, hydrogen and liquid fuelled powertrains were added, and the calculation timeframe was extended to 2050 from 2030. Gas powertrains which currently meet the eURo VI only were used (Element Energy, 2016). The powertrain types that were included in the model are shown in Table 5.

The updated model included representation of the HGV sector in terms of operation segments and vehicle wheel plan, a key conclusion from the project workshops. Table 6 presents the new vehicle categories included in the Freight model. Information on the wheel plan that was used for each category was taken from a report prepared by Element Energy for the ETI (Element Energy, 2018). The blue blocks indicate the new vehicle categories, i.e. which vehicle configuration each operation type uses.

Table 5: Powertrain types and fuel sources

<table>
<thead>
<tr>
<th>Powertrain type</th>
<th>Fuel source 1</th>
<th>Fuel source 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE Diesel</td>
<td>Diesel</td>
<td>–</td>
</tr>
<tr>
<td>ICE Diesel Hybrid (Std Euro VI diesel engine with the addition of energy recovery)</td>
<td>Diesel</td>
<td>–</td>
</tr>
<tr>
<td>ICE Diesel Revolution</td>
<td>Diesel</td>
<td>–</td>
</tr>
<tr>
<td>ICE Gas HPDI (LNG)</td>
<td>LNG</td>
<td>Diesel</td>
</tr>
<tr>
<td>ICE Gas Stoichiometric (CNG Steel)</td>
<td>CNG</td>
<td>–</td>
</tr>
<tr>
<td>ICE Gas Stoichiometric (CNG Comp)</td>
<td>CNG</td>
<td>–</td>
</tr>
<tr>
<td>ICE Gas Stoichiometric (LNG)</td>
<td>LNG</td>
<td>–</td>
</tr>
<tr>
<td>Battery Only</td>
<td>Electricity</td>
<td>–</td>
</tr>
<tr>
<td>Hydrogen + Bat Regen</td>
<td>Hydrogen</td>
<td>–</td>
</tr>
<tr>
<td>Hydrogen / Battery Hybrid</td>
<td>Hydrogen</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

Table 6: Vehicle wheel plan for each operation type – vehicle categories

<table>
<thead>
<tr>
<th>Operation segment/ Wheel plan</th>
<th>2 Axle Rigid</th>
<th>2 Axle Artic</th>
<th>3 Axle Rigid</th>
<th>3 Axle Artic</th>
<th>4 Axle Rigid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parcel Delivery (PD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haulage (H)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Haulage (LH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMCG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retail Haulage (RH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food Haulage (FH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction (C)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Vehicle cost model

A vehicle cost model was developed, where data on current and projected vehicle powertrain costs, baseline EURO VI vehicle cost, fuel consumption and annual mileage for each operation category were used to calculate the total vehicle cost for each operation type and powertrain option.

Body and trailer costs for the HGV’s were derived for the five vehicle configurations used in the model (3 axle articulated, 2 axle articulated, 3 axle Rigid, 2 axle Rigid, 4 axle Rigid) and they had no impact on vehicle powertrain selected. The baseline powertrain costs were derived from the zero emission database from the ETI knowledge zone (ETI, 2017) and the baseline EURO VI vehicle costs as well as the remaining other powertrains were derived from the ETI models workbook (ETI, 2019).

Data from the ETI analysis report were used to determine energy expenditure percentages for battery and fuel cell sizing (Element Energy, 2018). These expenditures were used to calculate the CAPEX and OPEX of the different powertrains for each segment.

Real world data on fuel consumption for the Baseline diesel EURO VI engine, for each segment category, were collected from ETI Data Analysis Project (Element Energy, 2018). Powertrain and vehicle efficiency improvement were then applied to this data, year on year, to derive the efficiencies for all powertrains in the different vehicle segments.

In terms of fuel supply assessments, the Freight model focuses on tank to motion fuel consumption to predict the uptake of alternative powertrains in HGVs and generate outputs at fleet level for each reporting year up to 2050.

In the WtM model, each vehicle category is associated with one type of refuelling station, major distribution hub or haulier depot refuelling station. For a more realistic approach, the freight model allows, were appropriate, the segment categories to use both types of refuelling stations.

The Freight model was updated by excluding on site liquefaction of natural gas. The model includes Gas grid LTS connection, Gas grid IP connection, LNG station served by a road tanker and LCNG station served by a road tanker.

Input parameters were updated to the most recent available data: commodity prices of fuels (gas, electricity and hydrogen), HGV’s demand projections, vehicle cost (CAPEX and OPEX), fuel consumption; see Table 7 and literature review for more details.
4.2 Assumptions

The assumptions made for the modelling work are summarised in Table 7.

### Table 7: Modelling assumptions

<table>
<thead>
<tr>
<th>Area</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freight model</strong></td>
<td></td>
</tr>
<tr>
<td>Vehicle categories</td>
<td>Created 13 categories based on Element Energy (2018) and on the categories currently existing in the market e.g. 4 axle rigid vehicles</td>
</tr>
<tr>
<td>Powertrain categories</td>
<td>10 categories plus 4 categories for catenary, powertrain options that do not meet the Euro VI standards were excluded</td>
</tr>
<tr>
<td>Projected demand of HGVs per segment category</td>
<td>Calculated based on DfT Projections • Traffic growth rate from 2015 (%) (DfT, 2018) • Freight Sector Demand Splits (%) (DfT, 2019) • Demand (BtTonnekm) (DfT, 2016) • Average Freight Carried Per Vehicle Per Trip (Tonnel) (ETI, 2019) • Annual Distances (km) (Element Energy, 2018) and 253 working days (used as assumption top elevate average daily mileages)</td>
</tr>
<tr>
<td>Starting stock of HGVs per category (no sales after and including 2015)</td>
<td>Calculated based on: • 2015 demand for each category derived for the projected demand of HGVs per segment category • Real sales for 2015-2018 (DfT, 2019) • For 2015–2050 apply the same retirement rate as in WIM model.</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Derived efficiencies for all powertrains in each segment based on fuel consumption data from Element Energy (2018) using the vehicle cost model.</td>
</tr>
<tr>
<td>Vehicles costs</td>
<td>CAPEX and OPEX calculated for each powertrain and for each segment using the vehicle cost model.</td>
</tr>
<tr>
<td>Battery and hydrogen sizing</td>
<td>Battery packs and hydrogen fuel capacity sizing derived based on sources from Element Energy (2018) using the vehicle cost model. • Cycle duty derived • Estimated energy consumption on road types</td>
</tr>
<tr>
<td>Average lifetime of vehicles per segment</td>
<td>Values from WtM matched to the Freight categories</td>
</tr>
<tr>
<td>Time horizon for evaluating the TCO</td>
<td>Same as WtM – based on fleet interview conducted for Element Energy’s previous studies for Birmingham and Sefton Councils</td>
</tr>
<tr>
<td>Resale</td>
<td>Same as WtM – calculated based on DfT data</td>
</tr>
<tr>
<td><strong>Freight model cont.</strong></td>
<td></td>
</tr>
<tr>
<td>Penalty on sales</td>
<td>Applied the same penalty for gas powertrains from the WtM model, to the hydrogen and electric vehicles to reflect that some operators might not choose alternative powertrains due to concerns about resale values, reliability etc. Penalty is applied the first year of the powertrain deployment and it is gradually decreased to zero in 20 years.</td>
</tr>
<tr>
<td>Vehicle supply cap</td>
<td>Apply the same supply cap for gas vehicles from WtM (sales capped at a few hundred sales per year the first 4 years of deployment) to hydrogen and electric powertrains to reflect limited availability of vehicles as HGV manufacturers begin to ramp-up production</td>
</tr>
<tr>
<td>Hydrogen refuelling stations</td>
<td>Hydrogen produced on site; i.e. no network connection cost</td>
</tr>
<tr>
<td>Deployment years of powertrains</td>
<td>• Gas powertrains: WtM model • Hydrogen, electric powertrains: 2025 with supply caps and by 2030 no sales caps to match with ESME</td>
</tr>
<tr>
<td>Learning rate for infrastructure</td>
<td>• A learning rate per year is applied for doubling the infrastructure in hydrogen refuelling stations and electric chargers • For gas refuelling stations no learning rate is applied – calculations are kept the same as in the WtM model</td>
</tr>
</tbody>
</table>

