elementenergy

Analysis to provide costs, efficiencies and roll-out trajectories for zero emission HGVs, buses and coaches

Final report

for

The Committee on Climate Change

12/11/2020

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Executive Summary

Introduction

This report examines the potential rate of uptake for zero-emission (ZE) heavy-duty road vehicles (HDVs; trucks, buses and coaches) in the UK. The Committee on Climate Change (CCC) commissioned this work to feed into the setting of the 6th carbon budget, covering the period 2033-37. This will be the first carbon budget set since the new target of net-zero emissions by 2050 was announced in 2019.

After a decade of policy support, zero emission options for Light-Duty Vehicles (LDV) such as cars and vans are on track to achieve mass market adoption. However, with the exception of buses – where pressure to improve urban air quality has driven a rapidly expanding market in ZE vehicles – significantly less progress has been made in the ZE HDV market. The reasons the zero-emission truck and coach markets have not progressed to date are:

- **Policy:** Policies to support ZE vehicles and policies to penalise fossil fuel-powered vehicles are much weaker and have been implemented later for HDVs compared to LDVs.
- **Vehicle supply:** The established truck and coach OEMs are only now developing their first ZE vehicles and few are producing models for sale.
- **Operational requirements:** Many HDVs are used all day, every day. This means that they cover very high daily and annual mileages. Meeting these mileage needs requires large on-board energy storage, which is challenging to provide with batteries or hydrogen, both in terms of packaging and cost.

The early stage of development of ZE HDVs and their associated infrastructure means that it will take another 5-10 years before the industry is in a position to deploy these vehicles at scale. Given that the average lifetime of HDVs is over 10 years, meeting the 2050 target will require an end to the sale of fossil fuel powered HDVs by 2040 at the latest. These two factors mean that there is a small-time window of 5 to 10 years, between 2030 and 2035/2040, where ZE HDV production must be scaled up from a niche market initially to the majority of all HDV sales in the UK. This is a major challenge, and it will require significant investment and planning over the next 10 years to ensure that this rapid transition is possible.

Content of Report

The aim of this study is to understand the timeline and zero-emission powertrain technology mix of the UK HDV market over the next 30 years, under a range of different trajectories. These findings will support the CCC in the setting out of the 6th Carbon Budgets and will provide readers with an understanding of the policy/stakeholder actions needed to drive this market. In this analysis of ZE HDV uptake trajectories we consider 5 vehicle size categories, 4 vehicle powertrain technologies and 5 refuelling options, summarised in the table below.

Table 1: Vehicle size, powertrain and refuelling options modelled

Vehicle Sizes	ZE Powertrains	Refuelling Options
Small Rigid Truck	Batter Electric Vehicle (BEV)	In depot BEV recharging
Large Rigid Truck	Fuel Cell Electric Vehicle (FCEV)	BEV recharging at depot and public mega-charger station
Articulated Truck	Range Extended Fuel Cell Electric Vehicle (RE-FCEV)	In depot RE-FCEV refuelling
Bus	BEV or RE-FCEV with pantograph to use an electric road system (ERS)[1]	FCEV refuelling at depot and public HRS
Coach		BEV or FCEV recharging/refuelling at depot and at public ERS

This work looked at 5 Trajectories to understand the role of different technology mixes, fuel prices and infrastructure rollout rates. The trajectories modelled are:

1. **Trajectory 1:** HRS are deployed as the only public recharging/refuelling option for HDVs, all BEV are excluded from this trajectory
2. **Trajectory 2:** Mega-chargers are the only public recharging/refuelling option for HDVs, all FCEV are excluded from this trajectory
3. **Trajectory 3:** ERS is the only public recharging/refuelling option for HDVs, both BEV and FCEV with depot recharging/refuelling are deployed alongside ERS
4. **Trajectory 4:** All 3 public recharging/refuelling options are deployed, alongside depot recharging/refuelling
5. **Trajectory 5:** All 3 public recharging/refuelling options are deployed, alongside depot recharging/refuelling, but at an accelerated rate compared to Trajectory 4. Manufacturers are also assumed accelerate production of ZE HDVs under this trajectory.

The model used to develop the trajectories is designed to follow as closely as possible the decision-making process of commercial vehicle purchasers when selecting vehicles for their fleets. The outcome of the model is the cost optimal mix of zero-emission powertrains in each year. The results are not a prediction of future zero-emission vehicle uptake as technology “lock-in” is not modelled (and vehicle OEM product development choice might vary from the assumptions made), but instead show important trends that can help to shape government and industry next steps. The inputs used when assessing this decision-making process include:

- **Operational suitability** of the ZE options in terms of range and refuelling times based on the packaging constraints of ZE powertrain and refuelling practicalities.
- **Total cost of ownership** (TCO) of ZE options versus diesel vehicles based on purchase and operational costs.
- The **availability** of ZE HDV options from vehicle manufacturers.
- ZE depot and public refuelling **build out rates**.
- Level of government **policy support**.

[1] A catenary system that would install electric cabling over major roads so that electric vehicles fitted with a pantograph to create a contact with the cables can charge their batteries while in motion.

Key Findings

Figure 1 shows a summary of the results from the mixed Trajectory 4 where all infrastructure and drivetrain options are allowed to compete. The main trend we observe is that hydrogen FCEV are an important part of the zero-emission sales mix, making up approximately 40% of truck, bus and coach sales in 2035. However, hydrogen FCEV sales peak in 2035 and drop off significantly by 2050, displaced by the growth in BEV. This result, which is repeated across many of the trajectories, highlights several trends detailed below.

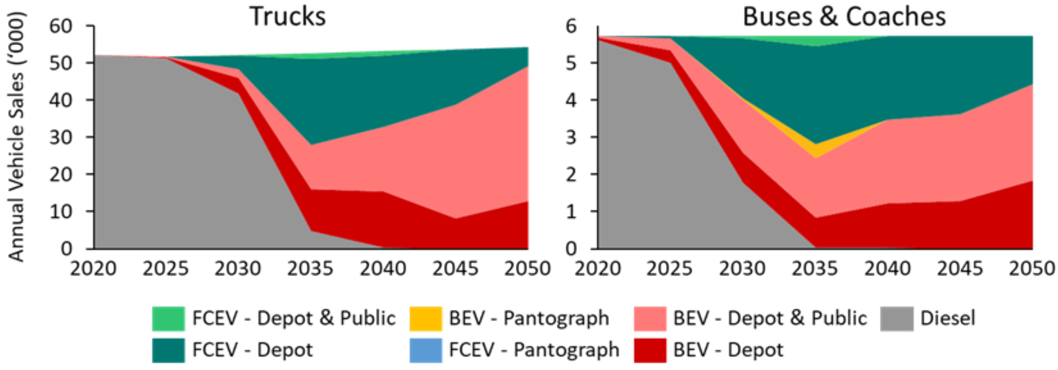

Figure 1 - Results of Trajectory 4 - All Refuelling Infrastructure Options Deployed

<u>Hydrogen FCEV</u>

- Hydrogen FCEVs are capable of meeting the range requirements of most HDV operators by the early 2030s. Including FCEVs into the technology mix is therefore important to maximise the uptake of zero-emission vehicles in the 2020s and 2030s when BEV are still range limited.
- It is possible to rollout hydrogen FCEVs relying predominantly on depot-based refuelling, which helps to overcome the chicken and egg situation for the early introduction of public refuelling infrastructure and vehicles. Again, this highlights that FCEVs are an important technology for the early uptake of zero-emission vehicles, especially for longer range vehicles.
- The level of financial support needed to bring BEV into the market in large numbers in the 2030s is also sufficient to encourage significant sales of FCEV suggesting technology neutral policy support will lead to a mix of both technologies in the market
- By 2050 FCEV HDVs are not as cost effective as BEV HDVs using depot and public (mega-charger) refuelling. However, significant numbers of FCEVs are expected to remain (see Figure 2) because infrastructure investments will have already been made, locking in some technology purchasing decisions. In addition, FCEV refuelling is easier to manage than BEV recharging, and some operators may be willing to pay a cost premium for the vehicles to save driver time and operational complexity.

<u>BEV</u>

- BEV sales grow rapidly alongside FCEV sales, especially for shorter range vehicles. For buses, BEV sales are expected to grow quickly from today.
- From 2025 to 2035, despite the high cost of fuel cells and H_2 fuel, BEV and FCEV are relatively competitive on a TCO basis as BEV require very large batteries to meet the needs of long-range vehicles. However, from 2035 the rapid expansion of the public mega-charger network makes it possible for HDV with smaller batteries

to be a viable option with en-route refuelling. Falling battery size requirements from 2035 make BEV an increasingly cost-effective option, displacing FECV sales.

- This result suggests that accelerating the uptake of the public infrastructure rollout will favour BEV sales over FCEV

The success of BEV and FCEV in this analysis is based on the assumption that:

- Zero-emission trucks are given a 2-tonne additional weight allowance and zero-emission buses and coaches a 1 tonne additional weight allowance to cover the added weight of the zero-emission powertrain[2]. Battery powertrains, which are much heavier than hydrogen powertrains benefit the most from this change.
- Zero-emission long-haul articulated trucks are given an additional length allowance (assumed here to be 1 meter) to allow for improved aerodynamic design and increased volume for packaging of batteries and hydrogen tanks
- Zero-emission fuels remain untaxed and fuel prices drop significantly from today reflecting the benefits of smart grids in the case of electricity and increased production volumes in the case of hydrogen

However, it is important to note that BEV success is based on two additional key assumptions:

- For long range vehicles, operators are willing and able to recharge the vehicles twice a day, once during the drivers break (recharging is assumed to be automated not requiring input/time from the driver) and once at the end of the day. This assumes a network of recharging points every 50km across the whole motorway and A road network of the UK as well as chargers in company depots.
- Significant battery improvements in cost, lifetime and energy density continue to be delivered by the industry (just as batteries were not suitable for most LDV applications 10 years ago but are today). Batteries are not suitable for most HDV applications today but are projected to be in 10 years' time.

The other clear outcome of Trajectory 4 (Figure 1) is that, when all refuelling options are allowed to compete, very little ERS use is observed (labelled 'pantograph' in the graph). The reason for this is timing: if zero-emission HDVs were widely deployed today, ERS would play an important role. This is because battery, fuel cell and hydrogen fuel prices are currently very high and battery performance is not at the level required for HDV operations. Using ERS can overcome many of these barriers and therefore could accelerate the uptake of zero-emission HDVs with current technology. However, in this modelling it is assumed that the early introduction of zero-emission HDV is limited by OEM production. This means that zero-emission HDVs aren't widely deployed until after 2030 when battery and hydrogen fuel costs are expected to have decreased and battery specifications improved, making ERS cost uncompetitive with the other refuelling options.

Figure 2 shows zero-emission HDV uptake under Trajectory 4 if technology lock-in is considered (top row) or if HDV operators and OEMs invest in BEV early following increased confidence based on the rate of progress in the LDV market (bottom row). The top row examines what happens if operators invest in the most cost effective technology at a given time but then experience technology lock-in as the investments made in depot refuelling infrastructure make it difficult to swap to a new technology. The bottom row looks at what could happen if confidence in the accelerated performance of BEV, from the LDV market, impacts the HDV market and HDV operators and vehicle OEMs alike back battery

[2] Based on discussions with Department for Transport. See Section 9.1.1 for more details

technology from the start for the expected price and energy density improvements coming in the future.

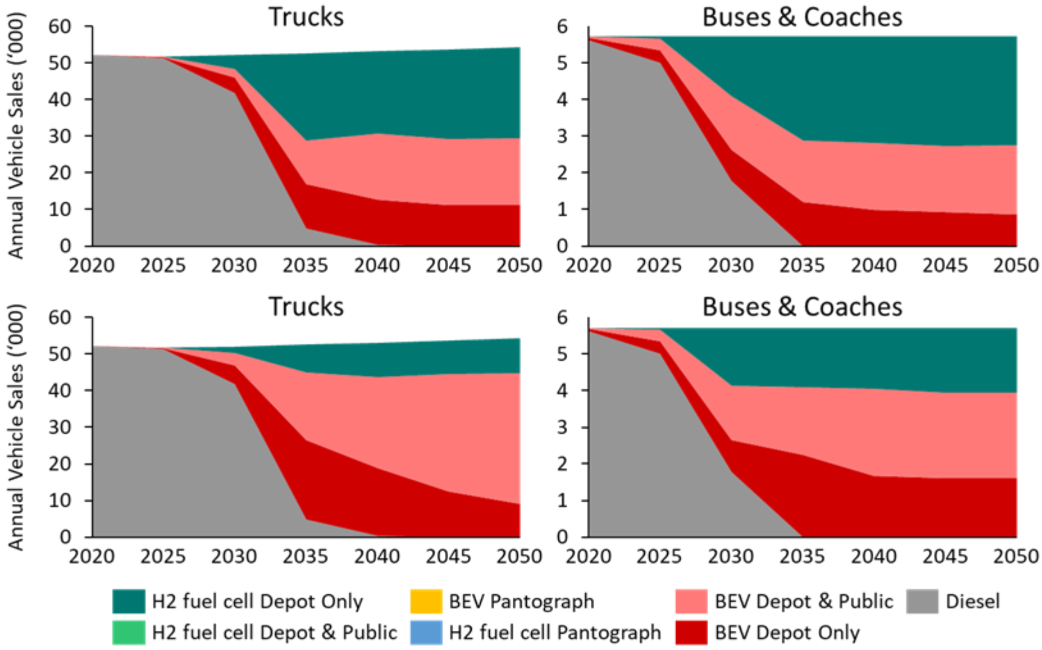

Figure 2: Results of Trajectory 4 updated to reflect lock in of early infrastructure investment (top row) and early investment towards the long term cost optimal solution (bottom row)

As shown in Figure 2, FCEV gain greater importance in the first case and BEV in the second case. Factors that could lead to these two different futures are:

<u>Technology Lock-In</u>

- The faster the decarbonisation of the HDV fleet occurs, especially if significant progress is made to decarbonising medium-range, non-urban HDVs in the 2020s, the more FCEV will be required and the more likely that their use will be locked-in
- The faster hydrogen production can be ramped up, and costs brought down, the more FCEV are likely to be introduced in large volumes by 2035. Transport by itself will not require sufficient hydrogen to achieve this. Hydrogen will need to be consumed in industry, heating and transport to bring the hydrogen price down sufficiently to achieve this outcome

<u>BEV Future</u>

- A slower growth in zero-emission HDVs in the 2020s favours this future as it gives time for battery technology to improve
- Surging battery investment for use throughout the economy could lead to new battery designs/improved chemistries that help to overcome battery constraints such as energy density, cost and recharging times. If the industry becomes increasingly convinced that these investments will lead to a step change in battery performance, then OEMs and vehicle operators may focus on BEVs in the early years even when they are operationally inferior

Even in a BEV-dominated future some FCEV are still expected in the mix because:

- Small fleets that do not currently refuel at depot may choose hydrogen as it will allow 100% public refuelling instead of installing charge points in the depot.
- Vehicles that do not return to a company-owned depot for several consecutive days will find it easier to complete 2 public hydrogen refuelling events each day compared to 2 public recharging events each day.

The results presented so far show zero-emission HDV sales trends at a fleet level. These trends vary significantly across the different vehicle size.

Rigid Trucks

- Sales are mostly dominated by BEV for smaller rigids and those used on urban routes.
- FCEV are an important technology for larger rigids used for inter-city distribution
- Rigid trucks are far less space constrained for the packaging of batteries or hydrogen tanks, making it possible to deliver a vehicle that meets operators range requirements earlier without reliance on the slow build out of public refuelling infrastructure.
- However, the main cost benefit of zero-emission vehicles comes from the fact that no fuel duty is raised on electricity or hydrogen making them cheaper than diesel. Rigid vehicles that only drive shorter distance do not fully benefit from these fuel costs savings making zero-emission rigids expensive.
- Zero-emission rigid trucks require the most policy support to encourage their introduction into the fleet. This means that while they may be technically suitable for operation before artic variants, they are unlikely to take off in large volumes without significant policy intervention.

Articulated Trucks

- The artic truck market is assumed to contain a significant share of FCEV sales out to 2050 reflecting the improved operational flexibility of FCEV.
- However, as for all truck sizes, BEV using mega-chargers are the cost optimal solution by 2050.
- In this work we assume that long-haul artic trucks used almost exclusively on motorways are given additional length allowance and truck operators are willing to store hydrogen tanks on the artic trailer[3]. These changes add significant CAPEX to the vehicle but significantly improve the operational capabilities. These changes would significantly improve the uptake of zero-emission artics because the TCO of long range artics is dominated by fuel costs not CAPEX. This means that once a functioning zero-emission artic design is realised it could be bought by operators quickly even without strong policy support as the TCO is very competitive.

[3] Additional length allowance of 1 meter is assumed to allow additional aerodynamic features to be added and to give more space for battery and hydrogen tank packaging. It is also assumed that some operators who do not want to consider refuelling outside of the depot choose to place some steel hydrogen tanks on the artic trailer. This allows for the creation of an 800km hydrogen vehicle that would only need to be refuelled at the end of the day (we do not assume large battery packs could be stored on the trailer as this would add significant cost as many operators have 2-3 trailers per tractor unit and it would raise issues around theft as batteries are significantly more valuable than steel hydrogen tanks).

Buses

- The bus market is already well advanced with BEV and FCEV models available. In general, buses are more expensive than trucks making the additional zero-emission powertrain costs proportionally less significant.
- The more advanced position of this market and the driving forces of climate change and air quality policy are expected to deliver a much faster rollout of zero-emission vehicles in this market than for trucks or coaches.
- The use of batteries for buses is constrained by the vehicle weight allowance. BEV are expected to be used for many urban bus routes and for longer bus routes where the geographical alignment of routes brings enough buses together at key locations to make opportunity charging infrastructure investment worthwhile.
- The use of hydrogen for buses is constrained by vehicle space, especially for double decker buses. FCEV are expected to be used for the longest routes and for routes that include long sections of higher speed driving.

Coaches

- Coaches see the highest sustained uptake of FCEV of any vehicle type. This reflects the fact that coaches are weight constrained but not particularly volume constrained making them well suited to hydrogen storage. Coaches are also often used on long routes across more varied road types than trucks, making planning for en-route refuelling for BEV more complicated.
- This results in FCEV maintaining 40% of the coach sales out to 2050.

Results Sensitivities

This study included multiple sensitivity runs to assess the impact of the modelled variables. The 10 runs with the greatest impact on the results are summarised in Table 2. The key trends observed from the sensitivities are:

- The final results are most sensitive to fuel prices which will be decided by system level changes and refuelling/recharging infrastructure utilisation. Overall any refuelling option could be competitive if system level changes (such as fuel tax rates, electricity system balancing costs and hydrogen production cost reduction, driven by demand in industry and heat) or high infrastructure utilisation (gain through key stakeholders selecting a technology winner) fall in their favour.
- Increasing BEV costs leads to higher FCEV **and diesel** vehicle sales but increasing FCEV costs only leads to higher BEV sales
- Higher mileage vehicles are less sensitive to increased costs, as long as zero-emission fuels are cheaper per kilometre than diesel.
- Increasing battery costs reduces the sales of BEV and FCEV refuelled in depot and increases the share of FCEV with depot and public refuelling, due to the difference in battery size between vehicle types.
- Low fuel cell costs significantly increase the uptake of FCEV with depot and public refuelling as these vehicles have by far the largest fuel cells
- If fuel cells and batteries need to be replaced within a vehicle's lifetime this will lead to diesels continuing to be the dominant technology out to 2050
- Removing public refuelling infrastructure does not lead to an increase in diesel sales as BEVs are capable and cost effective for short routes and FCEVs are capable and cost effective for long routes, though for some vehicles this would imply a more radical re-design.

- No sensitivity run resulted in a change to the uptake of ERS. It has been found that the price of ERS electricity needs to be reduced by 35% before this refuelling choice would match the share taken by vehicles using mega-chargers. However, it should be noted that ERS could become price competitive if utilisation is very high. This would likely require policy intervention to force use of the infrastructure by most HDV using a road section with ERS.

Table 2 - Summary of the impact of sensitivities on zero-emission powertrain mix of trucks (Green for increased sales, red for decreased sales. Grey – 3 or fewer percentage points different to baseline, light red/green – 4-10 percentage points different, dark red/green – more than 10 percentage points different)

<table>
<tr><th rowspan="2">Sensitivity</th><th colspan="7">Sales Breakdown by Powertrain in 2040</th></tr>
<tr><th>BEV depot</th><th>BEV depot & mega-charger</th><th>BEV depot & ERS refuelling</th><th>FCEV depot & ERS refuelling</th><th>FCEV depot</th><th>FCEV depot & public HRS</th><th>Diesel</th></tr>
<tr><td rowspan="2">Baseline</td><td rowspan="2">28%</td><td rowspan="2">34%</td><td>0%</td><td>0%</td><td rowspan="2">36%</td><td rowspan="2">2%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Battery Cost</td><td rowspan="2">9%</td><td rowspan="2">20%</td><td>0%</td><td>0%</td><td rowspan="2">30%</td><td rowspan="2">18%</td><td rowspan="2">23%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Low Battery Cost</td><td rowspan="2">40%</td><td rowspan="2">52%</td><td>0%</td><td>0%</td><td rowspan="2">8%</td><td rowspan="2">0%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Fuel Cell Cost</td><td rowspan="2">36%</td><td rowspan="2">42%</td><td>0%</td><td>0%</td><td rowspan="2">20%</td><td rowspan="2">0%</td><td rowspan="2">2%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Low Fuel Cell Cost</td><td rowspan="2">5%</td><td rowspan="2">9%</td><td>0%</td><td>0%</td><td rowspan="2">45%</td><td rowspan="2">40%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Low Diesel Price</td><td rowspan="2">12%</td><td rowspan="2">16%</td><td>0%</td><td>0%</td><td rowspan="2">17%</td><td rowspan="2">0%</td><td rowspan="2">55%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Electricity Price</td><td rowspan="2">16%</td><td rowspan="2">25%</td><td>0%</td><td>0%</td><td rowspan="2">38%</td><td rowspan="2">8%</td><td rowspan="2">13%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Hydrogen Price</td><td rowspan="2">36%</td><td rowspan="2">46%</td><td>0%</td><td>0%</td><td rowspan="2">13%</td><td rowspan="2">0%</td><td rowspan="2">4%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Fuel Cell and Battery Replacement</td><td rowspan="2">4%</td><td rowspan="2">5%</td><td>0%</td><td>0%</td><td rowspan="2">11%</td><td rowspan="2">0%</td><td rowspan="2">81%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Additional Battery Capacity</td><td rowspan="2">19%</td><td rowspan="2">31%</td><td>0%</td><td>0%</td><td rowspan="2">39%</td><td rowspan="2">5%</td><td rowspan="2">7%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">No Public Refuelling</td><td rowspan="2">52%</td><td rowspan="2">0%</td><td>0%</td><td>0%</td><td rowspan="2">45%</td><td rowspan="2">0%</td><td rowspan="2">2%</td></tr>
<tr><td colspan="2">0%</td></tr>
</table>

Note: These sensitivities assume a constant level of policy support. In most cases the uptake of ZE vehicles achieved in the baseline could still be achieved under the sensitivity scenarios but would require a higher level of policy support.

Limitations of results

The modelling conducted for this project explores three key aspects of ZE vehicles to assess their potential future uptake: the expected technical capabilities of the vehicles depending on packaging space and technology costs, ability to meet real operational range requirements, and total cost of ownership. The aim of exploring these aspects was to attempt to replicate the decision-making process faced by fleet operators when purchasing new vehicles. The limitations of this approach include:

- The model does not capture the practical considerations (space in depot for recharging/refuelling equipment, whether vehicle always return to depot each night or spend back to back days on the road, whether vehicles are regularly run at maximum weight capacity etc.) fleets will make when selecting vehicles. This is in part due to the heterogenous nature of HDV operators, making it hard to generalise the refuelling options that will suit the various possible use cases. Excluding these considerations from the modelling is likely to disadvantage hydrogen drivetrains, as they are expected to be more expensive than BEVs, but typically have longer ranges and can refuel much more rapidly.
- The model can only consider the average vehicle, in terms of mileage, payload carried etc., for each vehicle size. This will benefit both BEV and FCEV as it does not show the advantages of BEV in fleets only requiring very short mileages or for operators who never use the full weight limit of the vehicle. Conversely it does not show the benefits of FCEV for fleets with extremely high mileages, using limited depot refuelling.
- The model does not account for very disruptive events such as the introduction of fully autonomous vehicles which could increase the daily range requirements of vehicles limiting the opportunity for refuelling. This would likely favour the use of FCEV or ERS systems.

Recommendations for Government Support

The policies required to support the transition of the HDV fleet to zero-emission vehicles will need to cover both vehicles and infrastructure.