### ESME model

<table>
<thead>
<tr>
<th>Area</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>The latest DfT statistics were used for the tonne km demand from HGVs for each year. To align capacities between ESME and the Freight model predictions, constraints were added to ensure an absolute capacity of a technology each year.</td>
</tr>
<tr>
<td>Catenary infrastructure</td>
<td>Catenary infrastructure was linked to vehicles such that for every vehicle able to use it, 20m of catenary must be built. This proportion is derived from the maximum number of vehicles in the fleet that can be supported by catenary and the maximum amount of catenary that can be deployed.</td>
</tr>
<tr>
<td>Deployment years of powertrains</td>
<td>Gas powertrains: same as in the WtM model • Hydrogen and electric powertrains: 2030</td>
</tr>
<tr>
<td>2050 greenhouse gases</td>
<td>A target reduction of greenhouse gases by 80% was assumed.</td>
</tr>
<tr>
<td>Vehicle categories</td>
<td>Vehicle categories developed as part of the Freight model were adopted.</td>
</tr>
</tbody>
</table>
4.3 Scenarios

The outputs from the workshops were used to inform the modelling cases. An assessment process was followed to prioritise and select the aspects and features to be included in the scope of the modelling work. Complexity, data availability and expected impact were among the criteria used in the process.

The following aspects were included in the modelling scope:

- Stricter legislation scenarios:
  - Zero Emission Vehicles from 2040. Based on the recommendation from the National Infrastructure Commission to ban the sale of new diesel HGVs from 2040 and to reflect a stricter regulation similar to the road to zero strategy set by Government, in this scenario all new vehicles sold from 2040 are zero emission.
  - EU regulation scenario: Gradual reduction of emissions from HGVs in accordance to the EU regulations. For the purposes of this study and due to model limitations, the EU regulation was extrapolated to 2050 and was implemented so that the combined emissions of new vehicles for each HGV segment in a particular year are 2025: 15% of 2020 total 2030: 30% of 2020 total 2050: 50% of 2020 total.
  - Shift demand scenario: Demand from HGVs is been shifted to Medium Goods Vehicles (MGVs) and Light Goods Vehicles (LGVs) from 2030 onwards. This scenario represents a future increase of distribution hubs around cities with smaller vehicles used for last mile distribution as discussed during the workshops. Due to model constraints in ESME the scenario was implemented with 10% of HGV demand moved to MGVs and 10% of the MGV demand was moved to LGVs. In the Freight model a more gradual approach was followed with a 5% demand reduction in HGVs between 2020 and 2029 and a 10% demand reduction from 2030 to 2050.

- Carbon Capture and Storage (CCS) deployment scenarios: During the workshops concerns were raised around the timescales assumed in the current model for deployment of CCS. The impact of CCS deployment was addressed by two energy system scenarios modelled in ESME, one where CCS doesn’t materialise and one where deployment of CCS is delayed to 2040.

- Motorway catenary charging scenario: As a route to the electrification of HGVs, this scenario includes motorway catenary charging. The catenary technology was deployed in 10 phases and each phase supported a specific number of vehicles. The details of the catenary rollout strategy are shown in the Appendix.

The modelling runs are summarised in Table 8. To evaluate the effect of changes to the vehicle parcs, 3 cases were set up for the ESME model. In the first case (ESME standard case), ESME uses its standard vehicle categories and data for HGVs. The second case (ESME new vehicles ‘base case’) uses the new vehicle and powertrain categories and data for HGVs. The third case (ESME ‘base case’) employs the vehicle parc calculated by the Freight model. For all the other modelling runs in ESME the new vehicle categories and vehicle data are used.

For the Freight model base case, it was assumed that all vehicles apart from catenary vehicles are available and there are no constraints on emissions. For ESME, as it looks at the whole of the energy system, the Road to Zero targets were represented, and only zero emission cars, vans and MGVs are available for sale from 2040 onwards in all modelled cases.

4.4 ESME results

Figure 3 summarises the composition of the vehicle parcs for 2030 and 2050 when employing the standard ESME vehicle categories, the new vehicle categories and the vehicle parc provided by the Freight model. The introduction of the new vehicle categories with updated input data resulted in a ~25% reduction on the total number of HGVs, in all years, when comparing the ESME standard case to the ESME new vehicles base case. This was a result of the new techno-economic data for the new vehicles: updating vehicle efficiency and payload results in an overall increase in efficiency. Furthermore, as each powertrain option was optimised for the demand of each category, the kilometres travelled by each vehicle category were increased, resulting in fewer vehicles.

The introduction of the new powertrains and vehicle categories caused a dramatic change of powertrain selection. For the HGV vehicle parc in 2050 electric powertrains and the newly introduced diesel revolution powertrains get selected over gas fuelled and gas diesel hybrid vehicles.

The change can be attributed to the optimised usage, updated CAPEX, OPEX, efficiency and payload and illustrates the impact of techno-economic data as well as operators’ input on the overall modelling outcome. Quantification of the individual effects needs further exploration.

The vehicle parc constructed in the Freight model gives a greater variety of powertrains as a result of the choice model implemented. The absence of emission constraints in the base case resulted in only a few hydrogen vehicles being introduced from 2030 with most vehicles in 2050 being gas or diesel fuelled due to their lower TCO.

This resulted in higher emissions compared to the ESME new vehicle base case (7.38Mt of CO2 in the Freight model case compared to 4.84Mt of CO2 in the ESME new vehicle base case). Higher HGV emissions in the ESME Freight model case mean that emissions from other sectors (hot water and heat supply and power generation) are reduced to achieve the 80% reduction target.

<table>
<thead>
<tr>
<th>Table 8: Modelling cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ESME model</strong></td>
</tr>
<tr>
<td>1. Base case:</td>
</tr>
<tr>
<td>a) standard case</td>
</tr>
<tr>
<td>b) new vehicle ‘base case’</td>
</tr>
<tr>
<td>c) Freight model</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2. Stricter legislation:</td>
</tr>
<tr>
<td>4. CCS deployment:</td>
</tr>
<tr>
<td>a) CCS doesn’t materialise</td>
</tr>
<tr>
<td>b) CCS is delayed by 10 years</td>
</tr>
<tr>
<td>5. Motorway catenary charging</td>
</tr>
</tbody>
</table>
Comparing the ‘ESME new vehicles’ cases to the ‘ESME Freight model’ cases indicates that the availability of new powertrains will need to be complemented with other measures and interventions in order to reduce emissions from the HGV sector. Operators’ costs, infrastructure and deployment need to be aligned to support the inclusion of zero emission powertrains on a large scale, i.e. encourage operators to select such vehicles.

In terms of stricter regulations, the modelling confirmed that a target of 80% reduction in carbon emissions can be achieved by following the limits set by the EU regulations. To understand mechanisms to reduce emissions further the impact of stricter regulations was evaluated, where only new sales of zero emission vehicles are allowed from 2040. In this scenario a zero-emission powertrain is selected for the whole fleet (Figure 4). As electric powertrains have lower cost, they are selected over hydrogen powertrains. For both the base case and the stricter legislation scenarios the diesel revolution vehicle is selected by the system before 2040. The diesel revolution powertrain, with lower emissions compared to the gas vehicles is selected over gas powertrains up to 2040, making up a good proportion of the vehicle parc. When regulations for zero emission vehicles are introduced the diesel revolution powertrain is replaced by electric vehicles.

The aim of the shift demand scenario was to represent a concept of more distribution centres around cities with an increased number of smaller vehicles delivering goods within the cities. This shifting of demand had a significant effect on the number of MGVs on the road; the vehicle parc in 2050 grew by 6.5 times. Demand increases from 2030, initially covered by liquid fuelled vehicles, but from 2040 a sharp increase of electric and hydrogen vehicles can be seen across the cases as the road to zero policy is implemented (Figure 5). This shift resulted in a decrease in overall CO2 emissions by about 10% in 2050, where a slight increase in emission ratios to MGVs and LGVs can be observed (Figure 6).
Generating hydrogen from fossil fuels with near to zero emissions requires the use of CCS. In the absence of CCS, hydrogen is produced from electrolysis. The delayed deployment of CCS from 2040 onwards and excluding hydrogen utilisation in the transport sector remains at similar levels compared to the new vehicles base case (Figure 7). Hydrogen utilisation in the industry sector most, consuming less hydrogen from 2040, consequently resulting in higher ratio of net emissions (Figure 8). As the energy system would need to achieve its carbon emissions target in 2050, the HGV fleet is fully converted to zero emission vehicles for the no CCS case and there is an increase of battery powered HGVs in the delayed CCS case (about 40% more).

4.5 Freight Model results

In the base case, the TCO view for the operator is very similar across the 13 categories for natural gas powertrains. Driven mainly by the lower natural gas price ‘at the pump’. For battery powertrains, the TCO view is marginally different across the 13 categories and it is very dependent on the average daily mileage and therefore, the battery capacities of the vehicles in each of the categories.

• Battery vehicles become competitive for all 3 axle artic categories in the 2035–2040 timeframe except for the haulage 3 axle artic category and FMCg category (2045) with powertrains optimised for UK daily mileages and follow the trend of the liquid haulage 3 axle artic, as shown in Figure 9. Battery vehicles are the second cheapest on a TCO basis, battery vehicles are competitive in all rigid vehicle categories in the 2025 timeframe, and are selected more frequently after that time. In all rigid vehicle categories except the haulage 2 axle rigid the battery powertrain is the cheapest from 2045 onwards.

Due to the lower daily mileage a smaller battery capacity is needed, reducing the TCO for battery powertrains in 2 axle articulated categories. In all 3 axle artic categories they have the lowest TCO and in other categories they are only surpassed by battery vehicles beyond 2025. The diesel revolution vehicle has the lowest TCO of all carbon fuelled vehicles. All vehicles which utilise hydrogen have a very high TCO, even when the powertrain is optimised for daily driving distance.
The competitiveness of all battery vehicles increases as the vehicle costs decrease through the years and due to the reduction in investment costs of the chargers as the number of chargers installed is increased. The spike in battery powertrains’ TCO in all segments in 2025 has been attributed to an increase in electricity commodity price compared to 2024.

Across the whole freight vehicle parc there is a wide mix of vehicle powertrain deployments. Gas vehicles are favoured by all categories in the short and long terms with significant declines in diesel sales (Figure 10). Unsurprisingly, in consideration of TCO, hydrogen vehicles are deployed in very small numbers in only a few categories. Across the entire fleet diesel sales decline sharply as natural gas vehicle sales pick up and make up most vehicles in the fleet beyond 2025. Battery vehicles start to be deployed in significant numbers beyond 2030 and they make up a good portion of the entire fleet in 2050 as it is illustrated in Figure 11.
In the stricter legislation scenario, where only zero-emission new vehicles are sold from 2040 onwards, the sales of hydrogen and battery vehicles are increased when gas and diesel vehicles can no longer meet the carbon target.

In this scenario, the TCO view for the operator is similar to the base case scenario (see Figure 12). It illustrates when (on a TCO basis) the battery vehicles become competitive among the different segment categories. A main difference is the drop of TCO between the two scenarios. In the stricter legislation scenario, there are only three zero-emission options for new powertrains from 2040 onwards. Interestingly, based on the choice model, hydrogen vehicles are selected by operators despite having higher TCO. The increase in required hydrogen infrastructure combined with the learning rate applied on the infrastructure cost leads to the TCO dropping faster in the stricter legislation scenario compared to the base case scenario, especially for hydrogen vehicles. Even though the increased deployment of hydrogen vehicles is gradually leading to a reduction in the TCO, the cheapest option between the three powertrains with no tailpipe emissions is still the battery powertrain in all category segments.

Figure 12: Comparison of TCO between base case and stricter legislation scenarios

Across the whole freight vehicle parc a wide mix of vehicle powertrains is deployed up to 2039. From 2040 onwards the battery vehicles are favoured by the other two categories as it is shown in Figure 13. Hydrogen vehicles are deployed in higher numbers compared to the base case scenario.