The range of vehicle policies needed is expected to include:

- **Large scale commercial demonstrations** to provide information for operators about how zero-emission HDVs will work for them.
- **Information campaigns** to inform HDV operators about zero-emission HDVs.
- **Aggregation and clustering of zero-emission HDV orders** to encourage supply, reduce costs and facilitate infrastructure rollout.
- **National fiscal measures** to make zero-emission HDVs more cost competitive (this will include subsidies to make zero-emission models cheaper but also tax increases to make diesel vehicles more expensive).
- **Local fiscal and operational measures** to make zero-emission HDVs more competitive (this will include subsidies to make zero-emission models cheaper but also tax increases to make diesel vehicles more expensive).
- **Support** to ensure battery/fuel cell lifetimes meet operators' requirements through guarantees or financial compensation in the early years of the market when the technology is unproven.
- **Flexibility in HDV weight and size restrictions** to allow zero-emission powertrain to be packaged on the vehicles.

The range of infrastructure policies needed is expected to include:

- **Fiscal support** for early infrastructure providers to help overcome the first mover disadvantage of installing infrastructure when the equipment costs are high.
- **Planning support** to ensure infrastructure can be built to the tight timeframes required.
- Infrastructure such as ERS will only be built once on a particular road resulting in a natural monopoly for the infrastructure operator. **Policy oversight** will therefore be required to ensure a fair price is set for vehicle operators and that high prices do not lead to a delay in zero-emission vehicle rollout.

Contents

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Organisations Interviewed	Organisations Represented at the Workshop
Iveco	ICCT
BYD	BYD
Caetanobus	UK Power Networks
Hyundai	DfT
Arcola Energy	Arcola Energy
TevvaMotors	LowCVP
Road Haulage Association	Road Haulage Association
Vantage Power	
Freight Transport Association	
UPS	

Acronyms

To be completed on finalisation of the results

BEV – Battery Electric Vehicle
BNEF – Bloomberg New Energy Finance
CCC – The Committee on Climate Change
CCS – Carbon Capture and Storage
CO2 – Carbon Dioxide
DfT – The Department for Transport
ERS – Electric Road System
FC – Fuel Cell
FCEV – Fuel Cell Electric Vehicle
H2 - Hydrogen
HDV – Heavy Duty Vehicle
HGV – Heavy Goods Vehicle
HRS – Hydrogen Refuelling Station
kWh – Kilowatt Hour
kW - Kilowatt
LDV – Light Duty Vehicle
OEM – Original Equipment Manufacturer
REEV – Range Extender Electric Vehicle
RTFO – The Renewable Transport Fuels Obligation
SMR – Steam Methane Reformation
SOC – State of Charge
TCO – Total Cost of Ownership
VED – Vehicle Excise Duty
ZE - Zero Emission – this refers to tailpipe emissions in this report

1 Introduction

1.1 Background

The Committee on Climate Change (CCC) was established in 2008 under the Climate Change Act to provide independent advice to the government on its response to the challenges of climate change. This includes advice on setting carbon budgets that are in line with the overall objective of achieving net-zero carbon emissions by 2050, and actions the government should take in order to stay within these budgets. The CCC is working towards publishing the Sixth Carbon Budget, covering the period 2033-37. Element Energy have been commissioned to provide analysis of the potential for decarbonising the heavy-duty road vehicles (HDV) segment by 2050 to feed into the CCC's assessment of the contribution this sector can make towards the carbon budget.

With strong policy support and technological development over the last decade, significant progress has been made towards decarbonise light duty vehicles. Despite this, production volumes are still low with battery electric cars making up just 5% of annual sales globally. This is due to the multiple challenges faced in building acceptance of new vehicle technologies, including: lack of consumer understanding, perceived risk of adopting a less well-known technology, limited variety of models, high purchase costs and limited refuelling infrastructure.

These barriers also apply to zero emission (ZE) HDVs. Buses serving urban areas where local air pollution concerns are high have stood out amongst HDVs for having begun the transition to zero emission drivetrains. For trucks and coaches, the challenges are compounded by the long distance, time-sensitive, low margin nature of their operations, creating additional demands on zero-emission options before they will be viable in these sectors. This report aims to address some of these challenges and identify the possible technology and policy options to overcome them, highlighting the scale of action that must be taken to ensure this segment can meet the 2050 net zero target.

1.2 Objectives

The overall objective of this report is to provide a detailed analysis of the suitability of zero-emission drivetrains to meet the needs of operators in the truck, bus and coach sectors. This includes an assessment of how the cost of these vehicles is likely to change over time, allowing potential uptake trajectories to be constructed that reflect the increasing attractiveness of these vehicles as the technologies mature.

Achieving the resulting uptake trajectories in practice, and achieving net zero within the 2050 timeframe, will require a proactive, concerted effort from a range of stakeholders. This report therefore also sets out what these actions are and the associated policies in order to identify the most cost-effective pathways to achieving this goal.

The study objectives can be summarised into four key areas:

- **Provide an up-to-date evidence base** for the costs of zero-emission HDVs, focusing in particular on hydrogen fuel cells and batteries, and set out multiple scenarios for how the costs of these core technologies might fall over time under different circumstances.
- **Set out feasible uptake trajectories for zero-emission HDVs**, taking into account operational requirements, technology readiness, capacity of original equipment

manufacturers (OEMs) to produce these vehicles and possible deployment rates for new refuelling infrastructure.

- **Review these trajectories considering developments in other European countries** as HDVs often cross borders and will need access to compatible infrastructure.
- **Produce a series of policy recommendations** of the short- and long-term measures required to deliver the trajectories and assess the likely cost of such policies.

1.3 Scope

The aim of this report is to bring together existing evidence on zero-emission HDVs in order to build up possible future uptake trajectories of these vehicles. Several areas of analysis that this report builds on have been conducted in previous work that the CCC or Element Energy has already carried out. For example, the infrastructure roll-out rates used in this report were developed by Ricardo Energy & Environment[4] in a previous report for the CCC. Building on this work, the report brings together existing evidence to provide a wider- and longer-term perspective on the potential for decarbonising the HDV sector.

The main component of the analysis in this report has been informed by detailed modelling designed to project the number of zero-emission HDV sales for each 5-year period from 2020 to 2060. The model does not consider vehicles running on (bio)methane even though they are currently gaining popularity in some HDV segments and offer significant emissions savings compared to diesel. Instead this report focuses exclusively on the ZE drivetrains that have the potential to maximise emissions reductions from heavy duty transport in the long term and meet the net-zero goal.

1.3.1 Vehicle Categories

Although modelled at a more granular level, the results are aggregated into the following 5 vehicle categories for reporting; Small and Large Rigid Trucks, Articulated Trucks, Buses and Coaches (see below).

				
Small Rigid <18t gross weight	**Large Rigid >18t gross weight**	**Articulated Up to 44t gross weight**	**Bus**	**Coach**

These 5 categories are a simplification of the wide range of HDVs found on UK roads. In order to maintain a degree of disaggregation throughout the modelling and capture some of operational differences across them, nine vehicle categories were analysed throughout the modelling, which were aggregated into the 5 final categories to produce the trajectory results. The new categories were made by taking a weighted average of the smaller vehicle categories. The original categories and their groupings into the 5 categories in which the results are presented are listed below:

[4] Ricardo Energy & Environment, 2019, Zero Emission HGV Infrastructure Requirements, https://www.theccc.org.uk/publication/zero-emission-hgv-infrastructure-requirements/

- <7.5t Rigid (Small Rigid)
- <18t Rigid (Small Rigid)
- 25/26t Rigid (Large Rigid)
- 30/32t Rigid (Large Rigid)
- 36/38t Articulated (Articulated)
- >40t Articulated (Articulated)
- Single deck bus (Bus)
- Double deck bus (Bus)
- Coach

1.3.2 Zero-Emission Drivetrains

Three core zero-emission drivetrain options were assessed in the modelling: pure Battery Electric (BEV), Hydrogen Fuel Cell (FCEV) and Hydrogen Fuel Cell Range Extender (H2FC REEV). Each of these core options was further differentiated into 4 variants: (1) vehicles that only refuel/charge at depot; (2) vehicles that refuel/charge at depot and at public stations; (3) vehicles equipped with additional pantographs to connect to an Electric Road System (ERS), which refuel/recharge at depot and on the road from a public ERS network; (4) 'long-range' variants where some of the energy storage limitations are removed, allowing vehicles refuelling only in depot to complete a larger proportion of range requirements without the need for public refuelling.

The key differences between vehicles that only refuel at depot and those that also make use of public infrastructure is that publicly refuelling vehicles have lower upfront costs due to reduced on-board energy storage but pay more for their fuel when using public facilities. These vehicles are also able to meet a wider proportion of daily operational ranges with the option for a public refuel in the middle of each driver shift. Conversely, the depot-based vehicles are more expensive due to greater on-board energy storage capacity but refuelling in-depot gives them access to lower fuel costs. The long-range variants (discussed in more detail in Section 2.3) are significantly more expensive do to their substantially increased on-board energy storage, but are able to take advantage of cheaper in-depot refuelling and also benefit from refuelling that is more similar to today's diesel vehicles.

The full list of zero-emission drivetrain options assessed is below:

- Battery electric (Depot Charging Only)
- Battery electric (Depot Charging & Public Charging)
- Hydrogen Fuel Cell Range Extender (Depot Refuelling/Charging Only)
- Hydrogen Fuel Cell (Depot Refuelling/Charging & Public Refuelling)
- Battery Electric with Pantograph (Depot Charging & Public Charging)
- Hydrogen Range Extender with Pantograph (Depot Charging/Refuelling & On-Road Charging)

1.3.3 Zero-Emission Refuelling Infrastructure

This study considers five zero-emission refuelling options. These are:

- Battery recharging in the depot from a charge point
- Battery recharging at a public stationary charge point (referred to in this work as mega-chargers, very high-power chargers with power rating expected to be close to 1MW for many applications, due to the high charge rates)
- Battery recharging and direct vehicle propulsion on the move from an Electric Road System (ERS) (refuelling option for both BEV, FCEV and FCEV REEV)

- Hydrogen refuelling in the depot from a Hydrogen Refuelling Station (HRS)
- Hydrogen refuelling at a public HRS

This analysis builds on an earlier study conducted by Ricardo for the CCC in 2019[4]. Ricardo's work explored the zero-emission recharging/refuelling infrastructure needed to support the rollout of zero-emission trucks. This work by Element Energy assumes that depot refuelling infrastructure construction rates do not limit the rollout of zero-emission HDVs and that this infrastructure is planned and introduced at the rate required to support zero-emission HDV rollout. The introduction of public refuelling infrastructure in this analysis is based on the outcomes of the Ricardo study. In the Ricardo work all infrastructure is complete by 2060, although annual build rates peak between 2035 and 2040. Assuming the peak build rate from the Ricardo analysis is continued, then the public refuelling network could be completed by 2045. This forms the core infrastructure assumption for this study, with a faster build out rate where the infrastructure network is completed by 2040 analysed in the most ambitious trajectory ('Trajectory 5').

1.3.4 Trajectories

This work looked at 5 Trajectories to understand the role of different technology mixes, fuel prices and infrastructure rollout rates. The trajectories modelled are:

1. Trajectory 1. This trajectory explores a world where only hydrogen is used as a zero-emission HDV fuel.
2. Trajectory 2. This trajectory covers a future where mega-chargers are the only public zero-emission refuelling infrastructure developed.
3. Trajectory 3. This trajectory covers a future where ERS is the only public zero-emission refuelling infrastructure developed.
4. Trajectory 4. This trajectory reflects the current uncertainty about the future and assumes that all zero-emission public refuelling options are supported until 2035, when it becomes clear which refuelling options are dominating the market and from then on further rollout of infrastructure if focussed only on the winning technologies.
5. Trajectory 5. This trajectory aims to understand how quickly the HDV market could be decarbonised. This trajectory is accelerated relative to the other trajectories by increasing the OEM supply of zero-emission vehicles and increasing the rollout rate of public refuelling infrastructure. Other measures (summarised in Table 13) were also assessed such as shifting truck freight to rail, but this was found to have a limited impact on how quickly zero-emission trucks become range suitable. None of these measures show significant opportunity to accelerate the rollout of zero-emission HDVs and so none of them have been included in Trajectory 5.

1.4 Structure of the Report

This report is divided into 6 main sections.

- Chapter 2, on the Challenges of Decarbonising the HDV Sector, sets out the key barriers, including; the currently limited supply of ZE HDVs from OEMs, physical constraints for packaging ZE drivetrains into the structure of HDVs, the need to meet the range requirements of operators, access to refuelling infrastructure and the currently higher total cost of ownership (TCO) of ZE options.
- Chapter 3, on Infrastructure in Neighbouring Countries, examines how some of these challenges are being confronted in the rest of Europe, particularly in France and Germany where policy and technology decisions are likely to have a major impact on other European countries.

- Chapter 4 describes the process used to model the uptake of ZE HDVs and the different scenarios explored.
- Chapter 5 presents the results of the modelling, providing the uptake trajectories under different scenarios and exploring the impact of these scenarios across the technology options and vehicle types.
- Chapter 6, on Sensitivities, analyses the robustness of the core model results under a range of alternative futures, including variations in the expected costs of fuels or components such as batteries, as well as changes in operational requirements, such as operators requiring additional on board energy storage to ensure vehicles never risk running out of fuel.
- Chapter 7, on Required Government Support, explores the options for policies to overcome the challenges identified and ensure that the modelled uptake trajectories can be achieved ahead of the 2050 net-zero target.
- Chapter 8 sets out the study conclusions.
- The Appendices contain a more detailed breakdown of the modelling results

2 Challenges of Decarbonising the HDV Sector

The HDV sector is lagging behind the light duty vehicle (LDV) sector in terms of decarbonisation. This is primarily because producing zero-emission vehicles suitable for the HDV market is much more challenging and because policy has placed very little focus on the HDV sector until recently. This chapter provides an overview of some of the challenges that need to be overcome to decarbonise the HDV sector and provides context for the rest of the report.

2.1 Policy

In the LDV sector, policy focused on reducing emissions has been in place for over ten years. For example, the EU has had tailpipe CO_2 emissions targets for car OEMs since 2009. In the UK, the Government has set Vehicle Excise Duty (VED) by CO_2 emissions bands since 2000 and has provided capital grants for zero-emission cars since 2011. By contrast, EU CO_2 targets for truck OEMs were only introduced in 2019 and are only applicable to 4x2 trucks over 16t and 6x2 trucks. This is because the policy focuses on logistics trucks. This means there is still no policy driver to decarbonise other truck sectors, such as urban deliveries or construction vehicles and the bus and coach market is currently not included at all[5]. UK tax also does not penalise operators for using high emissions vehicles, with both registration and annual tax the same for high and low polluting HDVs, and capital grants were only extended to ZE trucks in 2016. The capital grants provide up to 20% off the purchase price of new ZE trucks, up to a maximum of £20,000 for the first 200 sold, falling to £8,000 after this. HDVs have benefited from policies designed to decarbonise fuels such as the Renewable Transport Fuel Objective (RTFO) but these polices are not designed to drive large-scale uptake of zero-emission tailpipe fuels required to meet the UK's emissions targets. This lack of policy has hindered zero-emission HDV rollout as it has not encouraged supply and it makes the TCO of diesel vehicles very competitive.

The only exception to this trend has been the effort to reduce emissions from buses in urban areas. Initially, this has been driven by the need to reduce emissions of air pollutants rather than greenhouse gases, but it has resulted in accelerated development of zero-emission buses which has reduced emissions of both pollutant groups. To achieve this change, city and regional government has had to support zero-emission bus trials and rollout, often looking to UK Government or EU funding to overcome the initial high cost of zero-emission vehicles.

2.2 Zero-Emission Vehicle Supply

The supply of zero-emission HDVs is currently very limited and this can be a major challenge to the rollout of these vehicles even once cost barriers have been removed. This constraint is beginning to be overcome in the bus market. This is because the number of buses in the UK is small and the increasing interest in zero-emission buses by regional government across Europe means that there are now two zero-emission bus OEMs just in the UK and more than 30 OEMs around the world offering zero-emission bus models in Europe. With a small market and so many OEMs it would be possible to supply enough zero-emission buses for all UK bus sales from today.

[5] ICCT, 2019, CO_2 standards for heavy-duty vehicles in the European union, https://theicct.org/sites/default/files/publications/CO2%20HDV%20EU%20Policy%20Update%202019_04_17.pdf

However, the situation in the truck and coach sectors is very different. In the truck market most of the major European OEMs are now in the process of commercial trials of a limited number of zero-emission trucks, but few are producing models for sale. One manufacturer beginning to sell electric trucks in small numbers is DAF, who have been trialling 6 of their CF Electric 4x2 articulated trucks with several different customers in Europe since late 2018 and are now putting them into small batch production. MAN, who also began trials in 2018 are now beginning a small production run of their electric eTGM 26 tonne rigid. Figure 3 shows the ZE trucks that are in various stages of development in Europe and, as more of these manufacturers complete their trials, it is expected that zero-emission models will become available more widely by 2025. However, as can also be seen in Figure 3, the range capabilities of the heaviest vehicles being developed are very limited and each OEM is only focusing on a small number of truck types, leaving large parts of the market with no zero-emission options.

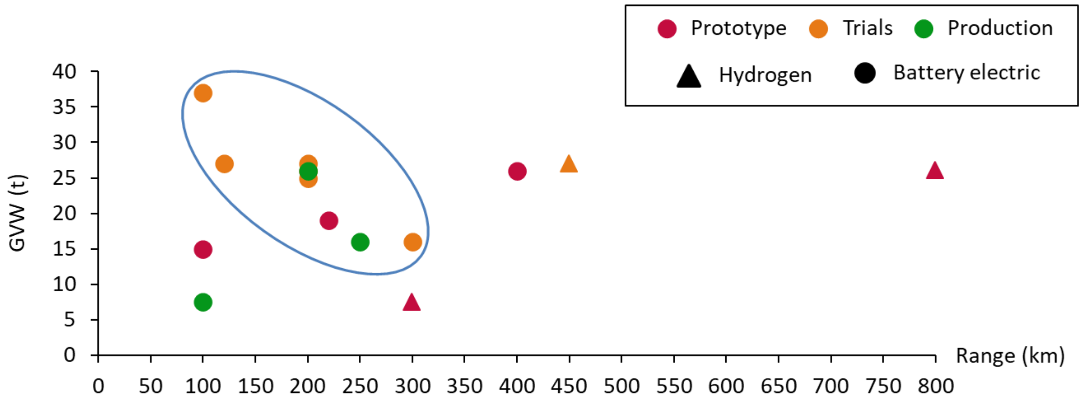

Figure 3: ZE HGVs from European OEMs at prototype, trial and production stage by gross vehicle weight (GVW) and range. Source: Element Energy review of OEM announcements

Established OEMs also face the challenge of rolling out zero-emission vehicles while limiting the value loss from stranded assets used in diesel vehicle production. It is, therefore, unlikely that these OEMs will drive a rapid growth in zero-emission truck supply, and this is likely to remain a barrier to the transition to zero-emission trucks throughout the 2020s and into the early 2030s. It looks likely that this barrier will be partially overcome by zero-emission truck supply from companies outside of the existing group of established OEMs. This will include companies such as:

- Hyundai and BYD who build zero-emission trucks for other markets and could move to supply in Europe
- Tesla who builds zero-emission cars and is looking to enter the HDV market
- Small domestic engineering companies with experience of zero-emission powertrain fabrication and installation who could increase their production capacities.

In the coach sector, zero-emission coaches are in small scale production and in trials from some OEMs. Zero-emission options are not being offered by the majority of OEMs, as is the case in the bus market, and volumes are still very limited. For example, a very small number of the Yutong TCe12 battery electric coach have been ordered and delivered in the UK. 70

of these coaches have been in operation in Paris for the last three years, but very few other zero-emission coach options can be ordered today.

2.3 Packaging Constraints

Diesel powertrains are relatively small, in terms of size and weight, for the power and range they provide. The greatest benefit of diesel is its high volumetric density that allows HDVs to carry very large stores of energy in a very small space. Diesel also has a much higher gravimetric density than batteries, meaning much more energy can be carried for a given weight, but not as high a gravimetric density as hydrogen. Packaging a zero-emission powertrain onto an existing HDV needs to take into account that a larger zero-emission powertrain (heavier or taking up a larger volume, energy carrier option densities are summarised in Table 3) will reduce the amount of goods/passengers that can be carried. This will be unacceptable for some operators as it means more vehicles are needed to move the same amount of goods/passengers leading to higher costs (some operators do not use the full weight carrying capacity of their vehicles and could accept some weight loss from zero-emission powertrains).

Table 3: Energy carrier densities

1 kWh of energy carried results in…	Diesel[1]	Battery pack	Hydrogen Tank[2]
… X kg of weight added to the vehicle	0.1	6	0.6
… Y litres of space taken up on the vehicle	0.1	5	1.7

1: Does not include the mass of the diesel tank as this has minimal impact
2: Includes the mass of the hydrogen tank itself and assumes a steel tank. This mass could be reduced with the use of lightweight materials such as carbon fibre.

The main challenge in packaging a battery powertrain is the additional weight. One kWh of energy carried in a battery adds approximately 6kg to the weight of the vehicle. The same energy carried as diesel only adds an additional 0.1kg. Even correcting for the greater efficiency of the electric drivetrain, diesel is an order of magnitude lighter as an energy carrier than batteries. Most HDVs are very large and have enough space to fit a battery powertrain. However, some vehicle classes such as over 32t 4 axle rigids, over 40t 3 axle artics and double decker buses are also very space constrained. In the truck classes, this is because the axles and wheels take up most of the space along the chassis rails. For the double decker bus, this is because the inside space is fully utilised, and no batteries can be packaged on the roof, as the vehicle height cannot be extended. For these vehicles, the low volumetric density of batteries is also an issue. For example, one kWh of energy carried in a battery takes up approximately 5l of space on the vehicle. The same energy carried as diesel only takes up 0.1l of space.

Hydrogen has a much higher gravimetric energy density than batteries or diesel. One kWh of hydrogen weighs just 0.03kg. With today's steel tanks this means carrying one kWh of energy results in an additional weight to the vehicle of 0.6kg. With improvements in tank design and greater use of alternative materials there is no reason why the hydrogen industry in the future will not be able to offer cost effective hydrogen storage at the same weight per useful unit of energy carried as diesel. The main challenge with carrying hydrogen is the volume required. Unpressurised hydrogen gas has a very low volumetric density, so it is pressurised to 350bar, 700bar or it is pressurised and cooled to become a liquid for transport fuel use. The common pressure for HDV use today is 350bar, as this requires less compression and is therefore cheaper than the other options. At 350bar, one kWh of hydrogen takes up 1.3l of space, but given that the hydrogen tank is a capsule shape there is also a lot of unusable space around the hydrogen tank that further increases the space requirements for one kWh of hydrogen. For example, a tank able to carry 200l of hydrogen could be approximately 0.4m in diameter and 2.1m long. This means the hydrogen tank requires a rectangular space of 340l or 1.7l per kWh of hydrogen carried. The final challenge of packaging hydrogen storage, relative to batteries, is that hydrogen tanks are more efficient at carrying hydrogen if they are larger as this leads to more hydrogen stored per unit of mass for the storage vessel. However, this means packaging a small number of large objects onto the vehicle which limits the number of places they can be stored. Batteries by comparison can be packaged in a larger number of smaller units that be spread around the vehicle (for example, under the seats in a bus) meaning there is much more usable space for packaging batteries compared to hydrogen.

The challenges of packaging zero-emission powertrains will be overcome by improvements in technology that will increase the energy density of batteries and hydrogen storage over time. The weight and size of vehicles is not constrained physically but is set by regulation for taxation purposes. It is therefore possible to adjust the regulation to allow additional vehicle weight or length for zero-emission powertrain packaging. There is already widespread precedent for a regulation change such as this. For example, the road vehicles (authorised weight) and (construction use) (amendment) Regulation 2017 allowed smaller HGVs 1 tonne of additional mass to account for the zero-emission powertrain. Discussions with the Department for Transport suggest that HGVs will be allowed an additional two tonnes mass for packaging zero-emission powertrains in the future, in line with Regulation (EU) 2019/1242 of the European Parliament and of the Council, and this is included as a core assumption in this work.

2.4 Operational Requirements

The key zero-emission vehicle requirements of operators are range (can the vehicle travel far enough in one day), refuelling time (if a refuelling stop is required in the middle of the day whether this can be incorporated into existing rest breaks), carrying capacity (whether the vehicle can carry the same amount of goods or people as a diesel vehicle).

Range is a major challenge for zero-emission vehicles because HDVs can be used to travelling up to 800km in a single day. Packaging sufficient batteries or hydrogen onto a vehicle to cover this range is very challenging because batteries/hydrogen are larger and heavier than diesel powertrains, meaning the zero-emission powertrain reduces the payload (goods or people) that can be carried. Zero-emission powertrains are also more expensive than diesel, so fitting a vehicle with 800km of independent range will greatly increase the vehicle cost, requiring greater policy support to become a competitive option for operators. For operators with shorter range requirements, shorter range zero-emission vehicles that refuel once a day in the depot are likely to be the best option. For operators with longer daily range requirements, shorter range zero-emission vehicles that are refuelled once in the depot and once at a public refuelling station every day are likely to prove the most cost-effective option.

If refuelling stops in the middle of the day are required, this raises the challenge of sufficient refuelling infrastructure and short refuelling times to fit in with existing rest breaks. From an operator’s perspective the optimal solution to this would be to use ERS refuelling as this is done on the move and has no impact on normal operations. However, this convenience is likely to come with higher refuelling costs, as the infrastructure is more expensive to build, so options to refuel at stationary refuelling sites are also considered.

As summarised in the box below, EU driving regulation requires drivers to take a 45-minute rest break after 4.5 hours of driving. This rest break cannot be used for refuelling the vehicle by the driver but could be used if refuelling is automated or is completed by an attendant. Making use of this refuelling option is then dependant on sufficient refuelling infrastructure being available. This is discussed in more detail in the next section.

Summary of Rest Break and Driving Hours Regulation

European driving hours rules (Regulation (EC)561/2006)[6] set out the following driving allowances and break needs:

Driving

- 9 hours daily driving limit (can be increased to 10 hours twice a week).
- Maximum 56 hours weekly driving limit.
- Maximum 90 hours fortnightly driving limit.

Breaks

- 45 minutes break after 4.5 hours driving.
- A break can be split into two periods, the first being at least 15 minutes and the second at least 30 minutes (which must be completed after 4.5 hours driving).

2.5 Infrastructure Deployment

As is clear from the earlier sections on operators' requirements and range requirements, public refuelling infrastructure will play an important role in allowing zero-emission vehicles to meet the daily range requirements of operators while avoiding delays or disruption to their operations. Good refuelling infrastructure also allows shorter range zero-emission HDVs, with smaller batteries/hydrogen tanks, to become a viable option for operators. This reduces the cost barrier to the introduction of these vehicles.

The rollout of zero-emission public refuelling infrastructure is currently delayed by two key factors. Firstly, it is unclear which technology (Mega-chargers, ERS, HRS) will win out in the HDV market, making early investment susceptible to becoming stranded assets if the wider market shifts direction to a different refuelling technology. Secondly, many HDVs travel all over the country, meaning they will need basic national coverage before a zero-emission powertrain becomes an option. Spreading infrastructure out in this way however leads to low utilisation and a challenging business case for infrastructure investors. Instead, infrastructure investors would prefer to build a cluster of refuelling sites around an area of high zero-emission HDV uptake. This model works well for buses and delivery trucks that remain in a single geographical area but is not helpful for long distance trucks and coaches, until there are a sufficient number of clusters to allow completion of long-distance routes.

[6] Department for Transport, European Union (EU) rules on drivers' hours and working time, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/856360/simplified-guidance-eu-drivers-hours-working-time-rules.pdf

The rollout of zero-emission refuelling infrastructure for trucks was assessed by Ricardo in their 2019 study[4]. The study calculated that close to 900 Mega-chargers, 4,000 HRS (public and depot) or 4,000km of ERS will be required. In this study, public infrastructure follows the Ricardo rollout pathway for trucks (Figure 56) resulting in a complete network across the UK by 2045. However, as can be seen with the petrol station network today, real refuelling networks that provide full national coverage and redundancies require more refuelling infrastructure than the mathematical optimum. The impact of this oversizing of the infrastructure is that it is more convenient for consumers, but the lower utilisation of each assets means that consumers pay a higher price for fuel. The box below explores this issue of network sizing for consumer needs.

Sizing the Refuelling Network for Operators Convenience

The strategic road network (motorways and major trunk roads) in GB is just 12,000km in length[7] but carries 52% of all rigid truck traffic and 83% of all articulated truck traffic[8]. The motorway and A road network in GB is 51,000km long and carries 85% of all rigid truck traffic and 92% of all articulated truck traffic. Assuming the inclusion of Northern Ireland does not significantly alter these statistics, then it is possible to estimate the number of refuelling stops needed. In order for a driver to find a refuelling station within the last 30 minutes of their 4.5 hour allotted driving shift, refuelling stops will be needed on the motorway and A road network every 50 km. This requires 1,000 refuelling stop locations in the UK of which 140 will be on the strategic road network. Assuming that the 140 refuelling sites on the strategic road network will require 5-10 refuelling spaces and refuelling sites on the rest of the A roads will require 1 refuelling space, then the total number of refuelling connectors required will be between 1,600 and 2,300, to minimise the impact of refuelling on operators' schedules.

For buses it is assumed that the majority of refuelling occurs in the depot as it does today. However, some routes will require a refuelling stop in the middle of the day. For BEV this can be achieved through flash charging (very high powered charger (>500kW) for less than 1-2 minutes at bus stops), opportunity charging (high powered charging (>150kW) for less than 10-20 minutes at the end of bus routes) or in the depot (medium powered charging for less than 1 hour at the depot) depending on the needs of the operator. For FCEV this can be achieved by returning to the depot to refuel or by placing an HRS at a key location such as close to a town's main bus station where multiple buses can refuel between routes. Given the more advanced position of zero-emission buses and the simpler job of planning refuelling infrastructure, given the set routes completed by buses, it is assumed that infrastructure can be completed for routes that need public/shared refuelling by 2035 in our base case and 2030 in our maximum case.

Coaches have the most varied set of use profiles. This ranges from uses such as school buses, which cover relatively short distances in urban areas, to others that offer an alternative to rail, connecting major cities over large distances where most of the driving occurs on the motorways. Coaches are therefore expected to make use of both truck and bus refuelling infrastructure. For example, coaches delivering people to schools or events in town centres could make use of bus depot/opportunity charging infrastructure while the

[7] DfT, 2018, Road Lengths in Great Britain, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/801357/road-lengths-in-great-britain-2018.pdf
[8] DfT, 2019, Road Traffic Statistics, Table TRA3105, https://www.gov.uk/government/collections/road-traffic-statistics

buses are in operations. Coaches completing long motorway routes will need to make use of public infrastructure at motorway service stations installed for trucks.

2.6 Vehicle Total Cost of Ownership

A major part of the decision to purchase a commercial vehicle depends on the expected total cost of ownership (TCO) over the vehicle's lifetime. This includes: the capex cost of the vehicle including purchase taxes and incentives, the cost of borrowing the capital to make the purchase, the residual value it is likely to retain for resale on the second hand market and the cost of refuelling and maintenance. TCO calculations will remain the key component of vehicle purchasing decisions for zero-emission HDVs and they will therefore need to be competitive on a TCO basis with diesel vehicles before they can be expected to enter the fleet in significant numbers.

In Figure 4, the projected TCOs of a large rigids with BEV and FCEV drivetrains are compared to their diesel equivalents, showing that the zero-emission vehicles made today are uncompetitive with the incumbent technology even with the current £8,000 purchase grant. Over time the costs of core components such as batteries and fuel cells are expected to fall, bringing them to TCO parity with diesel vehicles as demand and production volumes increase. However, in order to achieve the cost reductions expected over the next couple of decades, vehicles and infrastructure need to begin to be deployed today while they are relatively expensive and policy support will be required to drive up scale and bring the price down.

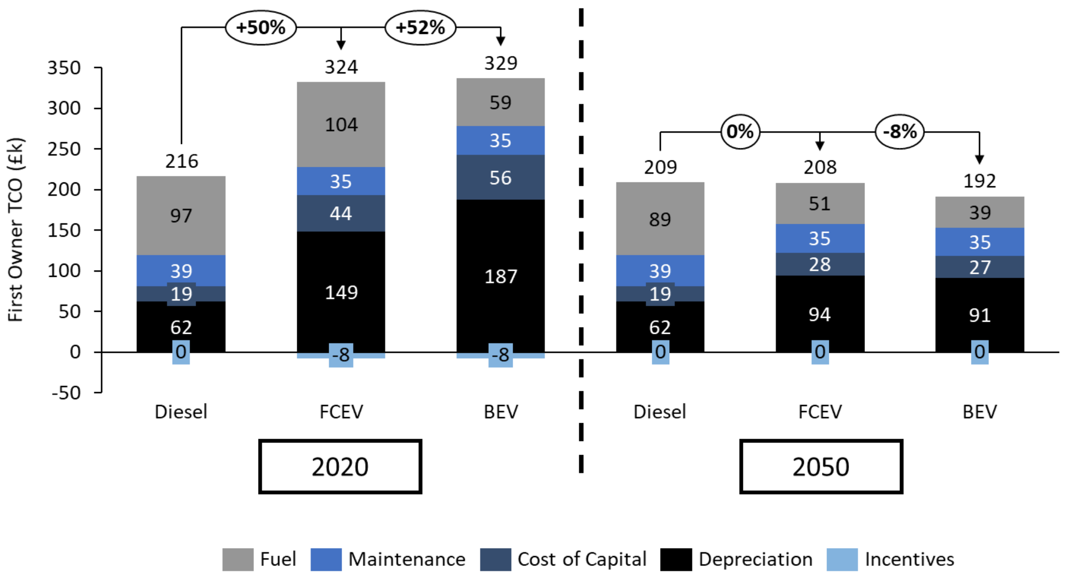

Figure 4 – First owner TCO comparison of large rigid diesel, BEV and FCEV drivetrain options in 2020 and 2050 (6-year 1st owner lifetime and 53,000km/y assumed)

3 Infrastructure in Neighbouring Countries

A significant number of the UK's HGVs and coaches undertake cross-border operations which will make it imperative for the UK's HDV refuelling infrastructure strategy to alignt with neighbouring countries. If this were not achieved and, for example, the UK targeted mega-charger deployment while France targeted hydrogen refuelling, it would have a significant impact on the ability of UK fleet operators to complete journeys in Europe and would adversely affect their business models.

This section explores further the need for infrastructure alignment between countries and assesses which countries it will be particularly important to align with. The two key countries identified – Germany and France – are then investigated further to identify any indications as to what HDV refuelling strategy they are likely to choose in the long term.

The main finding from researching HDV activity in France and Germany is that, much like in the UK, it is not clear yet what their refuelling infrastructure strategy will ultimately look like. As a result, it is too early for the UK to make decisions in order to align with these neighbouring countries. Early indications suggest Germany may be more likely and better placed to target hydrogen (if it is assumed methane reformation and carbon capture will be needed), but at the same time it is one of only three countries globally to be testing ERS. In France there has been a more concerted focus on battery electric buses, however it is not clear whether this will have a knock-on impact in the development of other heavy-duty vehicle sectors.

Overall, the situation in France and Germany is similar to in the UK - various technology options are being evaluated but no concrete commitments have been made. It will be important to keep monitoring the progress of the projects discussed in this section, and announcements coming out of neighbouring governments. Germany's upcoming hydrogen strategy may prove to be particularly important depending on the level of ambition and commitment included. This early stage of the industry, and the need for zero-emission vehicles to be rolled out quickly, suggests that agreements between governments regarding their zero-emission HDV strategy are needed. These agreements need not constrain the final "refuelling winner" in each country but should ensure that a basic infrastructure of a common refuelling type is available across the whole of Europe.

The development and deployment of zero emission HDVs and associated refuelling infrastructure are still in their early stages. The fact that a "winning" technology is yet to emerge in the market means that countries are not ready to commit to a particular strategy. This means, as stated above, it is not possible to definitely state what refuelling infrastructure countries such as France and Germany will target. However, by considering their zero emission HDV activity to date, commitment to zero-emission technologies in other sectors, and apparent capability to deploy different infrastructure options at scale, one can make an initial judgement on their ability to deliver a particular strategy and highlight evidence that suggests this may happen.

Germany is active in hydrogen, battery electric and ERS projects, but there is no clear indication as to what their future HDV strategy will look like. A cross-sector hydrogen strategy is currently under development and waiting to be finalised – this could suggest what role the technology will play. So far Germany has shown commitment to developing hydrogen capability across transport sectors, including light vehicles, trains and heavy-duty commercial vehicles. Moreover, Germany ranks highly in terms of its potential for wide-scale Carbon Capture and Storage (CCS) deployment, which may be crucial (in combination with Steam Methane Reforming - SMR) to deploying hydrogen technologies at the rate and scale required for rapid decarbonisation. However, it is also one of only two countries in Europe to install ERS, which represents a significant commitment and could indicate the intention of wider deployment beyond the current project.

France was slightly behind Germany in terms of its overall zero-emission HDV activity, but is now growing its deployment of both hydrogen and battery electric vehicles and infrastructure. It has shown a particular focus on the bus sector to date, with the fourth largest battery electric bus fleet in Europe and more than 400 hydrogen buses in planning. This is supported by the first French hydrogen bus manufacturer (Safra) entering the market. There is wider hydrogen activity ongoing, as in Germany, with 14 hydrogen trains to be deployed by 2022. However, France is deemed to be less well placed than Germany to deploy wide-scale CCS, which may impact its ability to produce hydrogen at the rate and scale necessary for rapid decarbonisation. Unlike Germany, France has not yet provided any indication that it will look to deploy an ERS network.

3.1 Importance of Infrastructure Alignment

In order to assess the relative importance of aligning with different European countries, the import and export of goods to and from the UK by road has been analysed. The figure below shows a breakdown of exports in UK-registered HGVs by destination country (left) and a breakdown of imports to the UK in foreign-registered trucks by country of origin (right). Note that both graphs are based on goods lifted.

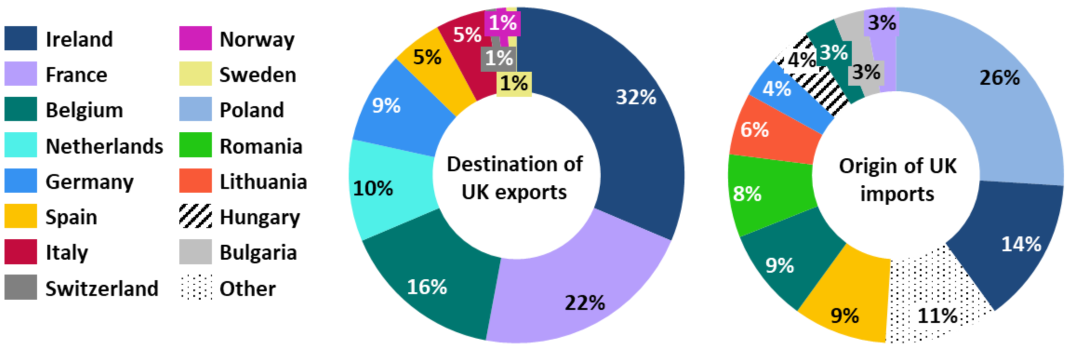

Figure 5: Breakdown of UK exports in UK-registered HGVs by destination country (left) and imports to the UK in foreign-registered HGVs by origin country (right). Based on 2018 DfT data on goods lifted.

Figure 5 shows that Ireland receives the highest proportion of goods being exported from the UK by UK-registered trucks followed by France. As expected, Belgium, the Netherlands and Germany also receive a significant share of the exported goods. It is reasonable to assume that, out of these top 5 countries, operations originating in the UK and travelling to Ireland, the Netherlands or Belgium could refuel at UK ports, complete a round trip and make it back to the UK before needed to refuel.

However, a UK-registered truck is more likely to need to refuel when travelling through France and Germany, due to the length of road networks in these countries. Furthermore, travelling to countries such as Spain, Italy or Switzerland, which also receive a reasonable share of UK exports (Figure 5) , would require travel through France or Germany. For these reasons, , in addition to the key political and economic role they play in Europe, infrastructure alignment with these countries is seen as particularly important.

The origins of goods imported to the UK do not align with the countries that the UK exports to (Figure 5). Trucks from Poland for example make up a significant share of the goods arriving in the UK by road. It is anticipated that these nations will also seek alignment with their neighbours which, in the case of Poland, would mean aligning with Germany. As a result, we have not investigated the potential zero-emission HDV strategies of these countries.

3.2 Zero-Emission HDV Activity in Germany

Germany has already explored hydrogen, battery electric and ERS HDVs and refuelling infrastructure. It has not made any clear signals as to which of these will be its primary method of decarbonising the heavy-duty sector but is pro-active in deploying and testing technologies.

Hydrogen

The wider hydrogen strategy is likely to provide an indication as to the future level of investment in hydrogen transport (including heavy-duty) and the country's commitment to developing a hydrogen-based economy. At the time of writing this report, a draft hydrogen strategy has been produced but the publishing of the final strategy has been delayed. During the drafting process there have been uncertainties around key decisions including whether hydrogen for heating will be included, and whether the strategy will be solely based on green hydrogen (from electrolysis) or whether hydrogen from SMR + CCS will be permitted (and if so what the electrolysis capacity requirement will be). It is still not clear what the final outcomes will be.

If hydrogen for heat is included in the final strategy, this would suggest a significant commitment to the production and use of hydrogen, from which the HDV sector could benefit. A key challenge in the hydrogen business case is creating sufficient demand and, if sectors such as heat also require hydrogen, this would increase overall demand and support the delivery of cost-effective hydrogen.

It is often thought that, if hydrogen were the technology of choice for HDVs (and other sectors), producing sufficient hydrogen quickly enough to enable rapid decarbonisation would require SMR with CCS. The Global CCS Institute indicate that Germany is well placed to deploy wide scale CCS and assign it a "Storage Indicator" score of 72/100. This considers CO_2 storage potential within national borders, the work done in identification of storage capacity at suitable sites, the number of storage (including monitoring) operations, experience within the country, and proactive development of storage resources.

The Global CCS Institute assessment places Germany 11th (out of 80 countries considered) and shows a relatively good level of CCS readiness. If the country's hydrogen strategy does not limit or prevent the use of hydrogen produced through SMR + CCS, this could be a key enabler to deploying hydrogen HDVs, were this to be the targeted technology.

The HRS activity in Germany to date indicates a significant level of commitment. A total of ca. 105 HRS (operational + in development) have been built across the country and form a well-developed network. This network services light-duty vehicles (>400 light FC vehicles were on the road in 2019) and was rolled out through the Hydrogen Mobility Europe (H2ME) project. As mentioned above, ensuring adequate demand in order to reduce the cost of hydrogen is a key challenge in deploying hydrogen vehicles / infrastructure and creating a viable business case. This is of particular significance in the light-duty sector, where hydrogen consumption per vehicle is low. As such, the fact that a large network has been built in these challenging conditions suggests a national ability to do so in the heavy-duty sector which offers higher demand and so a potentially a more favourable business case.

Further to the factors discussed above, Germany has announced a series of targeted funding streams which, despite not necessarily being significant in magnitude, may indicate a desire to develop the country's heavy-duty hydrogen vehicle fleet and related manufacturing capacity. In 2019, the Federal Ministry of Transport and Digital Infrastructure awarded ca. €23 million to projects including development and testing of a fuel cell system for heavy-duty commercial vehicles, development of hydrogen fuel cell fuel garbage collection trucks and the procurement of 89 hydrogen-powered industrial trucks.

ERS

In addition to being active in hydrogen-related activity, Germany is also showing commitment to ERS deployment. It currently has one project underway which is one of only three in the world and one of two in Europe (the other projects are in Sweden and California). The project is led by Siemens who have developed the "eHighway" solution which uses an overhead cable system to charge specially developed trucks, produced by Scania.

A 10 km stretch of eHighway has been deployed on a public autobahn and will be operated until at least 2022. The stretch of road is part of an artery from Frankfurt airport to a nearby industrial park. Further to this, a contract has been awarded by the Research and Development Centre at the University Kiel for the construction of a 5 km eHighway.

The fact that Germany already has an operational ERS, and one more upcoming, shows that they are world leading in this relatively immature sector. Moreover, the only company to offer a commercial ERS product (Siemens) is German, which makes the country well placed to expand their deployment and better placed than other countries to make ERS part of their HDV infrastructure offering.

BEV

BEV HGV development and strategy in Germany is less well known. However, although buses and their associated charging infrastructure do not directly impact alignment with neighbouring countries, electric bus deployment may provide an indication of the level of commitment to HDV battery electric vehicle technologies in general.

Electric bus deployment in Germany has been slower than many countries in Europe. However, there are now plans in place to roll out ca. 500 electric buses across 11 projects, and Hamburg's city bus fleet has committed to only order 100% electric buses from 2020. This shows that the fleet will be ramped up in the coming years which will need to be supported by increased bus charging infrastructure provision (depot and opportunity charging). As the bus charging market grows this may create synergies which help the wider depot / HDV charging market to develop.

3.3 Zero-Emission HDV Activity in France

France was slightly behind Germany and some other European countries in starting to deploy hydrogen HDV technologies but is now active in both the hydrogen and battery electric sectors and has a growing number of projects.

A significant focus to date has been on the zero-emission bus sector. Although the future bus strategy in France will not directly affect operations of UK-registered HDVs - as buses do not cross borders - it may provide insights into what the wider technology focus will be and whether the country is likely to target hydrogen or electric vehicles more generally.

The low and zero emission bus deployment so far in France has mainly been driven by the introduction of a series of Low Emission Zones across the country (e.g. Paris, Marseille, Toulouse, Lyon). These place restrictions on the vehicles that can access certain parts of a city based on their age and in turn emissions. The restrictions are becoming tighter and, in Paris for example, there is a planned ban on diesel vehicles in 2025 and all ICE vehicles by 2030.

This has led to the main Paris public transport operator (RATP) setting a target of operating a two-thirds battery electric fleet in 2025, requiring the purchase of more than 2,000 battery electric buses. Other cities are mirroring this sort of activity, such as Lyon which is looking to gradually electrify its bus routes between now and 2025. As a result, France had ca. 250 battery electric buses at the end of 2019, which represents the fourth largest fleet in Europe.

However, interest in fuel cell buses is also growing. A crucial example of this is in Paris, where initially the plan was for the remaining third of RATP buses to be natural gas in 2025. However, fuel cell buses are now being tested and look likely to make up a share of the fleet originally intended to be natural gas. This change in direction indicates that hydrogen has become more favourable than it was when the bus targets were originally set.

Moreover, fuel cell bus deployment across the whole country is set to increase significantly. With the first fleet of fuel cell buses now operational (in Pau), and others on order, a demand for at least 400 fuel cell buses in multiple French cities over the next couple of years is observed. This will mean fuel cell buses are competing in terms of numbers with battery electric buses.

The overall hydrogen transport sector in France is less developed than Germany, due to becoming active later, but there are signs that this is changing. As of February 2020, there are 27 operational HRS in France, 4 of which supply 700 bar hydrogen (compared to ca. 80 operational 700 bar HRS in Germany). However, plans are in place to expand the number of stations to more than 100 by 2023.

France also has a series of small-scale HDV hydrogen projects ongoing, including the development of a heavy-duty carrier truck (70t payload) for Ports, a hydrogen-powered refrigerated truck trailer project and a subsidiary of Renault working on the development of standard chassis for fuel cell HGVs. The sector has also expanded to trains, with 14 hydrogen trains to be deployed across 4 French regions (Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Grand Est & Occitanie), due to be tested by 2022 and fully operational by 2024.

The pipeline of hydrogen projects also includes the Zero Emission Valley project in Lyon. This received funding of up to €10 million from the European Union and aims to develop hydrogen in the region with a goal of supporting the launch of 1,000 fuel cell cars, 20 refuelling stations and 15 electrolysers over the next ten years.

This activity all shows a growing interest in and commitment to hydrogen in France which has occured since the publication of the national hydrogen plan in 2018. However, one factor which may impact France's ability to use hydrogen as the primary method of decarbonising the HDV sector (and others) at the rate and scale required is its CCS resource and capability.

The Global CCS Institute indicate that France represents a country with limited readiness for the wide-scale deployment of CCS and assign it a "Storage Indicator" score of 59/100 (basis of the score is discussed in Section 3.2). The Institute labels France a "Band C" country which means that most of the storage potential is considered only prospective resources, and storage project experience is typically limited to smaller-scale operations. If it is assumed that SMR + CCS would be necessary in addition to electrolysis to produce hydrogen at the scale, and speed, needed to decarbonise the HDV sector, this suggests that significant and timely investment would be required in CCS to make it possible.

To date France has not deployed any ERS projects on actual roads (apart from a failed solar powered road project in 2016) and there have been no announcements suggesting any are planned. However, given that only three ERS projects are operational globally, this does not indicate a particular lack of interest when compared to most countries.

3.4 Wider Zero-Emission HDV Activity in Europe

Despite infrastructure alignment with France and Germany being most important for the UK, it is crucial to understand what zero emission HDV projects are happening across Europe, as the outcomes of these projects could have knock on effects in other countries. For example, if a deployment of hydrogen vehicles is observed to be successful, this may act as a case study which plays a part in giving relevant industry players in France or Germany the confidence to invest in a project.