By 2050 the number of diesel and gas powertrains in the market drops significantly. There are no sales of new gas or diesel vehicles after and including 2040 and a significant number of vehicles are coming to the end of their lifecycle. As shown in Figure 14, the battery is the main powertrain in the HGV fleet. Comparing Figure 11 and Figure 14 shows that with stricter legislation the deployment of powertrains with no tailpipe emissions is enhanced enormously. The results illustrate that the application of stricter regulations is a powerful means to achieve a low carbon emissions energy system.
The scenario introducing a shift of demand from HGVs to MGVs is replicated in the Freight model as follows: between in 2020 and 2029 5% of the overall annual demand is shifted from the HGV sector to the MGV sector. From 2030 onwards 10% of the overall demand is shifted from the HGV to the MGV. Figure 15 shows the distinct drop in total HGV powertrains in 2020 as well as in 2030.

In the shift demand scenario, the TCO view for the operator is similar to the base case scenario and the choice of HGV powertrains was not affected by the reduced demand.

The gas vehicles are favoured by all categories in the short and long term with significant declines in diesel sales. As the Freight model focuses on the HGV sector alone, the shift demand results from the Freight model are not providing enough insights about the impact on the emissions of the transport sector overall, demonstrating the importance of considering these outcomes in the whole energy system model.

The TCO of vehicles which utilise hydrogen in all three scenarios is significantly higher compared to the other powertrains; a main contributor being the high vehicle costs of hydrogen powertrains.

Each scenario results in changes in the powertrain composition across the fleet. As a result, different numbers of refuelling stations are required among the different scenarios. The change of refuelling stations of gas, hydrogen and the number of electric chargers for each scenario from 2040 to 2050 is illustrated in Figures 16 to 18. As expected, the number of gas refuelling stations in 2050 is lowest in the stricter legislation scenario and highest in the base case scenario (Figure 16). More hydrogen refuelling stations are built during 2050 in the stricter legislation scenario compared to the other two scenarios, since the deployment of vehicles utilising hydrogen is higher (Figure 17). The number of electric chargers in the stricter legislation scenario is significantly higher compared to the other two scenarios as the main powertrain in the fleet is battery powered, requiring the installation of an increased number of chargers (Figure 18). Consequently, a higher number of hydrogen refuelling stations or electric chargers could result in a reduction in fuel prices (Figure 19) and thus, in a reduction of TCO of the powertrains (as seen in Figure 12).
Modelling

As an example, the prices for electricity and hydrogen in the stricter legislation scenario are lower compared to the other two scenarios from 2040 onwards; in 2050 the electricity prices are 0.3p/kWh lower and the hydrogen prices are 2£/kg lower.

This is thought to be driven by the learning rate for the infrastructure cost, affecting the fuel prices per year. The increased number of chargers installed, and the increased number of hydrogen stations built in the stricter legislation scenario results in reduced CAPEX of the infrastructure and leads to a reduction in the fuel price. In order to compare fuel prices across the energy vectors, fuel prices are shown in £/MJ (Figure 19). Hydrogen is much higher priced compared to alternative fuels. As commodity prices of the fuels are not significantly different, it is likely that the more expensive infrastructure for the hydrogen refuelling stations is the main contributor to the high price at the pump. It should also be noted that the electricity price becomes competitive between 2030–2035.

Figure 16: Number of gas refuelling stations in each scenario in 2040 and 2050

Figure 17: Number of hydrogen refuelling stations in each scenario in 2040 and 2050

Figure 18: Number of electric chargers in each scenario in 2040 and 2050

Figure 19: Fuel price in base case scenario
4.6 Discussion of results

The eSMe results presented gave a whole energy system view of the effect of the different scenarios whereas the Freight model provided a detailed look into the vehicle parc.

For all cases the eSMe results showed the importance of zero emission vehicle deployment in the HGV sector. As the project aimed to show the effect the operators’ choices have on the energy system, the outputs of the Freight model were used in eSMe. Results showed that when allowing the operator choice model to dictate the vehicle parc it allowed for higher emissions in the transport sector, which were compensated by reduced emissions in other sectors.

A commonality across all scenarios and models was that when regulations are set to control emissions from HGVs, electric powertrains were selected over hydrogen powertrains as their cost is predicted to be lower. In the Freight model battery vehicles start to be deployed in significant numbers beyond 2030 and make up a good portion of the entire fleet in 2050. More specifically, battery powertrains were more competitive in the segment categories which have low daily mileage and thus, a smaller battery capacity is needed.

High infrastructure CAPEX and vehicle costs resulted in a higher TCO for the hydrogen vehicles making them less competitive in both models. Since hydrogen vehicles can offer more advantages to the operator compared to a battery vehicle, such as faster refuelling and longer ranges, the mechanisms that will allow hydrogen vehicles to be competitive will have to be explored in future work.

To better understand how the refuelling and charging infrastructure will affect the decarbonisation of the energy system the consideration of the emissions produced during fuel generation, transmission and distribution needs to be assessed in the future. This was also concluded by the work published by the ETI (2019) due to the difference in powertrain cost, the deciding factor between hydrogen and electric powertrains will be the infrastructure costs and practicalities around fuel dispensing and distribution.

Regarding gas and diesel powertrains the same behaviour can be seen in both eSMe and the Freight model in all scenarios. Across the entire fleet diesel sales decline sharply as natural gas vehicle sales pick up and make up most vehicles in the fleet beyond 2025. The introduction of the diesel hybrid and the diesel revolution powertrains in both models results in a portion of diesel vehicles in the HGV fleet in 2050. Based on the modelling results the diesel revolution should be considered in future results as a transition vehicle to a zero-emission energy system.

Results showed that the quickest transition to less carbon intensive HGV fleet occurs with the introduction of stricter legislations from 2040 onwards. In the scenarios with stricter legislation the deployment of battery powertrains is very high after 2040 and by 2050 they are the main powertrains in the HGV fleet. The EU regulation case was only modelled in eSMe and had no further effect on the powertrain choice compared to the base case. Even though it’s a softer regulation compared to forcing the sales of only zero emission vehicles from 2040, such regulations would still enforce a gradual uptake of zero emission vehicles, and they will push operators into adopting such vehicles within their fleet.

Even though current cost projections on infrastructure and vehicles, electric powertrains look more attractive to the system, results showed the value that eSMe and the Freight model place on zero emission HGVs. Furthermore, results showed that a reduced emission diesel powertrain is selected by the model, thus these powertrains can be used as transition vehicles along with plug in hybrid vehicles. The measures that need to be taken to push operators to a higher uptake of zero emission vehicles would need to be further explored along with the pathway to provide the necessary infrastructure to support the large volume of zero emission vehicles by 2050.

The shift demand scenario did not affect the preference of the powertrain choice among the HGV operators as shown in the Freight model. Even though demand was reduced, the same powertrains were selected. At a system level though, shifting demand had a positive effect on the transport sector. By shifting demand to MGVs, emissions from the HGV sector were reduced and additional vehicles that will be required in the MGV and LGV sectors were all zero emission vehicles as the road to zero targets were implemented in the eSMe model. The total system cost was increased compared to the base case since the number of vehicles in the MGV and LGV sectors were increased but the total transport emissions were reduced.