The most significant planned deployment of hydrogen trucks is due to happen in Switzerland. Hyundai Hydrogen Mobility is a joint venture between Hyundai and H2Energy, who specialize in the production and supply of renewable hydrogen. The aim is to deliver 1,600 FC trucks to Swiss customers by 2025.

The project will rollout HGVs that are used for back-to-base retail operations and benefits from there being a significant market for the same type of truck. This will provide a high hydrogen demand which, due to the nature of their day-to-day journeys, can be met with a relatively low number of HRS resulting in an attractive business case. The project is unique because of the volume of trucks involved – this has enabled Hyundai to produce the vehicles at an attractive price, helped by high taxes for diesel alternatives. Although the HGVs will not be travelling cross-borders, the outcome of this project could have a significant impact on other countries if it proves a large hydrogen truck fleet and refuelling network can be delivered in a cost-effective way and operate as required.

Another important hydrogen truck deployment project is H2 Haul. This does not have the scale of the Swiss project but involves a wider geographic coverage. It aims to deploy 16 hydrogen heavy-duty trucks across four European countries – Germany, France, Belgium and Switzerland. As well as showing commitment from the two key countries from a UK perspective (Germany and France), this project also indicates a more coordinated approach to deploying zero-emission HDVs which, if successful, could help to prove the case for hydrogen trucks which will have implications for the UK.

4 Modelling Methodology Overview

This chapter briefly presents the methodology and structure of the model and some of the assumptions used to analyse the uptake of zero-emission HDVs across a range of powertrain/refuelling options under 5 different Trajectories. A mode detailed description of the modelling process is provided in the Appendices in section 9.1. The zero-emission powertrain/refuelling options considered in this work are:

- BEV with depot only recharging
- BEV with depot recharging overnight and public mega-charger recharging during the day
- BEV with depot recharging overnight and public ERS recharging during the day
- FCEV with depot only recharging/refuelling
- FCEV with depot recharging/refuelling overnight and public HRS refuelling during the day
- FCEV with depot recharging/refuelling overnight and public ERS recharging during the day
- FCEV REEV with depot only recharging/refuelling
- FCEV REEV with depot recharging/refuelling overnight and public HRS refuelling during the day
- FCEV REEV with depot recharging/refuelling overnight and public ERS recharging during the day

The five trajectories studied are set out in detail in the next section.

4.1 Trajectory Descriptions

In order to analyse the impact of deploying different types of public refuelling infrastructure on the speed of zero-emission HDV uptake, and the mix of drivetrains likely to be purchased, 5 trajectories have been developed (summarised in Table 4). The first three are narrative-based scenarios reflecting alternative states of the world, with different emphases on how to achieve a Net Zero HDV sector, each exploring the impact of deploying a single type of public refuelling infrastructure. The final two are mixed scenarios where all infrastructure options are deployed and compete under different assumptions around ambition and the possible rate of change. These trajectories are:

1. Trajectory 1. This trajectory explores a world where only hydrogen is used as a zero-emission HDV fuel.
2. Trajectory 2. This trajectory covers a future where mega-chargers are the only public zero-emission refuelling infrastructure developed.
3. Trajectory 3. This trajectory covers a future where ERS is the only public zero-emission refuelling infrastructure developed.
4. Trajectory 4. This trajectory reflects the current uncertainty about the future and assumes that all zero-emission public refuelling options are supported until 2035, when it becomes clear which refuelling options are dominating the market and from then on further rollout of infrastructure if focussed only on the winning technologies.
5. Trajectory 5. This trajectory aims to understand how quickly the HDV market could be decarbonised. This trajectory is accelerated relative to the other trajectories by increasing the OEM supply of zero-emission vehicles and increasing the rollout rate of public refuelling infrastructure. Other measures (summarised in Table 13) were also assessed such as shifting truck freight to rail, but this was found to have a limited impact on how quickly zero-emission trucks become range suitable. None

of these measures show significant opportunity to accelerate the rollout of zero-emission HDVs and so none of them have been included in Trajectory 5.

Table 4: Summary of vehicles powertrain refuelling options considered in each Trajectory (Green = included. Grey = not included)

Powertrain/ Refuelling Option	T1	T2	T3	T4	T5
BEV depot only refuelling	Grey	Green	Green	Green	Green
BEV depot & public mega-charger refuelling	Grey	Green	Grey	Green	Green
BEV depot & public ERS refuelling	Grey	Grey	Green	Green	Green
FCEV REEV depot only refuelling	Green	Green	Green	Green	Green
FCEV REEV depot & public mega-charger refuelling	Green	Grey	Grey	Green	Green
FCEV REEV depot & public ERS refuelling	Grey	Grey	Green	Green	Green

Table **5** summarises the different assumption across the trajectories. A significant proportion of the assumptions are the same across the different trajectories. This reflects the fact that the trajectories all need to meet the 2050 net-zero emission targets. The short time left to 2050 means there is limited flexibility within the timeline to meet the target. In the short term zero-emission vehicle production capacity needs to be ramped up. This is likely to take most of the 2020s without delivering significant numbers of zero-emission vehicles. At the other end of the timeline, fossil fuel powered vehicles can stay in the stock for 10-15 years, suggesting the sale of these vehicles needs to end between 2035-2040. This leaves a narrow 5-10 year window (2030-2035/40) where zero-emission trucks and coaches need to scale up from secondary fuels to diesel, to the main fuel options for all vehicles.

Table 5: Summary of trajectory assumptions

Trajectory Assumption	T1	T2	T3	T4	T5
Public Refuelling Option	HRS	Mega-Charger	ERS	All	All
Policy	FCEV with depot refuelling TCO competitive with diesel in 2035	BEV with depot refuelling TCO competitive with diesel in 2035	BEV with ERS refuelling TCO competitive with diesel in 2035	BEV with depot refuelling TCO competitive with diesel in 2035	BEV with depot refuelling TCO competitive with diesel in 2035
Public Refuelling Network Complete	Truck & Coach = 2045 Bus = 2035				Truck & Coach = 2040 Bus = 2030
OEM Vehicle Supply	Supply only by major existing OEMs. Supply heavily constrained till 2030				Supply by major existing OEMs and new entrants. Supply lightly constrained till 2030
Fuel Price (hydrogen price relative to electricity)	**Same prices as T4**	**Same prices as T5**	**Prices for T3**	**Same prices as T1**	**Same prices as T2**
	H_2 cheaper than in T3 until 2045, cheaper than T2,3&5 past 2045 relative to electricity	Cheapest H_2 until 2045 then becomes more expensive relative to electricity	Most expensive hydrogen relative to electricity	H_2 cheaper than in T3 until 2045, cheaper than T2,3&5 past 2045 relative to electricity	Cheapest H_2 until 2045 then becomes more expensive relative to electricity

4.2 Modelling Structure

The model that has been developed in this work, to analyse the uptake of zero-emission HDVs, has been designed to reflect as closely as possible the decision-making process of fleet purchasers. As summarised in Figure 6, the model starts with the total expected sales for each vehicle type and this total passes through a series of filters, reflecting decisions about vehicle range suitability and total cost of ownership (TCO) so that only zero-emission vehicles that are cost-effective and suitable for real operational requirements are counted. As the zero-emission vehicles improve over time, they pass through these filters in greater numbers, building up the volumes in the trajectories.

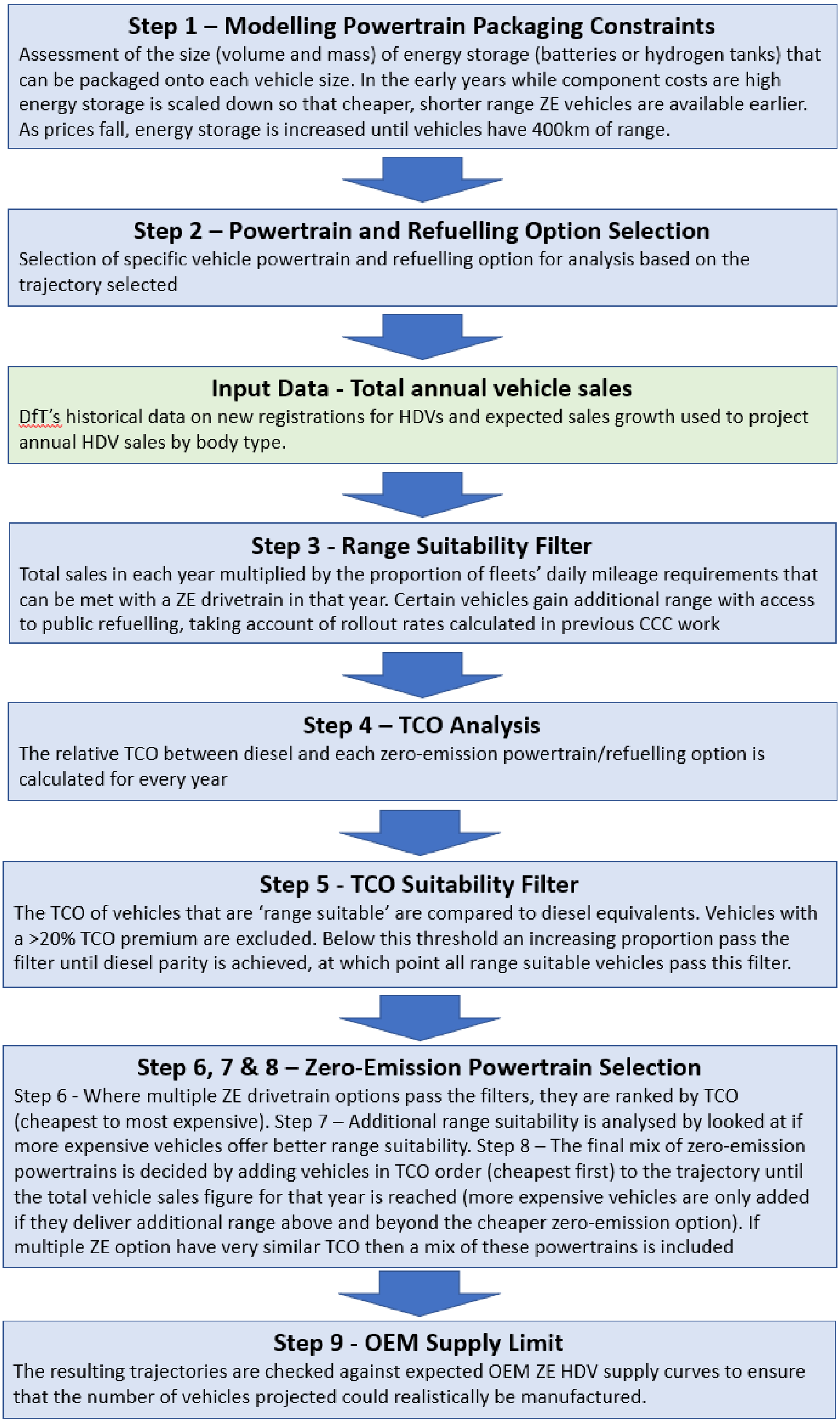

Figure 6: Modelling method summary

5 Zero-Emission HDV Uptake Trajectory Results

This chapter presents the results of the model, starting with an overview of the 5 Uptake Trajectories that discusses the relative speeds with which they result in zero-emission HDVs entering the fleet and the impact that supportive policies are likely to have in accelerating this process. Section 5.3 introduces the results of each of the Trajectories in terms of the specific mix of drivetrains adopted by buses and truck. Finally, Section 5.4 goes into more detail, examining the results for each of the 5 HDV categories, exploring the technologies that are likely to be most attractive for each application and the types of infrastructure likely to be required to support them. This chapter presents the results of a model that only considers zero-emission HDV supply, range suitability and TCO, as described in detail in Chapter 9.1. The model is unable to capture all of the nuances and practicalities that effect operators' real-world decisions. These results are therefore not a prediction of the future rollout of zero-emission HDV technologies but a guide to some of the major trends expected in the HDV sector in the future. Where real-world practicalities mean that the rollout of zero-emission vehicles is likely to differ from the raw model results, we have made this clear in the accompanying text.

5.1 Factors affecting the results across all Trajectories

Impact of government policies to support zero-emission HDVs

As the HDV fleet transitions to zero-emission emission drivetrains over the next few decades the demand for diesel from this segment will ultimately disappear. In 2019 the UK Treasury received roughly £6bn from the excise duty on diesel consumed by buses, coaches and trucks and as consumption falls the government is expected to gradually replace this income with other policies such as road user charging. This could mean charging every HDV (regardless of drivetrain) for the distance it travels on UK roads, and will be introduced incrementally to replace the lost earnings from diesel excise as diesel vehicles leave the fleet.

Since the introduction of road user charging is expected to affect all HDVs equally, this is not considered as a factor that will affect the uptake of zero-emission vehicles in this modelling. However, as diesel vehicles will continue to pay excise on their fuel, but zero-emission fuels are assumed to be excise free, they are expected to benefit from a significant fuel price differential compared to diesels. While this gives a significant advantage to the TCO of zero-emission drivetrains, for the highest fuel consumers such as Artics, Buses and Coaches, additional financial incentives are likely to be required to support the deployment of lower mileage vehicles such as Rigids. Section 5.2 explores the impact of these policies on the uptake of zero-emission HDVs in more detail, while the section on Recommendations for Government (Chapter 7) sets out the full cost of these policies to government.

Mega-charger Electricity Pricing

Figure 7 shows the depot and mega-charger electricity prices used across the five trajectories. The price of electricity from mega-chargers begins in 2020 about 25% more expensive than electricity from an in-depot charger. By 2050, all electricity prices fall 30-40% compared to 2020, with depot and mega-charger prices in trajectories 1, 3 and 4 converging between 11-13p/kWh. The lowest electricity prices from both depot charging and mega-chargers are used in Trajectories 2 & 5 suggesting BEV uptake will be highest in these two scenarios.

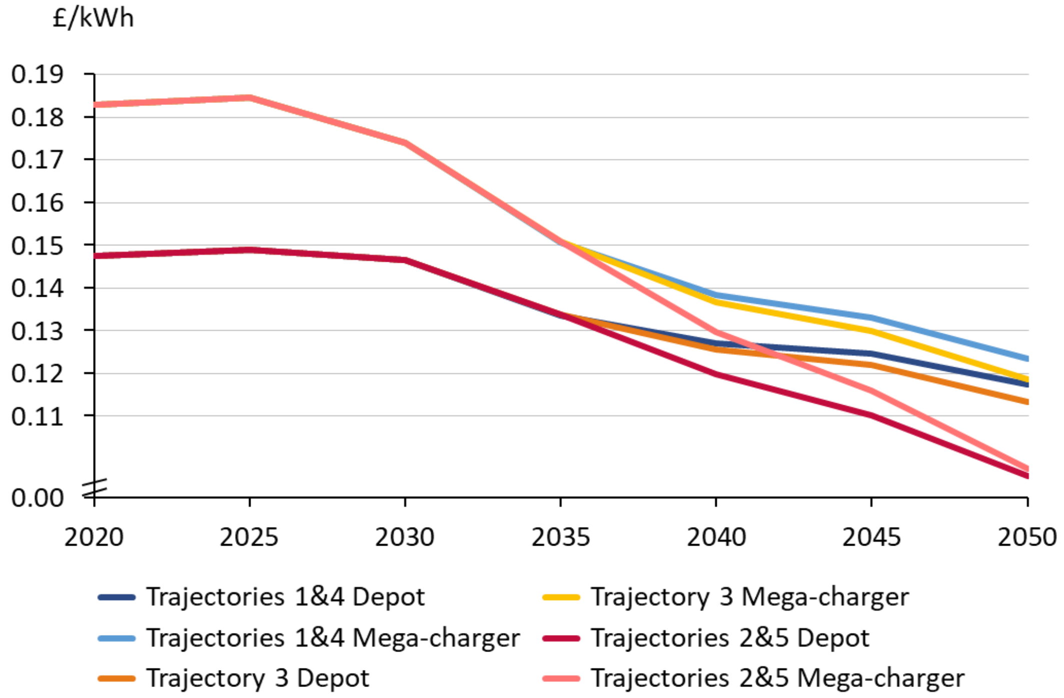

Figure 7: Depot and mega-charger electricity prices used in modelling

ERS Electricity Pricing

Figure 8 shows the depot electricity prices used across the five trajectories alongside the electricity prices for vehicles using an ERS network. ERS electricity starts in 2020 higher than both depot and mega-charger electricity at just under 21p/kWh. Unlike mega-charger electricity prices which fall more quickly across all trajectories than depot electricity, ERS electricity prices fall between 2025 and 2035 but remain relatively stable after 2035. The large electricity price difference between ERS and depot charging is the driving reason for the low uptake of ERS vehicles.

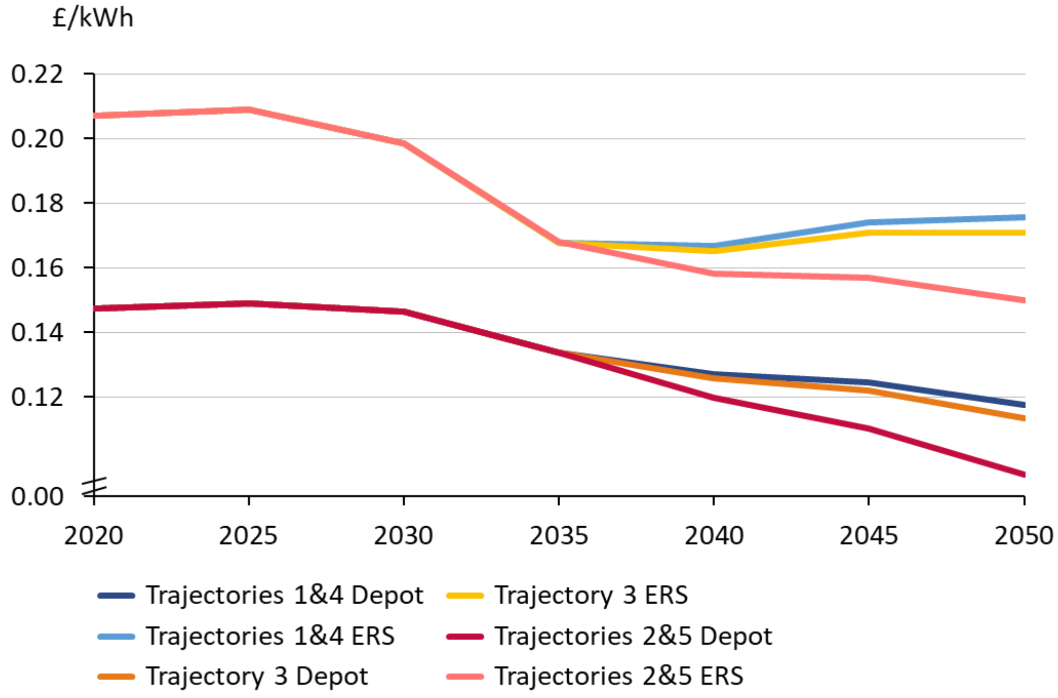

Figure 8: Depot and ERS electricity prices used in modelling

Hydrogen pricing

Figure 9 shows the hydrogen prices used in this modelling that would be paid by operators depending on whether the hydrogen is dispensed in-depot or at a public HRS. The prices shown are for hydrogen dispensed at 350 bar (these numbers are for comparison, the model also includes 700bar prices). Hydrogen prices begin in 2020 at just under £6/kg for hydrogen dispensed from a private in-depot HRS. This reflects the hydrogen price a company would pay if they invested in their own infrastructure and the price therefore reflects the production and distribution costs, as well the costs of installing the infrastructure, but no profit margin on the price of hydrogen dispensed. The price of hydrogen purchased from a public HRS, which does include a profit margin for the company that builds and operates this infrastructure begins at just over £7/kg in 2020. The hydrogen price is assumed to fall over time across all trajectories. The lowest hydrogen price scenario is used for Trajectory 5 to explore the fastest possible deployment rate, while Trajectory 1 where HRSs are the only public infrastructure uses a middling hydrogen price.

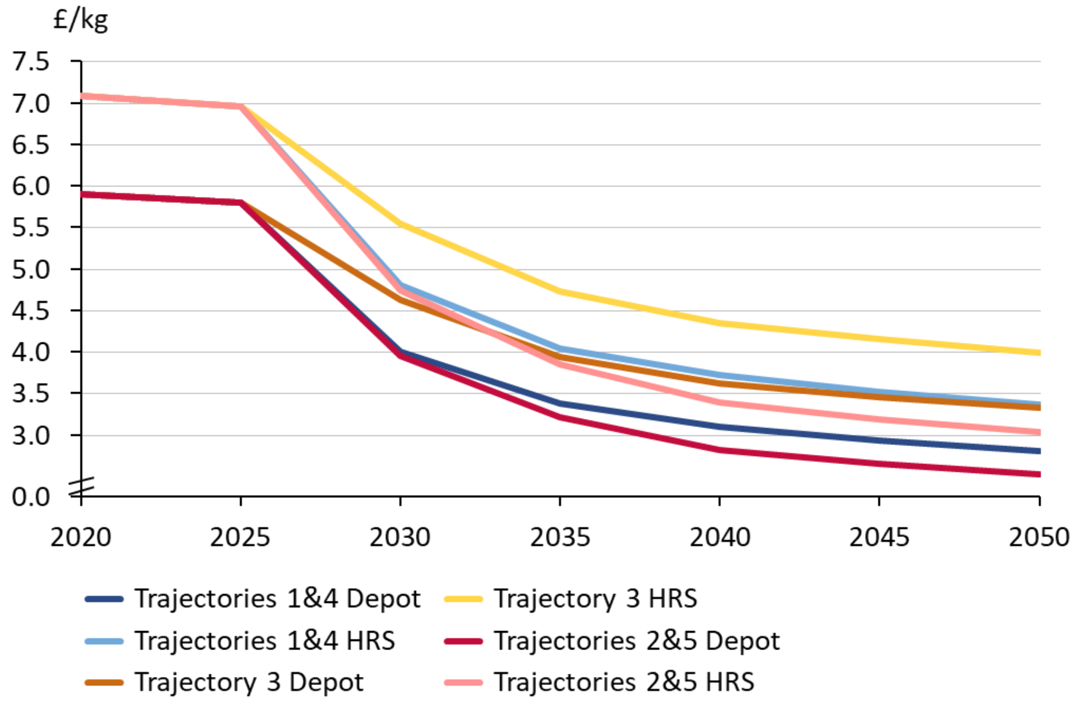

Figure 9: Depot and HRS 350 bar hydrogen prices used in modelling

Operational considerations

A fundamental assumption of this work is that in the future HDV operators will have to transition from the situation today, where vehicles are refuelling once a day, often in a depot, to a situation where many vehicles are refuelling twice a day, once in a depot and once at a public refuelling site (trucks, buses and coaches), depot (trucks and buses) or opportunity charger (battery electric buses). Fitting this additional refuelling event into the current operational profile of the vehicles, without impacting operations, will be challenging and will require an exceptional refuelling network to meet operator's needs. The lowest impact refuelling option for operators will be ERS as this does not require any change in operations. The next easiest option to fit in with current operational profiles is hydrogen. This is because current break regulations require 45 minutes of rest during a day of driving. This 45 minute rest can be split into a 15 minute rest and a 30 minute rest. Both of these rest times are sufficiently long to allow a complete hydrogen refuel, making it highly likely that a hydrogen refuel can be incorporated into existing driver rest patterns. Refuelling a BEV vehicle with a mega-charger will require at least 30 minutes. This means there is only 1 opportunity each day to align a rest break with a refuelling event. Aligning the rest break with the HDV being at a recharging location will be very difficult to achieve, meaning it is likely that reliance on Mega-chargers will impact operators driving time and productivity. These factors will impact operators' decisions above and beyond the TCO considerations modelled here. This means that some operators are expected to be willing to pay higher vehicle and fuel costs in order to have a vehicle that can fit in with their current operational profile.

5.2 Overview of the uptake Trajectories for zero-emission HDVs

The following sections provide a broad overview of the 5 Trajectories, exploring the effect of different infrastructure options on the overall speed of uptake of zero-emission HDVs and the impact that financial incentives could have on accelerating the process. The results for trucks and coaches are grouped together here as they require financial support in order to ensure that nearly all sales are ZE by 2035, resulting in the complete removal of diesels from the fleet by 2050. Buses are ahead of trucks and coaches in terms of technology deployment and costs and are not expected to require financial policies to support adoption.

5.2.1 Zero-Emission Truck & Coach Uptake Trajectories

The first chart in Figure 10 shows the rate at which zero-emission trucks and coaches could be expected to enter the fleet across the scenarios explored if no financial policies are put in place. What this makes clear is that without such policies to overcome the higher costs of these vehicles in the early years, compared to diesel incumbents, there are likely to be a significant number of non-ZE vehicles left in the fleet by 2050. Even in Trajectory 5, which represents the impact of the fastest possible rollout of public refuelling infrastructure for zero-emission vehicles, diesels still make up over half of all sales by 2035. This means that even in the most ambitious scenario, without financial support, many of the diesel vehicles sold between then and 2045, when zero-emission sales reach 100%, would still be on the roads in 2050.

The key impact of policies to financially support the deployment of zero-emission vehicles is to increase their deployment in the early years. Without such policy support, zero-emission vehicles make up 16-39% of sales in 2035, but the addition of policies raises this range to 75-97% of sales. While even with policies it takes another 10 years for sales to achieve 100% across all trajectories, this earlier reduction in the volume of new diesel vehicles being put onto the roads means significantly fewer will remain in the stock towards the end of the 2040s.

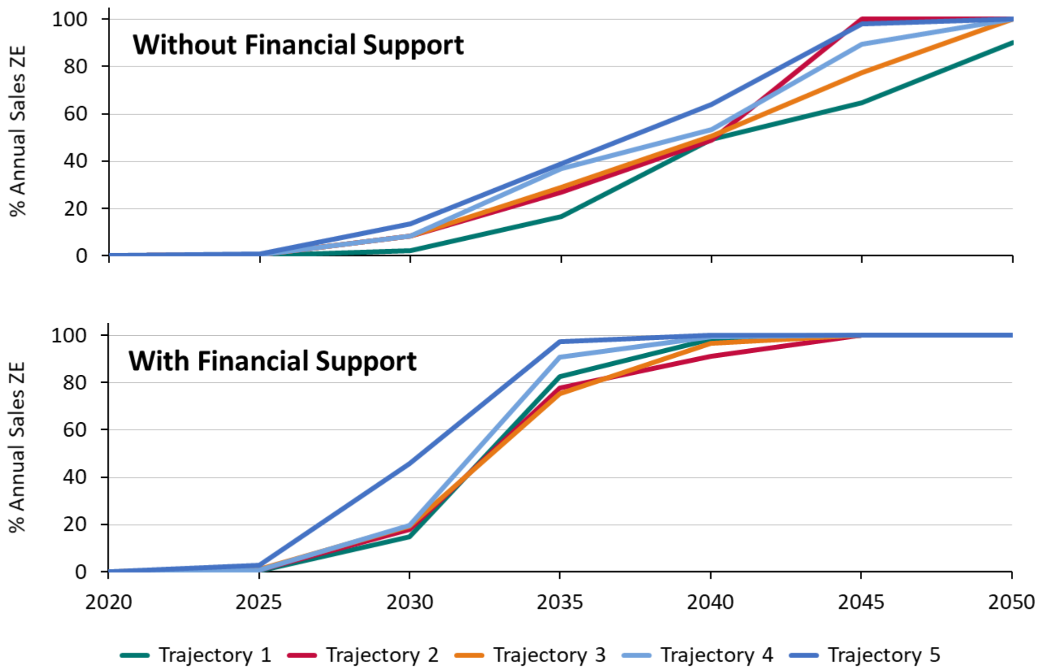

Figure 10: Comparison of zero-emission truck and coach uptake trajectories with and without financial policy support

Trajectory 1 – Hydrogen Refuelling Stations

Without financial policies to improve the TCO comparison of zero-emission trucks and coaches with diesels, Trajectory 1 where only hydrogen vehicles are considered, leads to the slowest deployment of zero-emission vehicles. This reflects the fact that while the capex for FCEVs is likely to be lower than pure battery electric vehicles, their higher fuel costs produce a TCO which is generally higher. This is exacerbated for the longer-distance vehicles such as artics, as their higher lifetime fuel consumption increases the cost difference compared to battery electric options.

However, with policy support hydrogen vehicles, which have a range advantage, can achieve a faster rollout than Trajectories 2 & 3. This is driven by the fact that although with policy support many of the ZE options are cheaper than diesels from 2035, they are not necessarily suitable from an operational perspective. With policy support, the last diesel sales are made in 2040 in Trajectory 1, while this only occurs in 2045 for Trajectories 2 & 3 when range constraints for battery vehicles are no longer a limiting factor.

Trajectories 2, 3 & 4 – Mega charger rollout (2), ERS rollout (3), all infrastructure rollout (4)

There is only a small difference in the speed of uptake for zero-emission trucks between the deployment of Mega-chargers or ERS, though as mentioned above, financial policies are less effective at accelerating the uptake of vehicles making use of Mega-chargers due to their range constraints. Particularly in the last decade 2040-2050, the benefits of financial incentives to support vehicles using an ERS in Trajectory 3 can be seen. The additional cost of the higher capex and fuel costs is the main barrier to adoption for ERS vehicles. With policies to counteract these higher costs, they are adopted at a similar rate to hydrogen vehicles in Trajectory 1 as both options can meet more operational range requirements than BEVs using mega-chargers.

Trajectory 4 demonstrates that regardless of policies to financially support the purchase of vehicles, having a range of infrastructure options leads to a higher rate of uptake for zero-emission vehicles. This is particularly clear in the early years in the first chart in Figure 10, when Trajectory 4 results in a higher proportion of zero-emission sales than Trajectories 1, 2 or 3 even though Trajectory 4 contains a mixture of the infrastructure options contained in each of these. In 2045, 100% sales are achieved in Trajectory 2 but not Trajectory 4 due to different fuel prices being applied to each of these trajectories and the electricity costs in Trajectory 4 falling more slowly than in Trajectory 2.

The accelerated adoption of ZE HDVs in Trajectory 4 is driven by the possibility for operators to select the technology that is best suited to each use case. While mega-chargers emerge as the cheapest refuelling option for most vehicle categories and can cover all operational range requirements in the smaller vehicle categories, this is not the case for artics and coaches. In the early years of deployment when refuelling infrastructure has not yet been fully rolled out, hydrogen vehicles provide a ZE option for these heavier, longer range categories. This ensures that in the early years, diesels leave the fleet more quickly than any of the trajectories that explore just one refuelling option. By the 2040s, with all public refuelling options deployed operators would have a range of ZE vehicles capable of the longest routes to choose between, and they would then be able to make this choice on the basis of their relative costs and the different operational implications of each option.

Trajectory 5 – Accelerated infrastructure rollout and vehicle supply

Trajectory 5, where all infrastructure is deployed at an accelerated rate and zero-emission vehicle production by OEMs is ramped up more quickly, Figure 10 shows the fastest uptake of zero-emission trucks and coaches. There are two key impacts from accelerating the infrastructure deployment rate that results in this faster uptake. Firstly, the earlier availability of infrastructure allows vehicles requiring the longest ranges to meet those requirements more quickly. In the results of this model, this predominantly benefits the heavier and longer-range vehicle categories, but increased access to public refuelling is likely to accelerate the uptake of zero-emission vehicles across the board. The second impact from deploying infrastructure more quickly is in reducing the TCO premium over diesel. Once vehicles can take advantage of public refuelling, they will require less on-board energy storage. In Trajectories 1-4 this occurs in later years when the cost of batteries is expected to already have fallen significantly. In Trajectory 5, reducing the need for batteries when they are still relatively expensive results in a larger TCO benefit, helping to remove this key barrier to adoption.

Accelerating the rate at which OEMs begin producing ZE HDVs at scale mostly impacts ZE vehicle sales in the late 2020s and early 2030s. It is not expected that OEMs would practically be able to ramp up production significantly by 2025, and in all trajectories the main transition to ZE vehicles takes place between 2030-35 to ensure diesels leave the fleet before 2050. However, in Trajectory 5 there are significantly fewer diesel sales in 2030 than Trajectories 1-4 where vehicle supply is a key limiting factor in adoption.

5.2.2 Zero-Emission Bus Uptake Trajectories

Under pressure from local authorities across the UK to reduce local air pollution, bus operators are already beginning to shift to zero-emission drivetrains. An example of the speed at which this transition is already taking place was the announcement in September last year, by the Confederation of Passenger Transport, that the operators it represents will only buy Zero or Ultra-Low Emission vehicles from 2025[9]. The progress being made in this area is likely to continue without the same level of direct financial subsidies needed for trucks. As Figure 11 shows, battery electric buses are already being deployed, and the rollout of infrastructure for opportunity refuelling/recharging at key points are likely to support this trend.

In Trajectory 1, hydrogen vehicles are only deployed in very small numbers until 2025, reflecting the fact that they are currently at an earlier stage of development compared to BEV models. By 2030 the ability of FCEVs to serve a wider range of routes means that Trajectory 1 overtakes 2 & 3 and allows ZE vehicles to be deployed at the same rate as Trajectory 4 where all options are used. Only Trajectory 5 has more ZE vehicles deployed, with 100% of sales achieved in 2030 due to the accelerated completion of refuelling infrastructure allowing the longest routes to be covered cost effectively 5 years earlier. Despite beginning ZE vehicle deployment earlier, Trajectory 2 has the lowest penetration of ZE sales in the bus market by 2030, reflecting the challenges of operating BEV buses on the longest and highest speed routes.

[9] The Guardian, 2019, UK bus firms vow to buy only ultra-low or zero-emission vehicles from 2025, https://www.theguardian.com/uk-news/2019/sep/09/uk-bus-firms-vow-to-buy-only-ultra-low-or-zero-emission-vehicles-from-2025

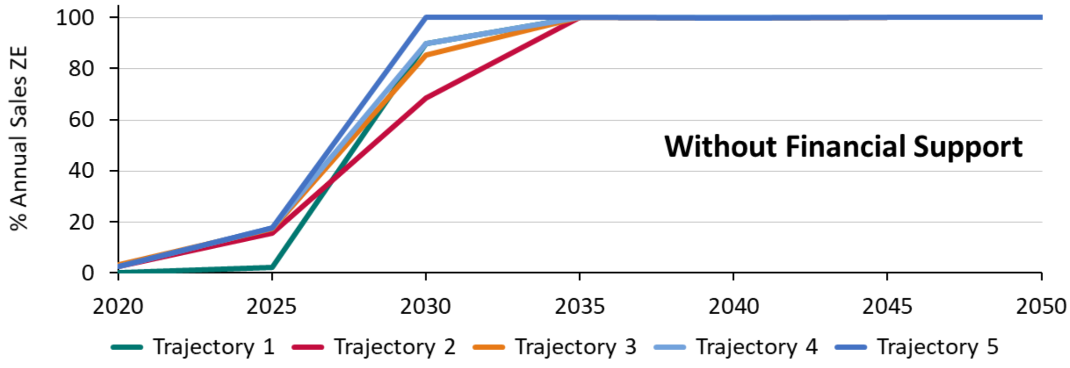

Figure 11 - Uptake of zero-emission Buses in the 5 Trajectories

5.3 Trajectory Technology Mix

The previous section sets out the overall introduction rate of zero-emission HDVs into the UK fleet under the different trajectories. In this section the sales of zero-emission HDVs are broken down by powertrain technology and refuelling options to show the resulting mix of technologies in each trajectory. The results in this section assume policies are introduced to make zero-emission vehicles cost competitive with diesel by 2035.

5.3.1 Trajectory 1: Hydrogen Refuelling Stations

Trajectory 1 explores a scenario where HRSs are the only public refuelling infrastructure deployed and FCEVs are the only vehicles used to decarbonise heavy duty road transport. Battery electric models are excluded from entering the HDV fleet to allow a comparison of policy costs and rollout rates with Trajectory 2, where mega-chargers are the only public refuelling option and FCEVs are excluded.

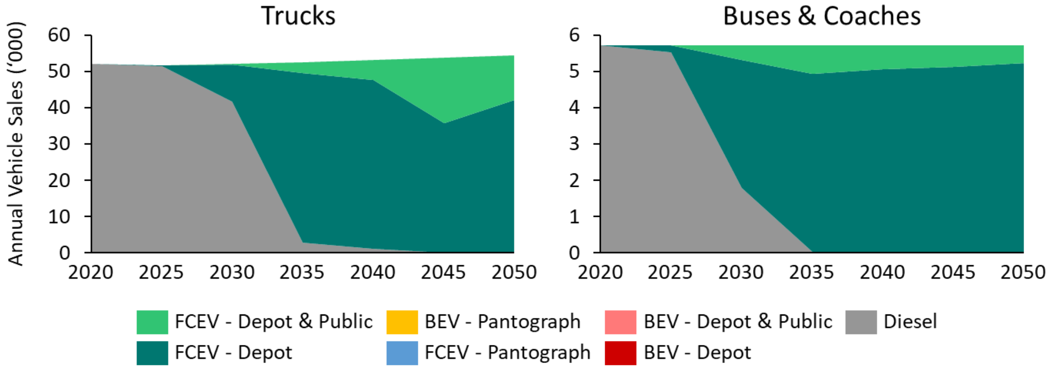

Figure 12 shows the mix of drivetrain technologies in annual sales of trucks, buses and coaches from 2020 to 2050. For trucks, hydrogen vehicles begin to become a viable alternative to diesel from 2025 and sales take off between 2030-2035. In the early years, the hydrogen trucks rely on depot refuelling as individual fleets can choose to invest in their own refuelling infrastructure before the public roll-out of refuelling infrastructure is complete. Short range vehicles that refuel only in depot are sufficient for all small rigids from 2035. Large rigids are also able to predominantly use depot only refuelling vehicles, though roughly half of these are long range variants. In the early years, the FCEV artics are also a mix of short- and long-range vehicles that only refuel in depot, but from 2045 the long-range variants are displaced by vehicles using the fully deployed HRS network. This allows nearly 100% ZE sales to be achieved in 2040.

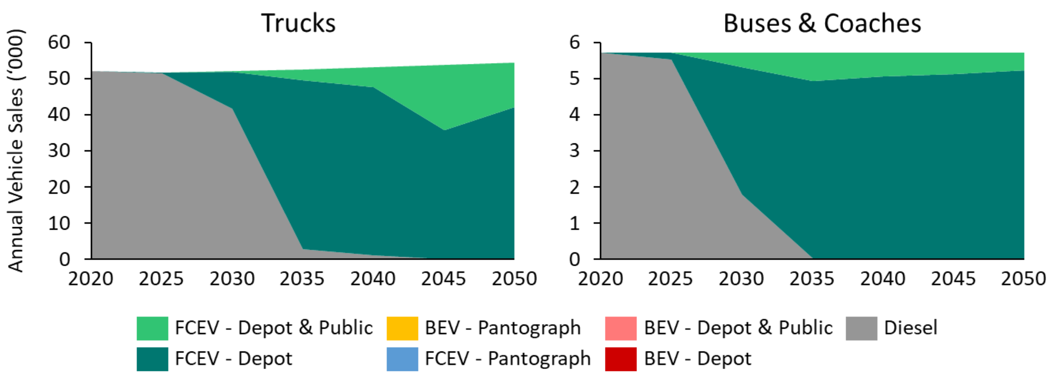

Figure 12: Trajectory 1 sales by technology type

In the bus and coach market, hydrogen vehicles make up a very small share of sales in 2025, due to the high cost of FCEV in the short term. As FCEVs are rolled out across all heavy-duty vehicles in the late 2020s, costs come down. Vehicle supply is less of a constraint for buses compared to trucks, and so sales ramp up very quickly to 2035. All bus and coach sales are ZE at this point. From 2035 onwards around 15% of buses require an additional refuel during the day, the rest refuel just once a day and roughly half of these are long range variants. All coaches refuel only in-depot, requiring about three quarters to be long-range variants.

5.3.2 Trajectory 2: Mega-chargers

In Trajectory 2, mega-chargers are the only public refuelling infrastructure deployed for HDVs and only vehicles with BEV drivetrains are included. All FCEV models are excluded, including those relying only on in-depot refuelling, to provide a comparison of policy costs and roll-out rates with Trajectory 1, where hydrogen is the only option deployed.

Figure 13 shows that until 2035 diesel truck sales fall at a similar rate in Trajectory 1 and 2, but by 2035-2040 diesel sales are significantly higher in Trajectory 2. This is driven by the limited range capabilities of BEV models in the heaviest vehicle categories. By 2035, FCEVs can meet all range requirements, but in Trajectory 2 the BEV artics are only suitable for just over half of all requirements. It is not until 2045 that the further rollout of public infrastructure means that these vehicles are able to economically package sufficient batteries to meet all range requirements in this category.

In the bus market, BEV models are already entering the fleet and currently make up just under 2% of new registrations[10]. In this Trajectory, sales grow to roughly 15% of sales by 2025 The production of BEV coaches is behind buses and sales of these models only begins in 2025. Sales of diesel buses ends in 2035, as it does in Trajectory 1, meaning that all diesel sales shown in the chart on the right of Figure 13 are coaches after 2035. In Trajectory 1 diesel coach sales end quickly after buses by 2040, but in Trajectory 2 diesel coach sales continue to 2045. This reflects the greater range requirements of coaches and the advantages that FCEVs have in this market in terms of providing sufficient range within the weight limitations of the vehicles.

[10] Department for Transport, 2020, Buses and coaches registered for the first time by propulsion and fuel type (VEH0653), https://www.gov.uk/government/statistical-data-sets/veh06-licensed-buses-and-coaches

For trucks, buses and coaches a significant proportion of public refuelling is predicted by the model for Trajectory 2. This reflects the very competitive fuel prices for Mega-charger refuelling in this work. In the real-world we expect that the added convenience of refuelling only in the depot will result in a much higher proportion of depot only refuelling in 2050.

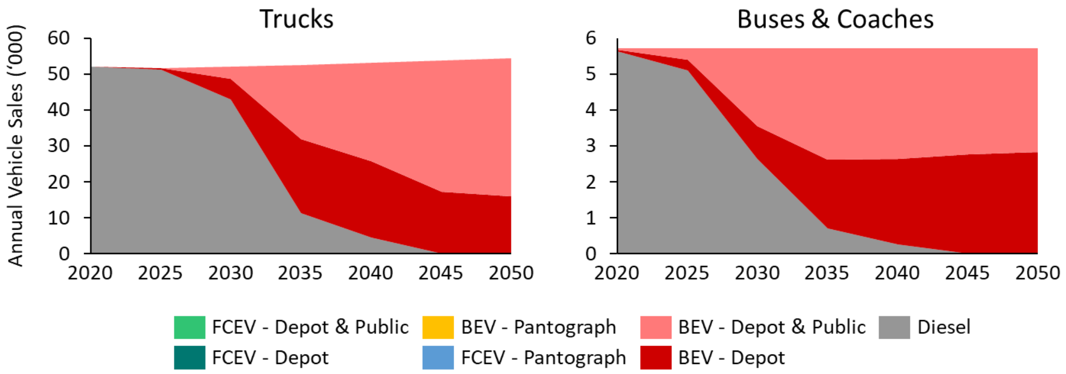

Figure 13: Trajectory 2 sales by technology type

5.3.3 Trajectory 3: Electric Road System

In Trajectory 3, an ERS is the only public refuelling infrastructure deployed, this is supported by BEVs and FCEVs using depot refuelling for routes not requiring public refuelling or for routes not covered by the ERS. For buses, an ERS would be a trolley-bus system for major urban roads. Some cities already have such systems deployed covering city centre streets, but where this would be a new system it would likely focus on major commuter routes into city centres from the suburbs, as well as ring roads.

For trucks, depot-only BEV models dominate, making up roughly half of sales by 2035 and four fifths in 2050. This is driven by the fact that from 2040, BEV vehicles in the small rigid category can meet all range requirements without the need for public refuelling. However, for the heavier and longer-range vehicles, FCEVs with depot refuelling dominate in the early years before the ERS system has been completed. From 2045 when the full ERS network has been deployed, this becomes the most cost-effective option for the fifth of vehicles on the longest routes. For articulated trucks, this is roughly a third of vehicles, but some large rigids also make use of the system. The relatively small share of trucks using the ERS is driven by the higher cost of electricity from the ERS system, meaning that any vehicles that can recharge in depot do so, and only those vehicles that require on route refuelling to achieve the longest distances are willing to pay the premium for recharging from the ERS.

For buses and coaches, the range capabilities of BEV models are only sufficient for 40-60% of vehicles in 2035, despite buses achieving TCO parity with diesel in the early 2020s and coaches in 2030. As a result, the pantograph versions of these vehicles play a larger role in meeting the longest-range requirements by the mid-2030s. From this point, the capability of battery vehicles that recharge in depot improves and they provide over half of all sales in 2050. Vehicles using the ERS remain a significant share for buses and coaches, reflecting the challenges of packaging sufficient energy storage to achieve the longest routes without additional refuelling during the day. Depot based hydrogen vehicles have longer range capabilities than BEV models helping to support uptake of zero-emission models before the ERS is fully deployed. Sales of hydrogen buses and coaches peak in 2035 and 2045 respectively. By 2050 there are very few FCEV sales as the TCO of pantograph vehicles is significantly lower by 2050 and can meet all vehicle range requirements. However, it should be noted that many of the longer, high speed routes completed by buses are rural/semi-rural routes where there is no business case for the rollout of trolley buses and so in reality hydrogen buses could take a significant share of those assigned as ERS here.

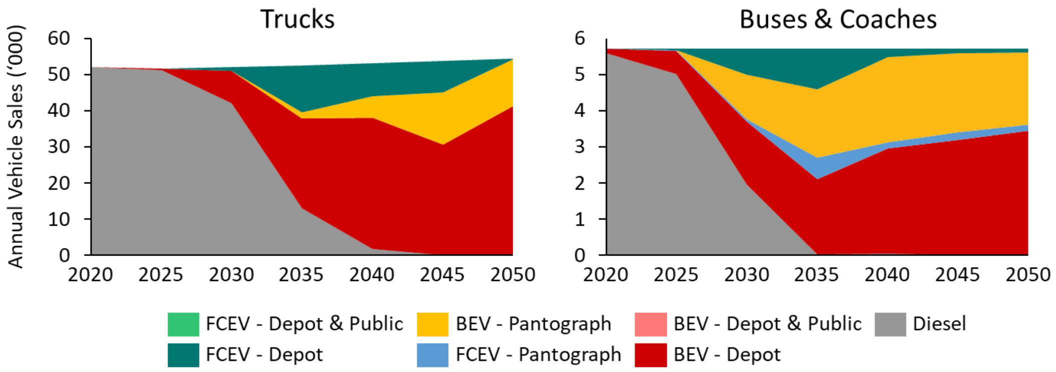

Figure 14: Trajectory 3 sales by technology type

5.3.4 Trajectory 4: Mix of Technologies

Trajectory 4 allows all drivetrain technologies and refuelling options to compete. Vehicles designed to make use of an ERS system do not appear in the results for trucks and only feature very briefly in the sales of buses and coaches. This reflects the fact that the electricity prices used in the modelling are higher from an ERS than from mega-chargers and that by the end of the period both options provide similar range capabilities. One difference is that vehicles can make use of the ERS once they have just 300km of independent range, compared to 400km to make use of the mega-charger network. This explains the brief appearance of BEV pantograph vehicles in coach sales in 2035, but these disappear again as vehicles become capable of utilising the mega-charger network.

With the availability of all drivetrain technologies and refuelling options, diesel truck sales fall faster in Trajectory 4 than in Trajectories 1, 2 or 3. In 2030-2035 sales are relatively evenly split between BEV Depot, BEV Mega-charger and hydrogen depot. After 2035 the sale of BEVs using depot recharging remain relatively constant at about a fifth of sales until 2050, but from 2035 onwards the share of BEVs using mega-chargers begins to dominate and the FCEVs decline.

Broadly this reflects the increasing range capabilities of BEVs, due to the expansion of the public infrastructure, allowing them to operate on lengthier routes and benefit from cheaper electricity compared to hydrogen. In practice, if many fleets have invested in private hydrogen refuelling infrastructure early on in this period, it is unlikely that the share of FCEVs would decline so significantly. FCEVs would likely maintain more of their 2035 share out to 2050.

The pattern for buses and coaches is broadly similar, though FCEV models maintain more of their share out to 2050, primarily due to the range requirements of coaches where they make up just under half of sales in 2050. By 2050, buses only require hydrogen for the longest ~15% of routes and the rest of the sales are BEV models. Over the period the share of BEVs that only charge in depot increases, reflecting their improved range capabilities and the reduced need for additional daily recharges, making these options more attractive for buses which can generally be recharged overnight.

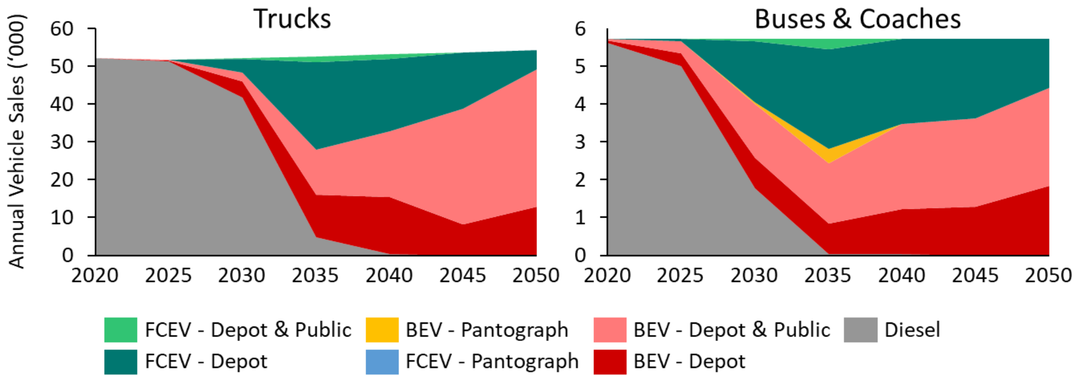

Figure 15: Trajectory 4 sales by technology type

5.3.5 Trajectory 5: Maximum zero-emission HDV Deployment

Trajectory 5 removes some of the limitations on the speed of uptake to explore the fastest practical rate at which ZE HDVs could be deployed. The two key factors affecting this trajectory are the supply of ZE vehicles from OEMs which is accelerated so that this is less of a barrier to adoption in the early years, and the rate of deployment of public refuelling infrastructure which is completed sooner, expanding the range capabilities of vehicles more quickly.