Furthermore, deployment of hydrogen vehicles in the MGV sector was drastically increased. Further work on how the increased deployment of hydrogen vehicles in the MGV sector can reduce infrastructure and fuel costs for hydrogen vehicles in the HGV sector should be explored. To better understand the concept local implications will need to be considered. Issues such as additional electricity or hydrogen demand and infrastructure requirements, increased traffic and land for additional depots will have to be evaluated further as the current work only looked at the energy system implications.

The effect of CCS availability in the energy system was also modelled. In both cases, delay of CCS deployment and no deployment, the deployment of electric powertrains in the HGV fleet was increased. Higher hydrogen prices affected the decarbonisation of industry and heat and hot water generation, forcing emissions from the HGV sector to be reduced.

When catenary motorway charging was included in the whole system model, this was envisaged as an alternative to battery vehicles. However, due to the high infrastructure costs, the technology was not selected by the model as part of the vehicle parc. Further work on vehicle and infrastructure costs as well as deployment plans would need to be done to be able to justify options of including this technology in the future vehicle parcs.
5. Conclusions

5.1 Key learnings

Introducing the HGV operators’ view and updating powertrain data into the whole energy system model had a significant effect on the overall modelling outcome of the HGV transport sector and reflects the importance of keeping fundamental modelling inputs up to date and tailored to the application.

However, the availability of new technologies alone will not achieve required emission targets. Including HGV operators’ decision parameters and behaviours into the modelling could inform policy interventions aligning operators’ choice with the required deployment of technologies and infrastructure.

Regarding the modelling outputs the following key points were observed:

**Powertrains**

The introduction of new powertrains and vehicle categories optimised to operators’ usage and updated techno-economic data affected the ESME vehicle parc. Quantification of each of these impacts will need further investigation. Electric vehicles are more cost competitive compared to hydrogen powertrains. To support uptake of hydrogen vehicles in the HGV sector efforts should be made to reduce technology costs. Further to cost reductions, other factors related to the operation of vehicles should be considered. Diesel fuelled vehicles with improved emissions could be used as transition vehicles.

**Infrastructure**

As with the vehicle costs, higher infrastructure costs for hydrogen resulted in a higher TCO for the operator. Based on a mix of generation technologies, the commodity price of hydrogen was comparable to the electricity price. High CAPEX costs for the refuelling stations increased the fuel price the operators see resulting in lower uptake of hydrogen vehicles. Similarly, catenary vehicles were not cost competitive because of high infrastructure costs.

**Policy**

Enforcing stricter regulations on emissions is likely to support the quickest transition to a zero emission HGV fleet. By 2050 the vehicle parc could move to zero emission vehicles. The methods by which policy can support operators in the transition to zero emission powertrains and mechanisms to ensure infrastructure is in place will have to be further explored.

**Literature review**

Prior to the workshops there was an extensive literature review conducted by the APC team. However, one thing that became clear reasonably early on in the project was that it was challenging to source the detailed data required for the ESME model from a literature review alone. Due to the timeframes and the commercial sensitivity surrounding some of the information in terms of cost and uptake of technologies it was not always easy to get the accurate information required for the modelling from industry sources. In addition to this, the literature review was conducted prior to the modelling beginning. In hindsight, the literature review should have been completed in parallel to the modelling so that the review could respond to the need for additional data as the complexity of the model increased.

The morning presentations were followed by each member of the team taking a specific topic of interest and moving around the stakeholders rather than asking the stakeholders to move. This meant that relationships were formed between stakeholders and they therefore, felt more comfortable giving their perspectives on the individual topics. However, the workshops emphasised that the sector categorises vehicles by wheel plan and operation segment. This outcome was reflected in the modelling and affected the results. Quantification of the impact should be further explored, but it is an indication of the importance of considering the operators’ view.

For future work it would be useful to have more time to interpret the data to understand how the results align with workshop outputs, and to have further discussions with industry representatives to obtain additional input data required. One of the hurdles is to ensure that a common language between the two sectors can be found. In addition to this there is a challenge with diversity within these sectors so to improve the gender balance for future events it may be necessary to target specific individuals.

The workshops worked very well; having two workshops in different parts of the country meant that there was a very broad range of stakeholders consulted. Each workshop involved several presentations to start the day, to provide insight into the ESME model and to give some thought provoking concepts.
5.2 Limitations and barriers

With this topic being very of the moment there is not a huge amount of publicly available data. There is some data from the academic community however, facts and figures in terms of costs, particularly those around infrastructure are very limited. This is recognised in the future work proposals through recommendations to work selectively with some commercial partners in the future. Some data gaps were identified and potentially could form future work or partnerships going forward. This includes gaps in powertrain and infrastructure uptake in terms of a cost projection versus time.

The following limitations of the input data should be noted:

- Challenges over future powertrain data is very scarce (including data on cost and fuel consumption), much of the research within this area is currently being conducted within the academic community so not fully demonstrated or published. In addition to this when commercial trials are undertaken these are generally not publicly available due to the competitive nature of the sector.
- As for all modelling endeavours, outcomes are only as good as the quality of the input data. Where data is lacking in this project, assumptions were put in place which should be checked once data are available.
- Data for construction rigid axle 4 are based mainly on assumptions.
- Projections for the hydrogen commodity price is not available and the values were generated from ESME.

The following limitations of the prototype Freight model should be noted:

- The model calculates an average fuel price for all the gas stations; i.e. the same gas price is used for CNG LTS, CNG IP, LNG, LCNG. Future work to differentiate the gas price for each gas station type is proposed.
- No differentiation is included between how many stations of LNG and CNG are built.
- The price of specific fuel for private infrastructure in each year is calculated based on the average price of all private stations (i.e. all private infrastructure of the same fuel belongs to the same operator).
- The fuel price in the Freight model is calculated assuming that the refuelling stations will be used in full capacity from year 1 until the end of their lifetime. However, in the model it is assumed that the infrastructure exists even if one vehicle utilising the specific fuel is deployed. Therefore, higher prices than the prices the Freight model generates might be needed for the cost recovery of the infrastructure.
- The regression used in the Freight model allows each powertrain category to be selected even if the TCO is very high. In the Freight model hydrogen powertrains are selected although their TCO is high. Future work is needed to restrict the choices of powertrains based on a maximum value above the minimum TCO so that the powertrains with extremely high TCO are not selected.
6. Future research opportunities

Based on the findings of the modelling work, limitations and outputs of the workshops, a set of future work topics were identified. The prototype Freight model developed as part of this project can be updated to enable more functionalities. Future research topics are presented in Table 9.