In this trajectory, the end of diesel truck sales occurs just after 2035, with just 1-2 thousand sales occurring in that year. That year, around a third of trucks sales are FCEVs, with the remainder BEV and a very small share of those using a pantograph for an ERS. Due to the accelerated deployment of public infrastructure and the lower cost of electricity, in Trajectory 5, BEVs using mega-chargers displace the sales of both FCEVs and diesels in 2035, compared to Trajectory 4. Their share grows to dominate truck sales by 2050, making up about 80% of the market. Again, in reality FCEVs would likely maintain at least some of their market share, but this suggests that an accelerated infrastructure rollout would benefit BEVs, by reducing the comparative range advantage of FCEVs.

In Trajectory 5, the end of sales for diesel buses and coaches is accelerated by 5 years, with sales ending in 2030 for buses and 2035 for coaches. As with trucks, FCEV sales are displaced by BEVs between 2035 when FCEV sales peak and 2050 when very few are purchased. By 2050, the sales are roughly equally split between BEV with depot recharging and BEV with depot and public recharging.

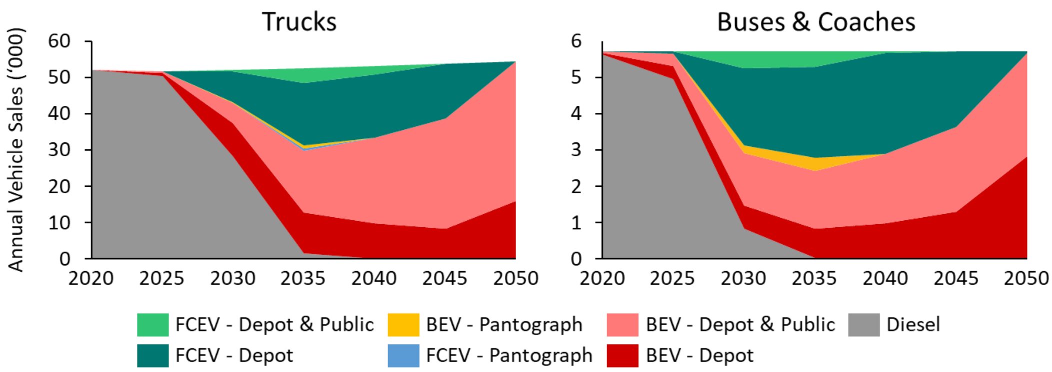

Figure 16: Trajectory 5 sales by technology type

5.4 Impact of Vehicle Size on Technology Trends

This section explores the impact of vehicle size and usage profile on the range suitability of zero-emission powertrains, TCO competitiveness with diesel and the most suitable zero-emission option.

5.4.1 Small Rigids

There are three major trends in the results for the small rigid category. Firstly, the TCO comparison of zero-emission drivetrains with diesel incumbents is more challenging in this segment and therefore the policy costs for supporting the sale of zero-emission drivetrains is likely to be higher than for other vehicle sizes. Secondly, the physical configuration of small rigids and their shorter daily range requirements mean that they are able to package sufficient zero-emission energy storage on-board to meet all their daily range requirements and so are less dependent on public refuelling infrastructure than vehicles in other categories. Finally, the combination of these two factors means that pure battery electric drivetrains emerge as the clear technology winner for this vehicle segment, as can be seen in Figure 17, though the ultimate mix of vehicles deployed is likely to be influenced by developments in other vehicles categories and by operational considerations. These trends are explored in more detail below.

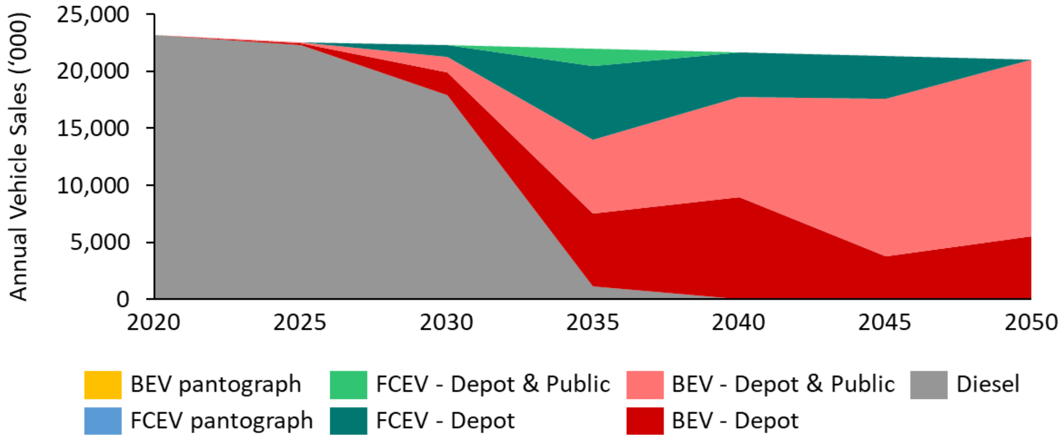

Figure 17: Annual sales by drivetrain for small rigids in Trajectory 4

Challenge for Small Rigid zero-emission options to achieve TCO parity with diesel

In the small rigid category, the higher total cost of ownership compared to diesel incumbents is likely to be the largest barrier to the uptake of zero-emission drivetrains. As can be seen in Figure 18, the TCO of zero-emission drivetrains is still higher than for diesels by 2035, despite the capital cost of these vehicles falling substantially compared to 2020. The higher TCO is driven by the fact that these vehicles travel shorter distances over their first owner lifetimes than the heavier vehicles, meaning that fuel costs are a smaller proportion of the TCO. This lower fuel consumption means they will benefit less from the expected lower cost of electricity and hydrogen compared to diesel. Also shown in Figure 18 are the TCO results for an articulated truck in 2035, where the high fuel consumption of these vehicles results in a competitive TCO for zero-emission vehicles by 2035. Without this benefit, small rigid trucks are likely to continue to require financial policies to support their uptake well into the 2030s.

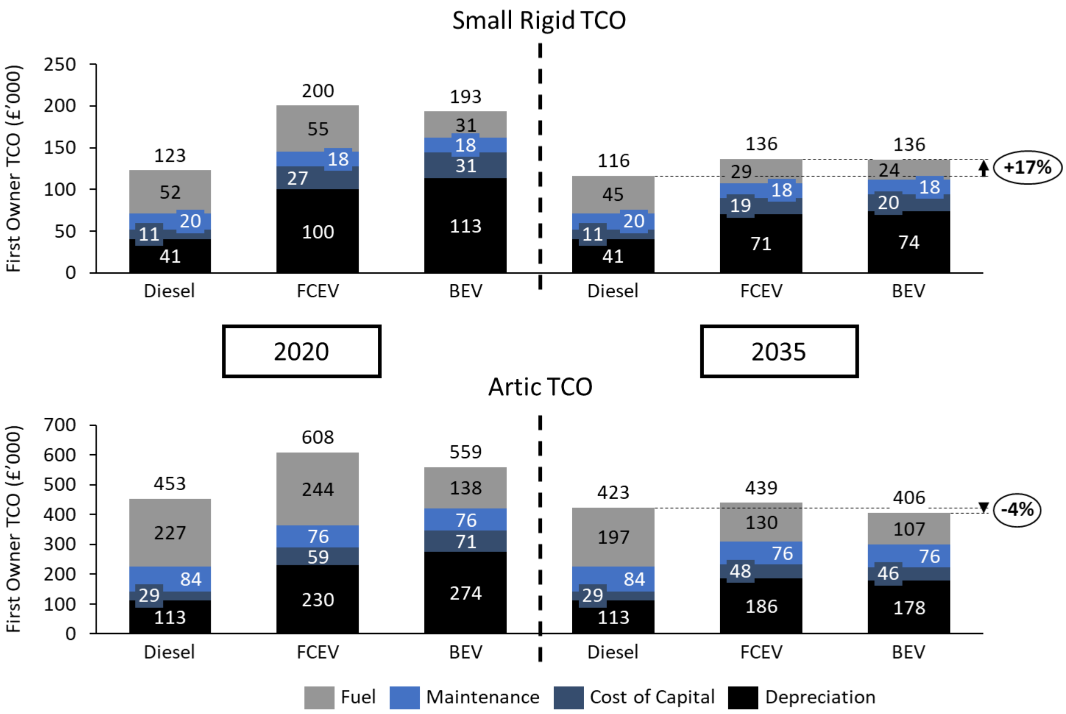

Figure 18: TCO Comparison of Small Rigid and Artic Drivetrain options in 2020 and 2035 Without Policy Support (6-year 1st owner lifetime, 42,000 km/year for Small Rigid, 116,000 km/year for Artic). FCEVs and BEVs refuel once a day in depot and each have 400km of range by 2035.

To overcome this TCO premium and ensure that diesel HDVs are out of the vehicle stock by 2050, the model applies financial incentives to trucks so that by 2035 the most cost-effective drivetrain option achieves diesel TCO cost parity. Without financial incentives to support the deployment of these vehicles, diesels are likely to remain the dominant drivetrain option in the small rigid category until 2045, with 100% zero-emission sales only achieved in 2050.

With policy support, 100% zero-emission sales of small rigids is achieved by 2040 in all trajectories, however the policy cost of achieving this is likely to differ depending on the type of vehicles supported and the speed of the infrastructure rollout. As can be seen in Figure 19, Trajectory 1, where policies are aimed at supporting the deployment of hydrogen vehicles, has the highest policy cost for small rigids. Trajectories 2, 3 & 4 have lower policy costs since these scenarios all support battery electric vehicles, which are the cheapest option for small rigids. Trajectory 3 has the lowest policy cost because fewer ZE vehicles are deployed by 2035, so fewer subsidies are paid while the level of support required is higher[11].

[11] Note that not all of the "policy cost" has to be a cost to Government. Some of the cost difference could be made up by increasing the cost for diesel vehicles which could be an increased income for Government

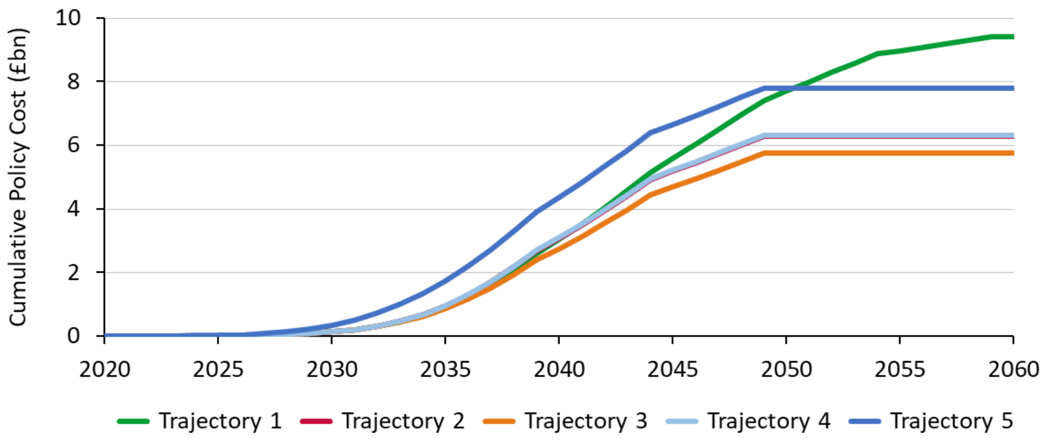

Figure 19: Cumulative policy cost to achieve uptake trajectories for zero-emission small rigids

The policy cost of supporting small rigids in Trajectory 5 sits between Trajectory 1 and Trajectories 2, 3 & 4 as more vehicles are deployed in the early years when costs are higher. This additional spending helps to ensure that diesel small rigids are out of the stock ahead of the 2050 net-zero target, reducing diesel sales earlier so that fewer remain in the stock by the end of the 2040s. One of the main measures implemented in Trajectory 5 is the increased rate of infrastructure deployment, but this is likely to have less impact on small rigids as they are not dependent on public infrastructure to meet their daily range requirements.

Ease of packaging energy storage onto small rigids reduces the need for hydrogen vehicles in the early years

While cost is a challenge for small rigids, it is relatively straightforward to package zero-emission energy storage components onto their frames. The structure of a small rigid provides ample volume along the sides of the undercarriage between the front and rear wheels and between the chassis rails for enough batteries or hydrogen storage tanks to cover all the range requirements of vehicles in this segment. With the expected additional 2-tonnes weight allowance for zero emission vehicles, they are also unlikely to be mass constrained. Without these mass and volume limitations, and because relatively small amounts of on-board energy storage are needed to cover the typically shorter daily distances of these vehicles compared to other HDV categories, zero-emission models are able to meet all the range requirements of small rigids very quickly.

Until 2035, FCEV and BEV models provide identical range capabilities and similar TCOs in the small rigid segment, resulting in a relatively even split of sales until that year. However, from this point on, the TCO of BEV models falls more quickly than for FCEVs, driven by the cost of electricity falling faster than hydrogen. FCEVs peak at about a third of sales in 2035 and by 2050 all sales are BEV models. Although depot based BEVs are capable of all small rigid range requirements from 2035, they only make up about a quarter of sales in 2050, with the remainder making use of the mega-charger network. This is driven by the reduced need for batteries on vehicles that recharge during the day, helping to reduce their capex costs while only slightly increasing fuel costs. In reality, this is unlikely to overcome the added practicality of depot recharging which is expected to be preferred.

Preferred technology option

As can be seen in Figure 20, by 2050 BEV drivetrains are the cheapest options for small rigids. The overall cheapest option is BEV with Depot and Public refuelling but operator’s preference for depot refuelling may mean that BEV with depot recharging dominates the market in 2050. Others with a lack of space for installing in-depot chargers, or who require the additional flexibility of refuelling en-route without needing to return to base will prefer to take advantage of public refuelling with mega-chargers. Once production has ramped up from OEMs, a range of BEV models will be available to suit the specific needs of operators and BEV models will be sufficient for most use cases in the small rigid segment.

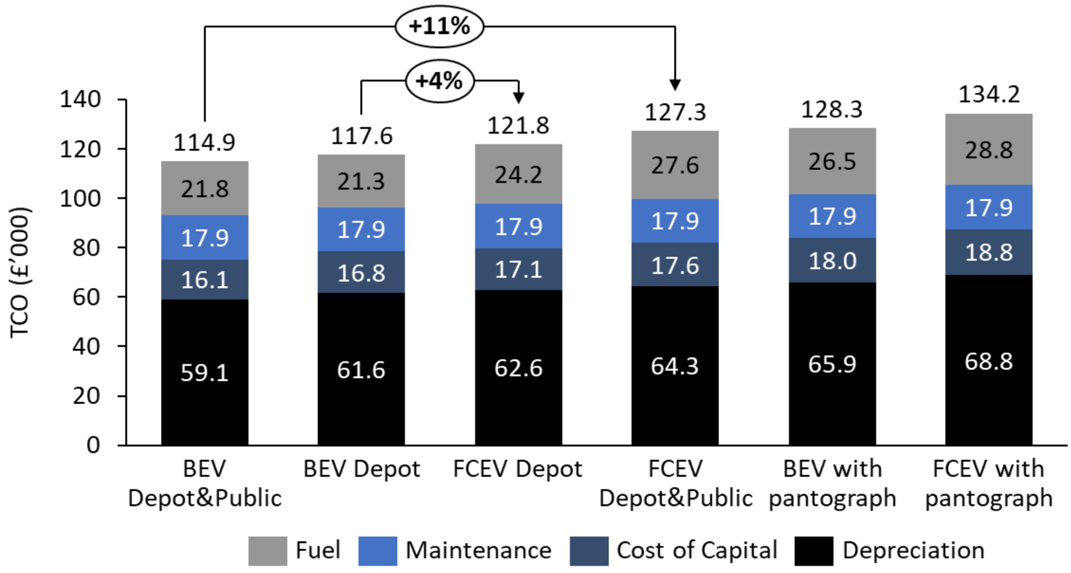

Figure 20: TCO comparison of zero-emission options for the first owner of a Small Rigid in 2050 without financial policy support in Trajectory 4 (6-year 1st owner lifetime, 42,000 km/y assumed)

5.4.2 Large Rigids

The results for the large rigid category are similar to the small rigids in certain ways. Firstly, by 2035 large rigids are able to package sufficient energy storage to cover all routes without the need for an additional daily refuel because the packaging of zero-emission powertrains onto the chassis is not volume or mass constrained. Secondly, the TCOs of zero-emission vehicles in the large rigid category are challenging compared to diesels meaning they will require significant policy support to ensure they are adopted quickly enough to meet the net zero targets, as is the case for small rigids. However, there are also some key differences between the two categories which are mostly driven by the higher fuel consumption of large rigids, resulting in a reduced difference in TCO between BEV and FCEV options. This can be seen in higher proportion of FCEVs in the results for Trajectory 4 shown in Figure 21.

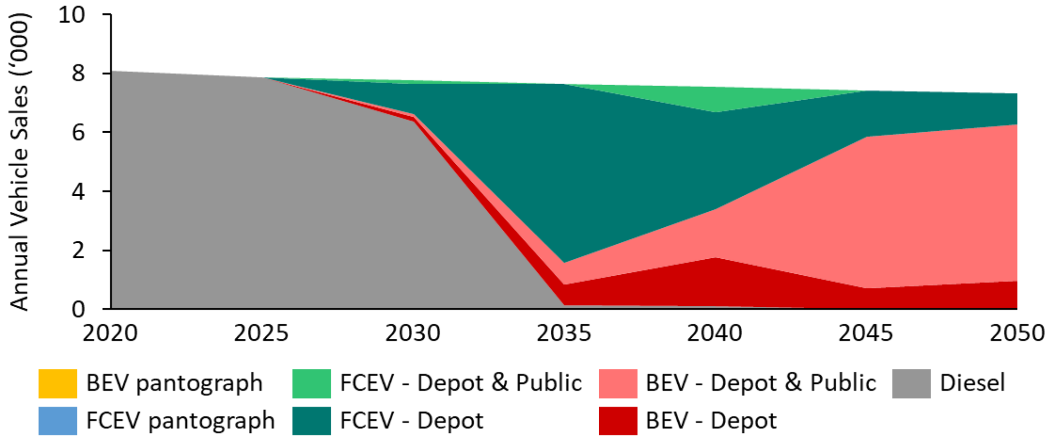

Figure 21: Annual sales by drivetrain for large rigids in Trajectory 4

Impact of higher fuel consumption

Figure 22 shows how the greater mass and higher mileage of large rigids impacts on the proportion of each TCO component compared to small rigids. Across all drivetrain options, fuel costs make up a greater proportion of the TCO for large rigids than they do for small rigids. The increased share of fuel costs and maintenance costs which are both driven by the higher mileages act to reduce the share of capex in the TCO for large rigids. Taken together these points mean that in general the choice between zero-emission options in this segment will be less sensitive to the upfront cost of vehicles and more sensitive to fuel prices.

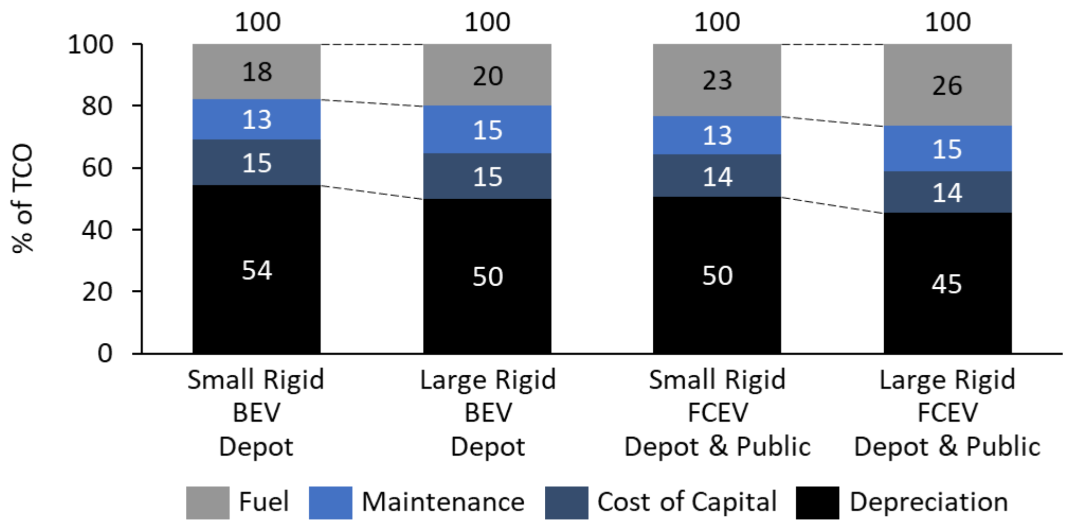

Figure 22: Comparison of percentage share of small rigid and large rigid TCO components for selected BEV and FCEV options in 2035 (6-year 1st owner lifetime, 42,000 km/y for small rigids, 53,000 km/y for large rigids assumed)

As can be seen in Figure 23, the TCO impacts of lower fuel costs and higher capex for BEV models roughly balances out with FCEV models, meaning that by 2035 there is very little difference in TCO costs between the two drivetrain options. However, as for small rigid, by 2050 large rigids are predominantly BEVs that make use of the mega-charger network. This is driven by the continued falling costs of electricity from mega-chargers modelled in this trajectory. However, since the difference in TCO between BEV and FCEV models is so small in the early years and because a significant amount of refuelling infrastructure will have been built to support the early deployment of FCEVs, these vehicles are, in reality, likely to maintain more of their share of sales out to 2050.

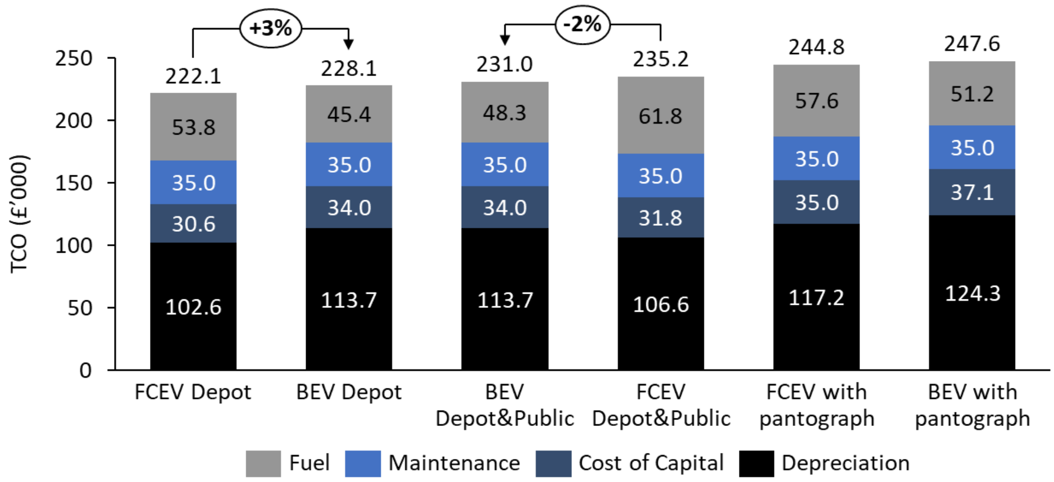

Figure 23: TCO comparison of ZE drivetrain options for large rigids in 2035 (6-year 1st owner lifetime, 53,000 km/y for assumed)

Policy costs to support deployment of zero-emission large rigids

Due to their higher fuel consumption, large rigids benefit from the lower cost of zero-emission fuels compared to diesel. As a result, while the absolute cost to support each vehicle is higher than for small rigids because they are larger and more expensive vehicles, the cost of supporting their deployment is proportionally less than small rigids. The market for large rigids is about one third of the size of that for small rigids and so despite the absolute level of subsidy required per vehicle being higher, this segment requires lower levels of total subsidy support. This can be seen by comparing Figure 19 where cumulative policy costs for small rigids range from £6-10bn by 2060, with Figure 24 where the costs range from £2.5-5bn for large rigids.

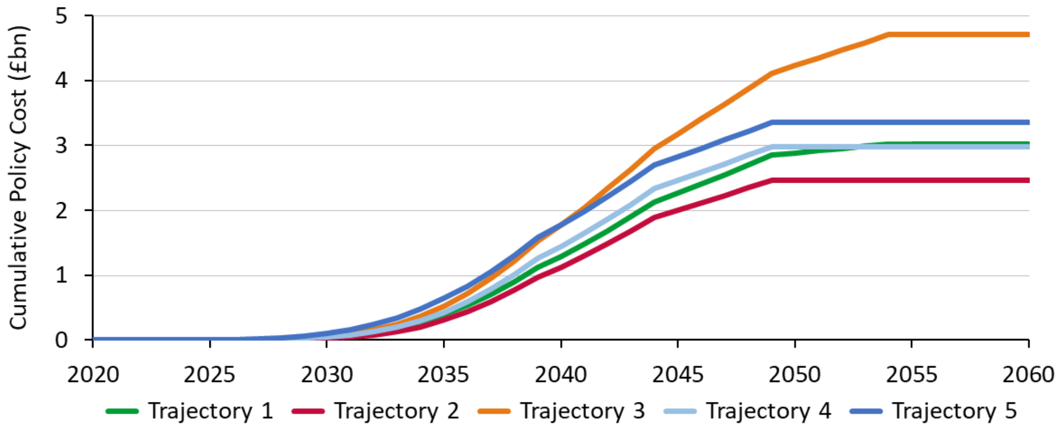

Figure 24: Cumulative policy cost to achieve uptake trajectories for zero-emission large rigids

Without policy support, the modelling suggests that the sale of diesel vehicles in this segment would end in 2045, assuming production continued to scale up and costs fall in-line with the baseline projections. This would likely leave many diesel vehicles in the stock by 2050 and so policy support will be necessary to support uptake of vehicles in this segment. Trajectory 3 results in the highest policy cost for supporting large rigids, due to the high proportion of hydrogen vehicles in this scenario during the early years (a similar share to Trajectory 4) and the higher cost of hydrogen in this scenario compared to all other scenarios.

Preferred technology options

As with small rigids, it is expected to be possible to package enough zero-emission energy storage onto a large rigid chassis to cover all typical daily range requirements with a single daily refuel. With the higher fuel demand of these vehicles, the energy storage required to complete these longer routes without making use of public refuelling can have a major impact on the capex of BEV models. Figure 25 shows that the additional batteries required to ensure a large rigid has sufficient range for all typical operations without relying on public refuelling would add 10% to the capex. By comparison, the additional capex for a FCEV that does not rely on public infrastructure is negligible, at around 1%.

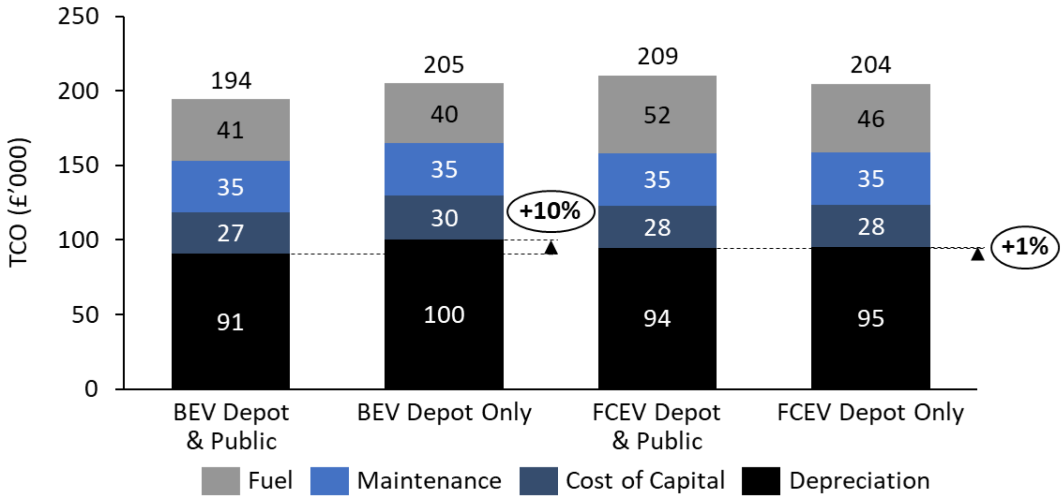

Figure 25 - TCO Comparison of zero-emission drivetrains for large rigids in 2050 showing the impact on capex of additional energy storage for vehicles not using public refuelling in Trajectory 4 (6-year 1st owner lifetime, 53,000 km/y assumed)

The TCO comparisons shown in Figure 25 assume that a complete rollout of mega-chargers and HRSs has been completed by 2045, which highlights the importance of infrastructure rollout on the likely speed of uptake of zero-emission large rigids. Since the TCO of BEV models is improved by reducing the amount of on-board energy storage, a faster infrastructure rollout would likely benefit these vehicles compared to FCEVs and allow them to compete with diesels sooner.

As for small rigids, BEVs using mega-chargers ultimately become the cost-optimal solution for zero-emission large rigids. However, until this infrastructure is deployed the longer-range requirements in this segment create a stronger role for hydrogen in the early years. As a result, the technologies selected will depend on the pace of infrastructure deployment. If mega-chargers can be deployed quickly, this option could quickly dominate this segment. A slower rollout would create a greater dependence on hydrogen vehicles to meet the longer range requirements as seen in the early years in the results for Trajectory 4 (see Figure 21). Once these vehicles become established it maybe more challenging for mega-charger vehicles to achieve the market share shown in these results as investments in refuelling and changes to operations will already have been made.

5.4.3 Artics

The challenges for artics to transition to zero-emission drivetrains are substantially different to those faced by rigid trucks. The limited volumes available within the structure of the tractor units and their longer-range requirements mean that these vehicles are unlikely to ever be able to meet the longest daily ranges in this category using only energy stored within the chassis. As a result, the rate of uptake in this segment is much more dependent on the rollout of public refuelling infrastructure, or alternatively on more radical vehicle designs that place some additional energy storage on the trailers.

Figure 26 shows the results for artics in Trajectory 4. During the early years, when very little public refuelling is available, around three quarters of the vehicles deployed are in short range applications, using either BEV of FCEV models that can refuel in depot. Between 2030-35 as zero-emission options become cost-competitive with diesels and the vehicle range capabilities improve, depot-based hydrogen vehicles dominate, making up just under half of all sales. Half of these hydrogen vehicle sales are depot-based FCEVs with additional hydrogen tanks fitted to their trailers to give them up to 800km of range and making them capable of the longest routes. However, by 2035 these vehicles still have a TCO premium compared to diesels and roughly 15% of vehicles purchases continue to be diesels. From this point on as the mega-charger network is completed between 2035 and 2045, the share of BEV artics using this infrastructure grows and their sales displace the more expensive FCEV vehicles. The driving force in this shift is fuel prices, which are lower for vehicles using electricity from mega-chargers. From 2045 the infrastructure rollout is complete, meaning that both BEV and FCEV models are technically capable of all the range requirements of artics and allowing BEVs as the cost-optimal solution to dominate by 2050.

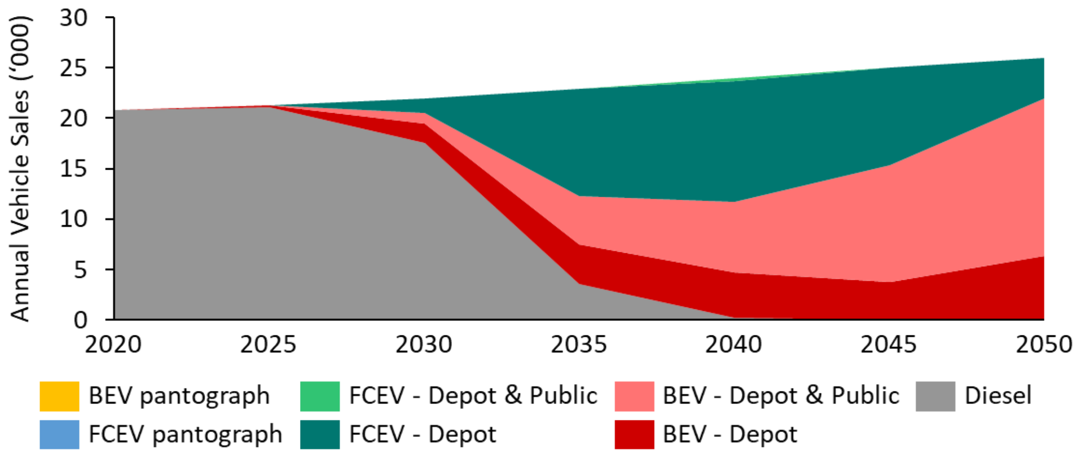

Figure 26: Annual sales by drivetrain for artics in Trajectory 4

Technology choice is likely to impact the speed of uptake of zero-emission artics

As can be seen from Figure 27, the type of drivetrain technology and public refuelling infrastructure chosen has a strong impact on the rate at which zero-emission artics can be deployed. Hydrogen vehicles achieve 100% zero-emission sales in Trajectory 1 five years ahead of Trajectories 2 & 3 where only ERS or mega-chargers are deployed. This is driven by the fact that hydrogen artics have sufficient range for 95% of daily requirements by 2030, despite just one fifth of the public refuelling infrastructure having been deployed. This means that as the cost of vehicles falls, they can quickly enter the fleet from 2030 onwards as the technical barriers are removed.

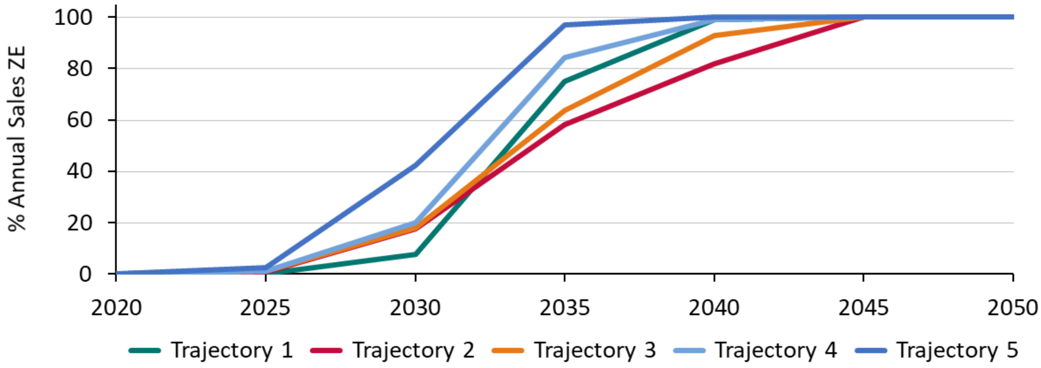

Figure 27: ZE sales as a proportion of total sales in the artic segment across all trajectories.

By contrast in Trajectory 2, BEV models are limited by the availability of public refuelling and are only suitable for half of the daily range requirements of artics in 2030. Only in 2045 when the rollout of infrastructure is complete are diesels finally removed from the artic market in this trajectory. In Trajectory 3, the deployment of an ERS network leads to higher zero-emission sales in 2035 and 2040 than in Trajectory 2, mostly driven by the inclusion of depot-based hydrogen vehicles and the ability of pantograph vehicles to make use of ERS infrastructure with less independent range.

Despite the short range requirements of vehicles using an ERS, and the fact that Figure 27 shows that this infrastructure on its own would likely accelerate the deployment of zero-emission artics, pantograph artics do not feature in the results for Trajectory 4 shown in Figure 26. This is because in this modelling, electricity prices for electricity from an ERS are significantly higher than from in-depot charging or mega-chargers, due to the far more extensive infrastructure investments required to deploy it (see Section 5.1 for more detail on fuel costs). Since fuel costs are a large proportion of the TCO for artics, this higher cost fuel makes these vehicles uncompetitive with other options.

The higher fuel consumption of artics does however provide some advantages, as both electricity and hydrogen are expected to be cheaper per kilometre than diesel. As a result, despite zero-emission artics continuing to be more expensive to purchase than diesel by 2050, the further they drive, the better their TCO comparison with diesel becomes. The impact of this can be seen in Figure 28, where a far lower level of policy support is required for artics than for rigid trucks, with the total cumulative policy cost ranging from £0.15-2.4bn depending on the trajectory. Trajectories 2 & 3 where mega-chargers and an ERS respectively are the only public refuelling options deployed lead to very low policy costs for zero-emission artics. This is due to fewer zero-emission vehicles being deployed in 2035-40 when support is still high. In addition, most of the vehicles deployed in these early years are depot-based BEV models that do not require policy support.

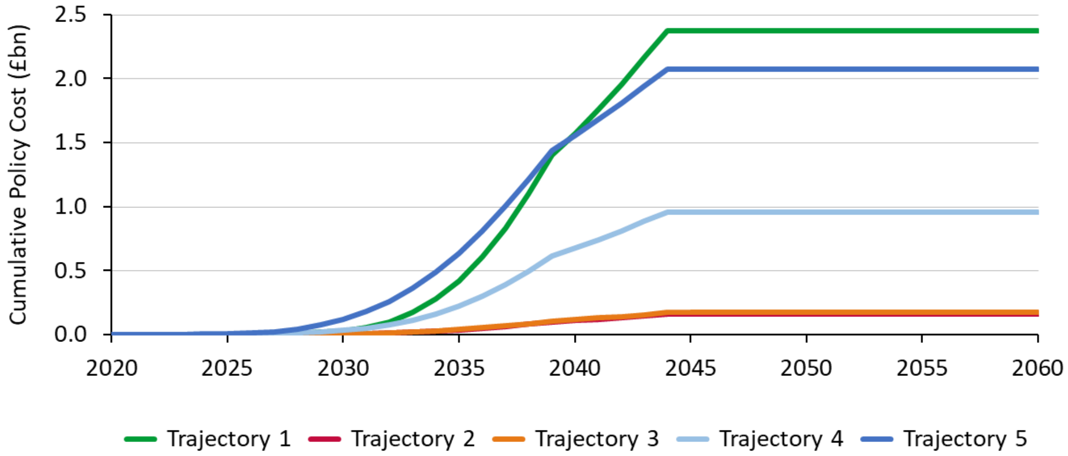

Figure 28: Cumulative policy cost to achieve uptake trajectories for zero-emission artics

Preferred technology option

Artic trucks cover a wide range of operations from short range distribution to heavy duty long haul and different zero-emission technologies are likely to be deployed depending on the application. BEV models are already being trialled in Europe for urban distribution routes where long range capabilities are not necessary. In the long term, with a full rollout of mega-chargers, BEV models could become a cost-effective option for even the longest and heaviest routes due to the lower cost of electricity compared to hydrogen modelled in this work. However, hydrogen vehicles are likely to be technically capable of meeting operators needs sooner, due to their ability to meet the longer-range requirements of these vehicles without being dependent on the rollout of infrastructure.

Figure 29 demonstrates that the likely higher cost of hydrogen fuel, compared to electricity, makes fuel cell vehicles a more expensive option for artics by 2050. However, this impact is relatively small for some vehicle types, ranging from a 3% higher TCO for short-range depot-based hydrogen vehicles to 13% when comparing BEVs using mega-chargers with long-range depot-based hydrogen vehicles. Operators may choose to pay this premium for the greater operational flexibility of hydrogen vehicles, as hydrogen options could exist that require no public refuelling during rest breaks, whereas BEV option will always require a recharging event in the middle of routes which could be challenging to coordinate with rest breaks.

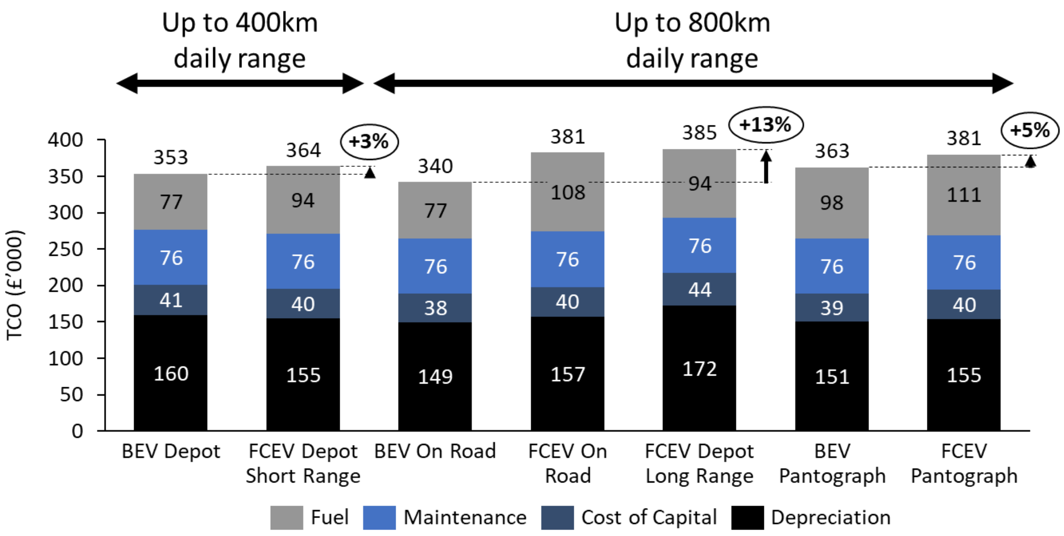

Figure 29: TCO comparison of zero-emission refuelling options for artics in 2050 (6-year 1st owner lifetime, 116,000 km/y assumed)

5.4.4 Buses

The some of the challenges for zero-emission buses are like those for artic trucks. In both vehicle categories, fuel costs are a large proportion of the TCO and limitations on packaging sufficient energy storage on the vehicles limits the range capabilities of certain drivetrains. As can be seen in Figure 30, this leads to a similar mix of FCEV and BEV models in bus sales as seen in Section 5.4.3 for artics. However, the refuelling infrastructure required for buses is likely to be substantially different to that for trucks, which will have an impact on the choice of technology deployed in this segment. Deployment of zero-emission buses is also more advanced than for trucks and the market is an order of magnitude smaller, suggesting that 100% zero emission sales is likely to be achieved 5-10 years ahead of trucks.

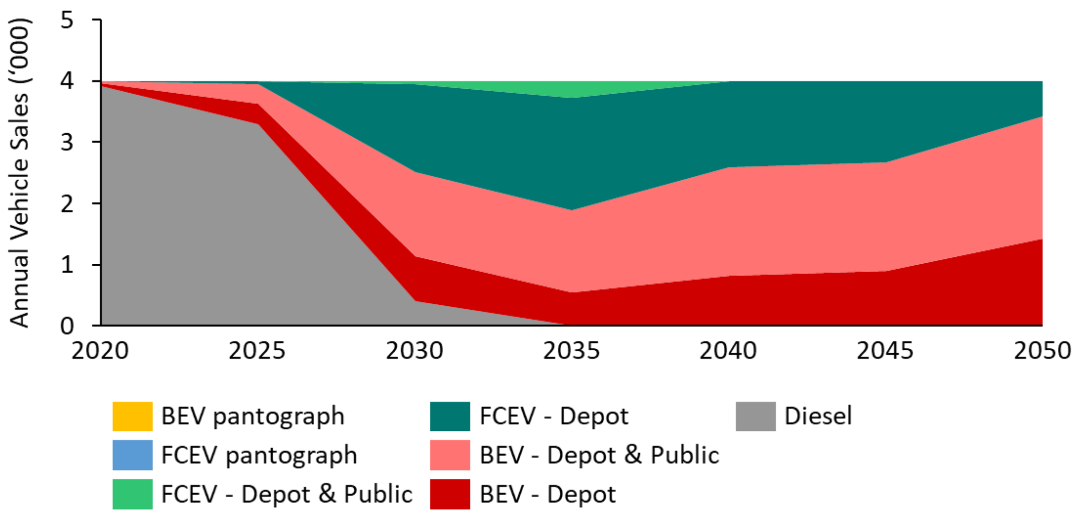

Figure 30: Annual sales by drivetrain for buses in Trajectory 4

Buses are likely to achieve 100% zero-emission sales faster than trucks

Electric buses are already in service across the UK and the pressure on local authorities to improve local air pollution means that their currently higher upfront costs compared to diesel buses are less of a barrier to adoption. The cost of these vehicles is falling quickly and both the technology and familiarity with it amongst operators is also improving. Due in part to the fact that these vehicles are already being produced at scale, they are expected to achieve TCO parity with diesel buses over the next few years, shown in Figure 31. Hydrogen powered buses are also at a more advanced stage of development than in the truck sector, and these are expected to achieve parity with diesels in the late 2020s. Both options are helped by the high fuel consumption of buses and the lower cost of electricity and hydrogen compared to diesel, as is the case for artics. These factors mean that there is significant momentum behind the transition to zero-emission drivetrains in the bus market already and no financial subsidies to improve their TCO in comparison with diesels are included in this modelling. Even without this support, buses are expected to achieve 100% zero-emission sales 5-10 years ahead of the truck market.

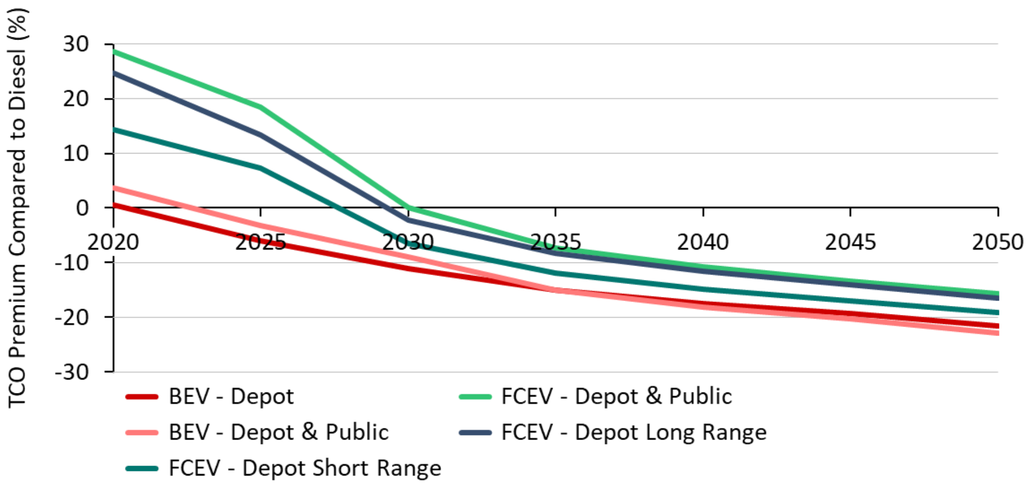

Figure 31 - TCO Premium of zero-emission Bus Drivetrain Options Compared to Diesel (8-year 1st owner lifetime, 60,000 km/y assumed)

Buses have different infrastructure needs to other HDV segments

Buses today are typically depot-based, returning after each shift and only needing to refuel with diesel once a day meaning operators are highly unlikely to shift to refuelling in public. This is due both to the operational complexity this would entail including health and safety challenges of refuelling high volumes of buses at public locations, but also because their operational profiles provide more opportunities to accommodate additional depot refuelling than those of trucks. As a result, zero-emission buses will have different refuelling infrastructure requirements to trucks and coaches, with the majority of refuelling likely to continue to take place in-depot.

Whilst for the other vehicle segments assessed in this work, 'public' refuelling refers to large public access HRSs or mega-chargers, for buses this would in practice simply mean additional refuelling at the depot, at bus stops (flash charging) or at the end of bus lines (opportunity charging). For hydrogen buses this would be a single refuel taking only a few minutes. For BEVs it would probably mean small top-ups of charge while the driver has a break at either end of a route. In this way the bus maintains enough charge to make it through a longer shift and return to the depot overnight for a full recharge. The dependence on in-depot infrastructure means that while hydrogen buses are currently significantly more expensive than battery variants, as costs come down, they could be an effective option on many routes, due to their greater range capability but also greater operational flexibility.

It is challenging to economically package sufficient energy storage onto buses

The key challenge for buses is packaging enough energy storage onto their chassis to meet their demanding energy requirements. As can be seen in Figure 32, BEV and FCEV models that only refuel once a day would only be capable of meeting just over half of the daily range requirements of buses by 2050. Despite having lower annual mileages than artic trucks (60,000km/y compared to 110,000km/y) buses tend to operate in urban areas with a lot of stop-start driving that increases fuel consumption. In addition, ancillary energy demand for heating and cooling varies by season and in the winter months, can produce significant extra fuel consumption.

As with Artics packaging energy storage onto a bus is very challenging as most of the space is already used. The challenge for buses varies significantly between different bus designs (double decker buses are more challenging as the energy storage cannot increase the hight of the vehicle) but all buses face the challenge of ensuring the bodywork is strong enough to hold the weight of the energy storage, especially if it is stored high up in the bus, a challenge which is less of a concern for trucks which are already deigned to hold significant weight.