Table 9: Future research

<table>
<thead>
<tr>
<th>Research area</th>
<th>Details</th>
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<tbody>
<tr>
<td>Net zero emissions by 2050 targets</td>
<td>As net zero targets were set while the project was ongoing, the ESME model was set up with an 80% emission reduction target. Reflecting the current political climate, it is proposed that the models and scenarios developed within the project are run in a net zero emission context.</td>
</tr>
<tr>
<td>Charging and refuelling infrastructure</td>
<td>Refuelling stations were split between private and public ownership and different costs were used. As infrastructure is seen as one of the defining factors for the vehicle choice, more detailed representation of infrastructure requirements and costs per segment would provide more granularity to the results. For example, based on the energy consumption different types of chargers can be used for each segment. Furthermore, the model can be expanded to show different pathways for hydrogen and electricity generation. For example, in the current model hydrogen is assumed to be generated on site with an average value used for the cost of the generation. The model can be further developed to include different methods for generation, transmission and delivery to the stations.</td>
</tr>
<tr>
<td>Vehicle powertrains</td>
<td>Certain vehicle powertrains were excluded from the scope of this work due to lack of data. It is recommended that these powertrains should be included in the model when data becomes available as these could be used as transition vehicles in reducing emissions from the HGV sector. Some examples include gas/electric hybrid and diesel/electric hybrid powertrains.</td>
</tr>
<tr>
<td>Scenarios</td>
<td>The workshops resulted in the formulation of various scenarios describing pathways for the decarbonisation of the freight sector but not all the scenarios were modelled within this project. A few examples include the implementation of taxation or incentives to promote zero emission powertrains and shifting demand from road to rail transport. It is therefore proposed that these scenarios will be modelled in the future to answer more of the industry questions around the potential routes to reduce emissions from HGVs.</td>
</tr>
<tr>
<td>Infrastructure synergies</td>
<td>The Freight model currently does not include infrastructure built for MGVs and passenger vehicles (where appropriate). This could reduce the TCO calculated by the model where new infrastructure is benefitting not only HGVs in the transport sector and consequently could potentially improve the uptake of the relevant powertrain options.</td>
</tr>
<tr>
<td>Lifecycle emissions approach</td>
<td>The model does not include emissions associated with the manufacturing of vehicles and vehicle components like the batteries used in electric powertrains. It is proposed that as net zero emission targets are set, the Freight model is updated with lifecycle emissions capabilities.</td>
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Table 9 cont.

<table>
<thead>
<tr>
<th>Research area</th>
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<tr>
<td>Validating / evaluating assumptions Sensitivities on assumptions</td>
<td>The lack of data was listed as one of the limitations the project encountered. It is therefore proposed that assumptions made are validated either by further research or by sensitivity analysis.</td>
</tr>
<tr>
<td>Air quality</td>
<td>Air quality related emissions should also be considered in future work. As ESME capabilities expand and air quality modules are introduced within the tool the scenarios modelled can be updated with further optimisation objectives to meet air quality constraints. This could potentially affect the vehicle parc composition.</td>
</tr>
<tr>
<td>Well-to-motion pathways</td>
<td>For the purposes of this project, the well to motion pathways for gas in the WtM model were simplified. Having the capability to evaluate the entire well-to-motion pathways for gas, electricity and hydrogen would add further value to the Freight model. In addition to re-introducing the gas well-to-motion emissions calculation, well-to-motion emission calculations could be developed for the other energy vectors used. This would allow emissions to be calculated for each station category separately.</td>
</tr>
<tr>
<td>Penalty value and penalty end year for gas, hydrogen and electric vehicles</td>
<td>A penalty on sales was introduced to reflect operator’s hesitation towards new technologies. The same value was used across all vehicle segments and powertrain options. Future work around identifying in which segments operators are more hesitant to adopt certain technologies would better refine these assumptions and would provide a more accurate representation of operator’s behaviour within the model.</td>
</tr>
<tr>
<td>Motorway catenary charging</td>
<td>Motorway catenary charging was included in the ESME model but not in the Freight model. Future work is needed on how the operators’ behaviour changes and which powertrains are selected when catenary powertrains are added to the fleet.</td>
</tr>
<tr>
<td>Development of an integrated toolset</td>
<td>In this project the Freight model was developed to reflect the operator’s choice on HGVs and the modelling outputs was used to assess the impact these choices have on the energy system in ESME. The data were transferred manually and not iterated. Automating the data transfer and introducing a feedback loop to inform the choice model with energy system implications and constraints, would add value to both models and would offer a more holistic view.</td>
</tr>
<tr>
<td>Competitiveness of powertrains</td>
<td>Investigate the parameters which need to be influenced and by how much for the hydrogen powertrains to be more competitive, e.g. subsidies on hydrogen infrastructure. Investigate the parameters which need to be influenced and by how much for the diesel and gas powertrains to be less competitive compared to battery in the long run, e.g. tax on fuel.</td>
</tr>
<tr>
<td>Distribution hubs around cities</td>
<td>The modelling results showed that in the scenario where demand is shifted from HGVs to smaller vehicles emissions from the HGV sector are reduced. This scenario would benefit from further investigation to better understand the infrastructure and additional energy requirements and the impact on traffic and land use.</td>
</tr>
<tr>
<td>Transition to a zero-emission fleet</td>
<td>The transition to zero emission vehicles and the infrastructure required to support zero emission vehicles will need to be further explored. The Freight model with the added modules on detailed infrastructure options and well to motion emissions will be able to provide recommendations on what steps would need to be taken for an optimised transition to a zero emission fleet.</td>
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</table>
Throughout the duration of this project the team engaged with different stakeholders from government, industry and academia. This activity flagged up several other activities that were currently occurring within the heavy-duty landscape. Table 10 below, gives further information of where future research and collaborations could take place, building on the discussions during the project.

Table 10: Future collaborations

<table>
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<tr>
<th>Organisations</th>
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<tr>
<td>Connected Places Catapult (CPC)</td>
<td>CPC are currently working with the Department for Transport (DfT) on the barriers for adoption of certain powertrain solutions for the heavy-duty freight market. It is suggested to review the work to compare and align assumptions and as a next step combine capabilities for future work.</td>
</tr>
<tr>
<td>Office of Low Emission Vehicles (OLEV)</td>
<td>One of the challenges with developing scenarios is looking at creating the right economic model to deliver on these various low carbon solutions for the future. There is often a large upfront capital cost in the infrastructure required to meet the demands of these future powertrains. Therefore industry needs to work alongside the UK Government departments e.g. Department for Transport, Department for Business, Energy and Industrial Strategy, Office of Low Emission Vehicles to ensure that the development of future fiscal models in terms of incentives / subsidises / infrastructure are in line with what is affordable not only to industry but the consumer as well. Such fiscal models provide a real opportunity to drive behaviour and deliver on the future emission targets.</td>
</tr>
<tr>
<td>Department for Transport (DfT)</td>
<td>A useful piece of work would be to collaboratively work with Highways England to understand their future planned investment in infrastructure and inform the models in accordance with when these are expected to occur. Understanding the current assumptions that are made by organisations such as Highways England in terms of the future technology mix as well as their proposed infrastructure investments particularly on routes like the Strategic Road Network would be of high interest.</td>
</tr>
<tr>
<td>Department for Business, Energy and Industrial Strategy (BEIS)</td>
<td>Due to the sensitive nature of much of the data that is required regarding powertrains, running and infrastructure costs there is an opportunity for future work to look at running some test cases. This could be done with the hauliers from the different sectors e.g. retail, consumables. These operators will have different requirements from their vehicles. Future projects could include working with the operators such as UPS, John Lewis or DHL who are very keen on decarbonising their fleet. Currently the LowCVP works with organisations such as the DfT and these hauliers to run real world testing for low carbon solutions so this is seen as a future opportunity for collaboration.</td>
</tr>
<tr>
<td>Low Carbon Vehicles Partnership (LowCVP)</td>
<td>With the commitments being made to achieve net-zero emissions by 2050 from the UK Government there is a need to look at how technology projections such as Carbon Capture and Storage (CCS) have an impact on the scenarios. Understanding how funding in Industrial Strategy Challenge Funds (iSCF) supports the development of these technologies as this could have an impact on uptake and timetables in terms of delivery of suitable vehicles to the operators. Inputting their planned projections and timetables into the model could give provide some evidence for the investment in the required supporting infrastructure. iSCF programmes which would be particularly relevant would include the Faraday Battery Challenge and Driving the Electric Revolution. However, it must be ensured that the assumptions that are made are up front and centre.</td>
</tr>
<tr>
<td>UK Research and Innovation (UKRI) Industrial Strategy Challenge Fund (iSCF)</td>
<td>Catenary systems may still be a potential option within the UK’s road network. Trials are currently occurring in Germany and within the UK the Centre for Sustainable Road Freight in Cambridge are investigating this as a viable solution for the UK. This poses an opportunity to update the data and model with the costs for both infrastructure development and vehicle requirements. This work could be done in collaboration with Highways England who manage the Strategic Road Network, aligning the model assumptions with updated costs and planned investment in infrastructure.</td>
</tr>
<tr>
<td>Centre for Sustainable Road Freight</td>
<td>With the commitments being made to achieve net-zero emissions by 2050 from the UK Government there is a need to look at how technology projections such as Carbon Capture and Storage (CCS) have an impact on the scenarios. Understanding how funding in Industrial Strategy Challenge Funds (iSCF) supports the development of these technologies as this could have an impact on uptake and timetables in terms of delivery of suitable vehicles to the operators. Inputting their planned projections and timetables into the model could give provide some evidence for the investment in the required supporting infrastructure. iSCF programmes which would be particularly relevant would include the Faraday Battery Challenge and Driving the Electric Revolution. However, it must be ensured that the assumptions that are made are up front and centre.</td>
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7. Future Collaborations

Future collaborations cont.
8. UKERC Whole System Network Funding

8.1 Gender balance

Team breakdown

The ambition of the UKERC Whole Network Funding programmes is to increase the gender balance within the project portfolio. The Decarbonising Road Freight Project team was selected based on both the basis of experience and expertise but considering the requirement of gender balance.

The core project team had an 83% female representation. With regards of the overall project effort, female contributions exceeded 76%.

Workshops

The Standard Industrial Classification (SIC) is a system for classifying industries by a four-digit code. Established in the United States in 1937, it is used by government agencies to classify industry areas. The SIC system is also used by agencies in other countries, e.g., by the United Kingdom’s Companies House. When looking at the SIC code that represents the Manufacture of motor vehicles, trailers and semi-trailers within the UK the gender balance is 86% male to 14% female. This does not improve significantly when you look at the SIC code that represents Wholesale and retail trade and repair of motor vehicles and motorcycles which breaks down to 83% male to 17% female. The UK’s Automotive Council is trying to address this imbalance and have formed a Diversity and Inclusion group. It is recognised by this group that diversity and inclusion not only improve the range of products that are being designed and developed, but it significantly improves a business’s competitiveness.

With this data and having experience of the sector the team was aware that one of the main challenges would be to get a good gender diversity at the workshops. The Birmingham workshops had 31 attendees of which only 5 were women. Traditionally an automotive manufacturing area, the resulting gender split of 84% male to 16% female is a fair representation of the current state of the industry.

At the London workshop efforts to increase female participation were more successful. Out of 38 attendees 9 were women resulting in a gender split of 76% male to 24% female.

The team invited as many females as possible with the appropriate expertise within this area. However, the workshop gender split showed that networking could not compensate significantly for the lack of female representation in the sector.

8.2 Impact for whole systems energy research

Impact for whole systems energy research and/or uptake of science/evidence for energy system transformation: the activity cannot benefit only an individual, or a single institution or even a specific discipline. Networking activities must be collaborative and cohesive.

This project brought together two different sectors to address the challenging area of decarbonising road freight. Moving towards a future of net-zero emissions the entire system needs to be considered. This was one of the first projects that has brought together two of the largest carbon emitting sectors collaboratively to look at energy and transport as one system. The workshops brought together different organisations from across the modes of transport in an attempt to capture the knowledge and insight from sectors such as rail and aerospace. In addition to this bringing in the energy sector who will ultimately need to provide the energy to these modes of transport.

The networking sessions of the project team and through the workshops has been a very positive experience. This can be seen through some of the suggestions for future collaborations. In addition to this a few quotes from some of the attendees from the workshops are listed below:

‘Thanks for this today. I think this was one of the best workshops on this type of subject I have been to in a while … the way the team moved round the tables worked really well to make sure the discussion flowed and cover the areas you wanted I feel.’

ULEMC – Attendee London workshop

‘The workshop up at the IMechE last week certainly provided some interesting discussion and I look forward to seeing the outcome of the study.’

Cox Powertrain – Attendee London workshop

‘Thoroughly enjoyed the Technology Trends Workshop on 8th April.’

Gasrec – Attendee Birmingham workshop

8.3 New voices

New voices: whether aimed at, or proposed by, early career researchers or bringing institutions together that have little interaction, the project must bring new, diverse, voices to the table.

In 2018 the Advanced Propulsion Centre (APC) and the Energy Systems Catapult (ESC) were brought together by the UK Energy Research Council (UKERC) and a workshop was held between the two teams to investigate possible research opportunities through forming this new partnership. The ESC and APC were familiar with each other’s organisation but had never thought of collaborating on a project. During the initial meeting multiple topics were discussed but it was deemed that the greatest opportunity for making use of both parties networks and expertise was seen to be the challenge that surround the UK’s need to define a cost-effective pathway to decarbonise road freight across the UK’s transport and energy systems. This project enabled a cross-sector activity to start from the outset bringing together networks from across the transport and energy sectors with great representation from industry, government and academia. Collaboratively a more robust understanding was developed of the influence that the propulsion systems of HGVs will have on the whole energy system.

The project benefitted from this highly collaborative approach from the start which was channelled into the stakeholder workshops to inform the modelling and analysis. The team believes that this work is an important step to help the transport and energy sectors align and work together.
### 8.4 Not business as usual

The Whole Systems Network Fund facilitated a strong alliance between ESC and APC in a short time frame. By working together, expertise from the automotive sector from industry and academia was used to improve the energy system modelling tool ESME and to develop the Freight model. Development of this relationship will continue as there is much more that can be done to support the UK in its transition to net-zero emissions.

### 8.5 Measures of success

Within the original proposal there were five important outcomes for the planned work. These are detailed below with information about how these requirements were met.

1. It will provide a set of scenarios in terms of future energy options to support understanding of upcoming needs for heavy duty and off-highway vehicles.

   Through running the workshops and conducting an intensive literature review the team were able to develop several scenarios. These are detailed above in the main body of the report. However, it was clear that just having the ESME model was insufficient and scenarios were complemented by detailed vehicle parcs provided by the Freight model.

2. ESME analysis of these scenarios will enable examination of the impact of different heavy-duty propulsion technologies on the wider energy system.

   These scenarios were fed into the model with the outcomes detailed above. Of particular note was the importance of detailing the assumptions that were made when running the model, if the UK is going to deliver a joined-up approach.

3. Make close connections between modelling and the ‘real world’ such as the thoughts and beliefs of key stakeholders by means of collaboration and co-creation.

   The team has worked very closely over an extended period to question the assumptions of the models that are being used by providing real world data. The team has engaged with many cross-sector stakeholders to ensure that the most up-to-date information and insights have been used to inform the models within this project.

4. Articulate industry needs in R&D and innovation to a broad range of academics across the energy system outside the directly automotive tech sector and encourage dialogue on these (‘ideas from the ground-up’).

   The project has been successful in engaging not only a group of cross-sector stakeholders but has worked with government organisations, industrial leaders and key academic experts within the automotive and energy sector. The project team used the content and data provided by the APC technology roadmaps which highlights the short, medium- and long-term R&D challenges that need to be addressed by industry and academia.

5. Generate new combinations of stakeholders across both the automotive and energy systems sectors who are engaged in the problem of freight decarbonisation and are more likely to collaborate on further projects.

   Both the workshops were very well attended and engagement with many of the stakeholders has continued post these events. In addition to this, there are multiple areas that have arisen of not only organisations where future collaboration could occur but also the opportunity of various types of research that could occur going forward. Details of these collaborations have been included in the report.

### 8.6 Authors

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  Advanced Propulsion Centre

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  Committee for Climate Change

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  UKERC

- David Stoker
  Communications Officer
  UKERC

- Liam Lidstone
  Business leader, Infrastructure and Engineering
  Energy Systems Catapult
9. Appendix

References


Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>DfT</td>
<td>Department for Transport</td>
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<tr>
<td>ESME</td>
<td>Energy System Modelling Environment</td>
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<tr>
<td>ETI</td>
<td>Energy Technologies Institute</td>
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<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>HDV</td>
<td>Heavy Duty Vehicle</td>
</tr>
<tr>
<td>HGV</td>
<td>Heavy Goods Vehicle</td>
</tr>
<tr>
<td>IP</td>
<td>Intermediate Pressure</td>
</tr>
<tr>
<td>LCNG</td>
<td>Liquefied-to-compressed natural gas</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>LTS</td>
<td>Local Transmission System</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operational Expenditure</td>
</tr>
<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
</tr>
<tr>
<td>WtM</td>
<td>Well to Motion</td>
</tr>
<tr>
<td>ZEV</td>
<td>Zero-emissions Vehicle</td>
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</tbody>
</table>

Posada, F., et al., 2016. Costs of emission reduction technologies for heavy-duty diesel vehicles, s.l.: ICCT.
Saur, G., et al., 2018. State of the art fuel cell voltage durability and cost status, s.l.: NREL.
James, B. D., 2016. Hydrogen and fuel cell program review, fuel cell vehicle and bus cost analysis, strategic analysis, NREL, ANL, s.l.: s.n.
Moultac, M., et al., 2017. Transitioning to zero emission heavy duty freight vehicles, s.l.: ICCT.
Transport and Environment, n.d. s.l.: s.n.
Catenary vehicles

The catenary technology was deployed in 10 phases and each phase supported a specific number of vehicles as summarised in Table 11. The maximum amount of catenary that can be deployed is covering 75% of motorways and 50% of A roads. For the catenary scenario four additional powertrains were considered as it is represented in Table 12.

Table 11: Catenary deployment phases

<table>
<thead>
<tr>
<th>Phase No</th>
<th>Total Length (km)</th>
<th>Cumulative Length (km)</th>
<th>No of Vehicles Supported</th>
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<tr>
<td>1</td>
<td>20</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>175</td>
<td>195</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>350</td>
<td>545</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
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<td>130000</td>
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<td>8</td>
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<td>3603</td>
<td>185000</td>
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<tr>
<td>10</td>
<td>413</td>
<td>4316</td>
<td>195300</td>
</tr>
</tbody>
</table>

Table 12: Catenary powertrains

<table>
<thead>
<tr>
<th>Catenary powertrains</th>
<th>Fuel source 1</th>
<th>Fuel source 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE Diesel PHEV Catenary Hybrid</td>
<td>Diesel</td>
<td>Electricity</td>
</tr>
<tr>
<td>PHEV Catenary with ICE RE</td>
<td>Diesel</td>
<td>Electricity</td>
</tr>
<tr>
<td>Battery Catenary</td>
<td>Electricity</td>
<td>–</td>
</tr>
<tr>
<td>Battery Catenary H2 Range Extender</td>
<td>Electricity</td>
<td>Hydrogen</td>
</tr>
</tbody>
</table>

Workshops participation

Birmingham Workshop 8th April 2019
- Advanced Propulsion Centre (x2)
- Alexander Dennis
- BAUMOT UK
- Energy Systems Catapult (x4)
- ETI
- Ford
- G-Volution
- Horiba-Mira (x4)
- Independent
- KPG Auto
- Loughborough University
- Nexans
- Punch Flybrid
- Queens University Belfast
- Railway Industry Association
- Road Gas
- SMMT
- The MTC
- Ultra-Electronics PMES
- University of Birmingham
- University of Brighton
- Vantage Power
- Vivarail
- Volvo

London Workshop 10th April 2019
- Company
- Advanced Propulsion Centre (x2)
- Aether
- Bennamann
- Brunel University
- Cadent Gas
- Cameon
- Carbotech
- Caterpillar
- Centre for Sustainable Freight
- Chelgate
- Cax Powertrain
- Dearman
- DfT
- E4Tech
- Energy Systems Catapult (x2)
- ETI
- EY
- Elevate LNG
- Gasrec
- London Fire Brigade
- Low CVP (x2)
- Millbrook
- Mint Green Services
- NCTX
- NPL
- Progressive Energy
- Ricardo
- RMI
- Transport Environment
- UkieRRC (x2)
- Ulemco
- University College London
- University of Brighton
- Zenobe
Decarbonising Road Freight