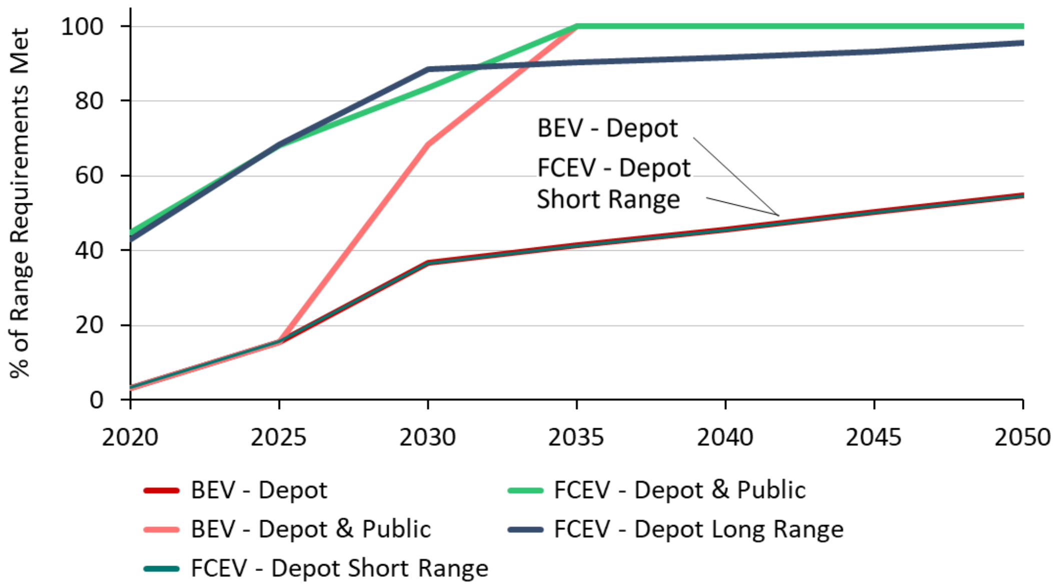

Figure 32: Range Suitability of zero-emission Drivetrain Options for Buses

Preferred technology option

By 2035, when zero-emission refuelling infrastructure is assumed to have been fully deployed for buses, both FCEVs and BEVs that carry out additional refuelling during the day can meet all requirements in this segment. BEV options result in a lower TCO, driven by the lower cost of electricity and are likely to be sufficient for most bus routes. This is reflected in their dominant share by 2050 in Trajectory 4 (see Figure 30 above). However, certain routes, such as those in rural areas which are significantly longer and include higher speed driving than typical urban routes, may be better suited to hydrogen vehicles that can package additional energy storage more cheaply. Taking into account other factors such as seasonal variations in energy demand, FCEVs may be preferred on a greater share of routes than shown in the results for Trajectory 4, especially if infrastructure investments have already been made in the 2030s.

5.4.5 Coaches

There are three key factors affecting the ability of coach operators to adopt zero-emission vehicles. Firstly, they tend to cover long distance inter-city or international routes, making it necessary to carry large amounts of on-board energy storage. Secondly, their relatively lightweight frames mean that there is a limit to the additional mass that can be added, providing an advantage to hydrogen in this segment as hydrogen tanks are lighter than batteries. Thirdly, the coach fleet covers a much wider range of routes (motorway and urban) than many long-distance trucks (mostly motorway) making the provision of a public refuelling network that meets all operators needs very challenging. The impacts of this can be seen in Figure 33, where depot refuelled hydrogen coaches make up a larger proportion of sales in 2050 than they do in any other vehicle category.

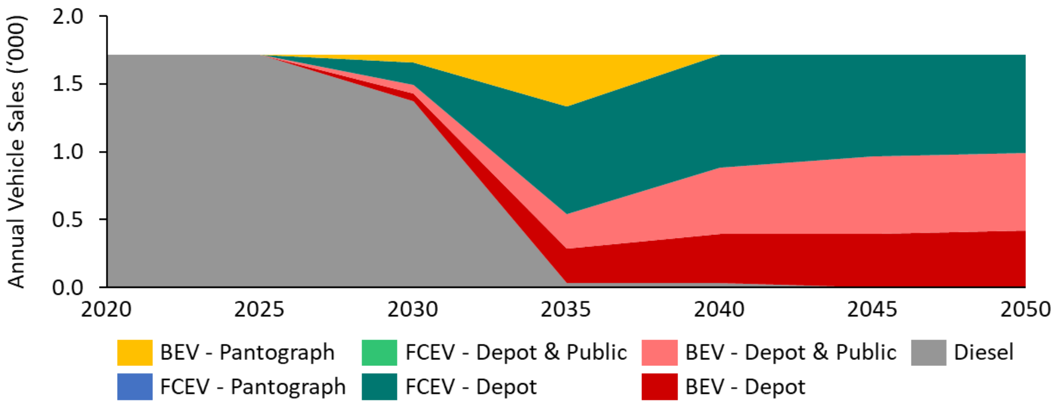

Figure 33 - Annual sales by drivetrain for coaches in Trajectory 4

The body structure of coaches limits the role of BEVs for the longest routes

Existing coaches are not structurally designed to carry a significant amount of additional mass and legal weight allowances to cover the additional weight of the powertrain are assumed to be 1 tonne for coaches, rather than 2 tonnes for trucks. As a result, BEV options can only achieve a limited proportion of the range requirements of coaches. Even by 2050 as the energy density of batteries improves, BEV coaches that do not take advantage of public refuelling could only package enough batteries to cover around 75% of routes before hitting their mass limit, as shown in Figure 34. However, coaches do have significant space within their structures, under the floor, on the roof or at the rear for packaging energy storage. Hydrogen drivetrains have a higher gravimetric energy density than batteries, and while they take up significant volume, they add less weight per unit of energy stored. The impact of this can also be seen in Figure 34, where FCEV models would already be capable of achieving 65% of coach range requirements today and this quickly rises to nearly 100% by 2030. The results for coaches in Trajectory 4 demonstrate that once the national mega-charger network is completed in 2045, this would be the cost optimal choice for long distance coaches. However, the nature of the coach business may make it more challenging to make use of mega-charger infrastructure, particularly if it was primarily deployed to support trucks.

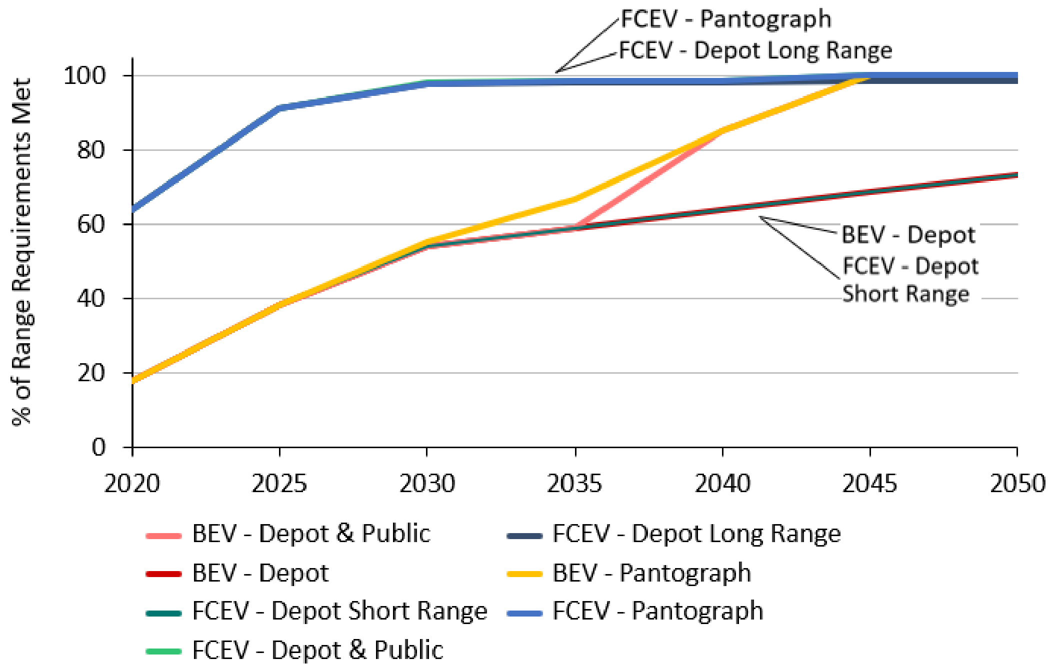

Figure 34 - Range Suitability of zero-emission Coach Drivetrain Options – All hydrogen drivetrains have the same Range Suitability

Coaches are likely to require public refuelling, but suitable locations may be limited

While the results for Trajectory 4 suggest BEV coaches using mega-chargers would be technically and economically suited to a large proportion of the coach market, operators may be reluctant to use mega-chargers deployed specifically for trucks. The coach market is about 25 times smaller than the truck market, and so any megawatt scale public recharging infrastructure for HDVs will be focused on serving trucks. The facilities at these locations are likely to be more restricted than the motorway services that coaches typically use for rest stops. Since service stations are further apart on the road network than the planned mega-charger infrastructure for trucks, coaches may require greater range to ensure they only recharge at locations with full services. This could be important as passengers may need to wait at these sites for an extended period for the vehicle to recharge and could have an impact on the business model of coach operators.

Although pantograph vehicles only briefly appear in the Trajectory 4 results for coaches, an ERS might be more beneficial for coaches in practice than a mega-charger network, allowing vehicles to charge while they drive. This option is more expensive than using a mega-charger, but it would be cheaper on a TCO basis than the depot-based long-range FCEV. However, for the ERS to be a viable option for coach operators it would need to be adopted in the truck market, as coaches alone would be insufficient to justify the cost of constructing such a major piece of infrastructure. If this does not happen, coach operators may need to opt for the more expensive long-range FCEVs. These could then either refuel only in depot or quickly at a public site, reducing the need for services to be available and making it more straightforward to use the same infrastructure built for trucks.

Preferred technology option

As can be seen in Figure 35, there is very little difference in the TCO of depot based BEV and FCEV models that would be suitable for short-range applications. For those routes beyond the capacity of these vehicles, BEVs using mega-chargers would be the cheapest option. If this is not a viable option for coaches, a BEV using an ERS would only be about 5% more expensive and a long-range depot-based FCEV 7% more expensive, as shown in Figure 35. The ability to rapidly refuel could be particularly attractive for coaches making international journeys if hydrogen infrastructure continues to be rolled out across Europe. For coach fleets that regularly operate over longer distances, or coaches that do not run regular routes and need the flexibility to cover longer distances when necessary, hydrogen is likely to be the preferred technology.

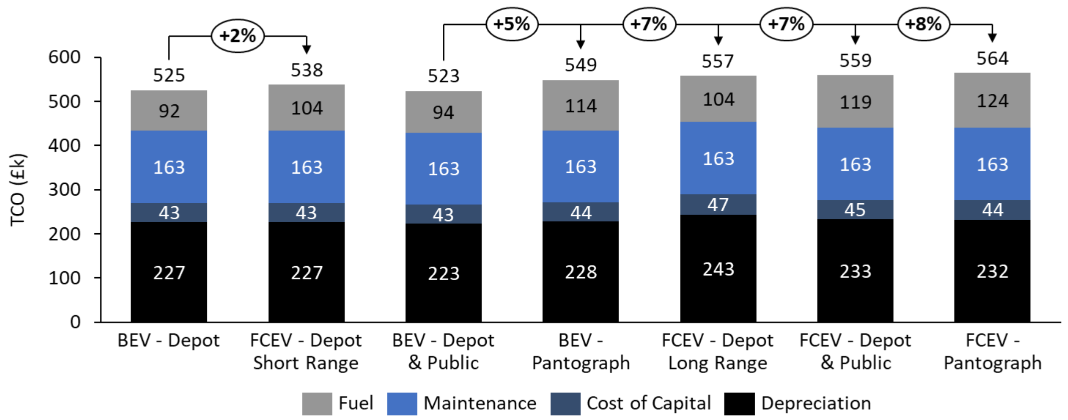

Figure 35 - TCO Comparison of zero-emission Drivetrain Options for Coaches in 2050 (8-year 1st owner lifetime, 100,000 km/y assumed)

6 Sensitivities

This chapter explores some of the assumptions that have been made in the modelling of zero-emission HDV uptake, to understand how robust the results are to a range of possible alternative futures. Trajectory 4 is taken as a baseline for comparison with a range of scenarios where the basic modelling assumptions are altered. The sensitivities explored are:

- Battery costs
- Fuel cell costs
- Fuel price (diesel, electricity and hydrogen)
- The need for a battery or fuel cell replacement within the first owner lifetime
- Requirement for additional battery capacity to cover irregular high fuel consumption events such as changes in routing, very bad weather etc.
- The case where no public refuelling infrastructure is installed

The main findings from the sensitivity analysis are:

The sensitivities that predominantly increase the cost of BEV models, compared to FCEVs, have the strongest impact on the number of diesels still being sold in the 2040s.

- Figure 36 shows that the high battery cost and high electricity price sensitivities result in significantly more diesel sales in 2040 than the high fuel cell and high hydrogen sensitivities. This is because BEVs generally have a lower TCO than FCEVS and so when their costs increase, a more expensive FCEV model is not always a suitable alternative from a cost perspective.

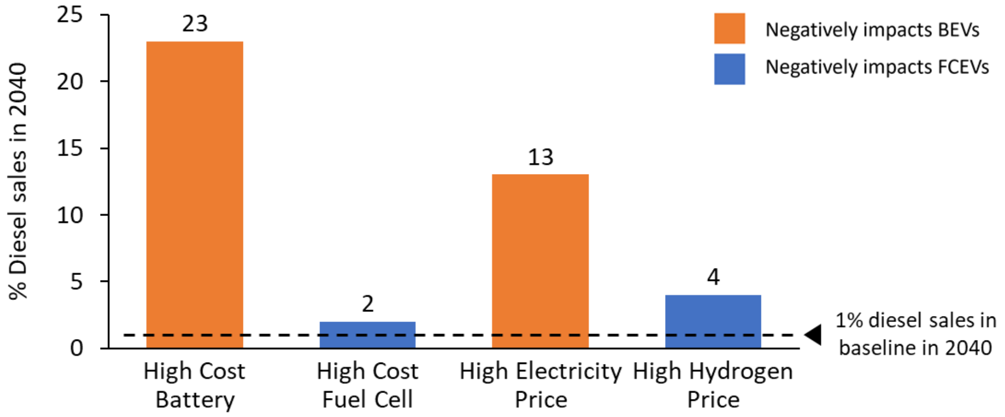

Figure 36: Impact on proportion of diesel sales in 2040 under key sensitivities affecting mostly either BEVs or FCEVs

- The results are most sensitive to the need for fuel cells and batteries to be replaced within the first owner lifetime of the vehicles. The additional capex implied by this means that zero-emission rigid trucks would not become competitive with diesels before 2050, while uptake of the higher mileage vehicles would be delayed by 10-15 years, leaving a large number of diesel vehicles on the road into the 2050s.
- No sensitivity run resulted in a change to the uptake of ERS. It has been found that the price of ERS electricity needs to be reduced by 35% before this refuelling choice would match the share taken by vehicles using mega-chargers.
- The vehicles with the highest annual mileages/fuel consumption (artics, buses and coaches) are generally affected in a similar way by the factors assessed in these sensitivities, due to their TCOs having a greater share of fuel costs and a lower proportion of capex costs. On the other hand, the results for the lower mileage rigid

truck segments are much more sensitive to increases in costs, compared to diesel, because the TCO benefits of zero-emission models are more marginal.

High mileage/fuel consumption vehicles (artic trucks, buses and coaches)

- Because zero-emission fuel prices are lower than diesel in this work, high mileage vehicles are typically able to overcome the challenges presented by sensitivities that increase their capex costs.
- The uptake of high mileage vehicles is more sensitive to higher FCEV costs (high cost fuel cell/high cost hydrogen sensitivities) because FCEV models allow them to meet to the longest-range requirements while public refuelling infrastructure has not been fully deployed.
- The uptake of zero-emission vehicles in the higher mileage segments is less sensitive to increased BEV costs because their high fuel consumption and the lower cost of zero-emission fuels compared to diesel make them better able to absorb higher BEV costs or switch to the more expensive FCEV models.
- High mileage vehicles are highly sensitive to a lack of public refuelling infrastructure and would require long-range models that package additional energy storage to achieve the longest 50% of routes with a single daily refuel in depot if no public refuelling were available.

Low mileage rigid trucks

- The capex of zero-emission vehicles is generally higher than diesels and capex is a higher proportion of the TCO of the lower mileage rigid trucks. This makes them much more sensitive to increases in cost compared to diesel than high mileage vehicles.
- Rigid trucks are more sensitive to higher BEV costs (high battery/electricity cost sensitivities) than the higher mileage vehicles. The TCO benefit of BEV options over diesels is marginal in this segment and any increase in costs results in more diesel sales rather than sales of the more expensive FCEVs.
- Zero-emission rigid trucks are also much more sensitive to low diesel prices, with three quarters of small rigids and one quarter of large rigids finding no viable zero-emission option by 2050 if diesel prices are 20% lower.
- The deployment of zero-emission rigid trucks is however less sensitive to higher FCEV costs than the high mileage vehicles because by 2035 they can meet nearly all of their range requirements with batteries and a single charge per day and so are not dependent on either hydrogen or public refuelling to decarbonise.

Table 6 summarises the sensitivities carried out and presents the technology mix in 2040 produced by each. This date has been selected as it is the last year where diesel vehicles could be sold, and the UK could still meet the 2050 net-zero target.

Table 6: Summary of the impact of sensitivities on zero-emission powertrain mix of HDVs (grey – 3 or fewer percentage points different to baseline, light red/green – 4-10 percentage points different, dark red/green – more than 10 percentage points different)

<table>
<tr><th rowspan="2">Sensitivity</th><th colspan="7">Sales Breakdown by Powertrain in 2040</th></tr>
<tr><th>BEV depot</th><th>BEV depot & mega-charger</th><th>BEV depot & ERS refuelling</th><th>FCEV depot & ERS refuelling</th><th>FCEV depot</th><th>FCEV depot & public HRS</th><th>Diesel</th></tr>
<tr><td rowspan="2">Baseline</td><td rowspan="2">28%</td><td rowspan="2">34%</td><td>0%</td><td>0%</td><td rowspan="2">36%</td><td rowspan="2">2%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Battery Cost</td><td rowspan="2">9%</td><td rowspan="2">20%</td><td>0%</td><td>0%</td><td rowspan="2">30%</td><td rowspan="2">18%</td><td rowspan="2">23%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Low Battery Cost</td><td rowspan="2">40%</td><td rowspan="2">52%</td><td>0%</td><td>0%</td><td rowspan="2">8%</td><td rowspan="2">0%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Fuel Cell Cost</td><td rowspan="2">36%</td><td rowspan="2">42%</td><td>0%</td><td>0%</td><td rowspan="2">20%</td><td rowspan="2">0%</td><td rowspan="2">2%</td></tr>
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<tr><td rowspan="2">Low Fuel Cell Cost</td><td rowspan="2">5%</td><td rowspan="2">9%</td><td>0%</td><td>0%</td><td rowspan="2">45%</td><td rowspan="2">40%</td><td rowspan="2">1%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Low Diesel Price</td><td rowspan="2">12%</td><td rowspan="2">16%</td><td>0%</td><td>0%</td><td rowspan="2">17%</td><td rowspan="2">0%</td><td rowspan="2">55%</td></tr>
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<tr><td rowspan="2">High Electricity Price</td><td rowspan="2">16%</td><td rowspan="2">25%</td><td>0%</td><td>0%</td><td rowspan="2">38%</td><td rowspan="2">8%</td><td rowspan="2">13%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">High Hydrogen Price</td><td rowspan="2">36%</td><td rowspan="2">46%</td><td>0%</td><td>0%</td><td rowspan="2">13%</td><td rowspan="2">0%</td><td rowspan="2">4%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">Fuel Cell and Battery Replacement</td><td rowspan="2">4%</td><td rowspan="2">5%</td><td>0%</td><td>0%</td><td rowspan="2">11%</td><td rowspan="2">0%</td><td rowspan="2">81%</td></tr>
<tr><td colspan="2">0%</td></tr>
<tr><td rowspan="2">No Public Refuelling</td><td rowspan="2">52%</td><td rowspan="2">0%</td><td>0%</td><td>0%</td><td rowspan="2">45%</td><td rowspan="2">0%</td><td rowspan="2">2%</td></tr>
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Note: These sensitivities assume a constant level of policy support. In most cases the uptake of ZE vehicles achieved in the baseline could still be achieved under the sensitivity scenarios but would require a higher level of policy support.

6.1 Detailed Sensitivity Results

The following section presents the results for each sensitivity in greater detail, showing the impact of each on the baseline Trajectory 4 scenario and describing the driving factors for each HDV segment. Each sensitivity only alters the parameter being tested to understand the impact while other factors remain the same. This means that the level of policy support applied remains the same across all sensitivities at the level applied in Trajectory 4. It should therefore be noted that where a sensitivity increases costs so that zero-emission vehicles do not become competitive with diesels, this could be overcome with increased financial policy support.

6.1.1 Baseline – Trajectory 4

Trajectory 4 provides a useful baseline for assessing the sensitivity of zero-emission HDV uptake to a range of different factors. Trajectory 4 has been selected because it includes all infrastructure options and drivetrains, making it possible to see the impact of the sensitivities across all fuel options. Figure 37 provides an overview of the results of the baseline assumptions combined for trucks and buses and coaches. Broadly, for both these vehicle groups, in the early years before infrastructure is fully deployed depot-based FCEVs are the most popular zero-emission technology choice. By 2050, BEVs making use of mega-chargers emerge as the dominant technology in all HDV sectors. For trucks, buses and coaches, depot-based FCEVs and BEVs make up a small but significant proportion out to 2050. For all HDVs, diesels are less than 10% of sales by 2040 and 100% zero-emission sales is achieved in 2040.

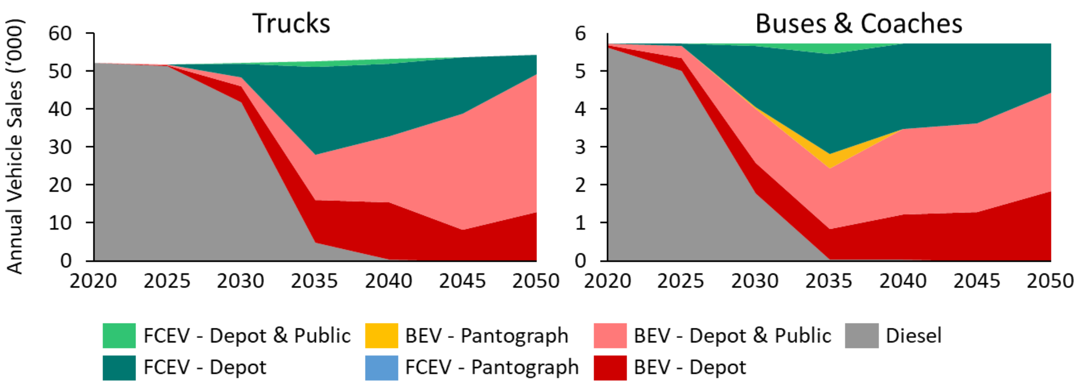


Figure 37: Zero-emission Truck and Bus & Coach Uptake in Trajectory 4

6.1.2 Battery Cost Sensitivity

Batteries are a key technology for all zero-emission drivetrains and the cost reductions that are achieved as this technology matures will have a major impact on the rate at which HDVs are able to adopt zero-emission drivetrains. BEVs which rely entirely on batteries for their energy storage are the most sensitive to changes in the cost of batteries. The pure FCEV models in this work have very small batteries and the different battery cost scenarios have a negligible impact on the overall TCO. The long-range hydrogen range extenders that only refuel in depot have larger batteries and see a larger effect from battery cost changes, but their primary energy storage is hydrogen and so the impact is limited.

The low battery cost scenario explores the potential for HDVs to benefit from the cost reductions and increased scale that has already been achieved in batteries for LDVs. In this scenario, costs for HDV batteries fall at the rate projected for LDVs but delayed by 5-years to account for the later development of vehicles in the HDV segments. It is however still unclear whether the battery cost reductions achieved for LDVs will be applicable to HDVs, as their more demanding duty cycles could result in a permanent cost premium over the systems suitable for light duty applications. The high battery cost scenario explores the impact of these challenges being insurmountable and HDVs requiring substantially different battery technologies to LDVs with their costs continuing to be higher.

Figure 38 shows the impact of the high and low battery sensitivities on the TCO of large rigid BEV models that refuel in depot only and those that make use of mega-chargers. Until 2040 the TCO of the two BEV variants are similar, but they diverge after this point as the public infrastructure nears completion and vehicles using public refuelling are able to carry fewer batteries. The high battery cost scenario has a more limited impact on the TCO, delaying the point at which BEV achieve parity with diesels by roughly 5 years. It does however leave BEV models that recharge only in depot more expensive than diesel models by 2050, though this may be less of a concern if the mega-charger network were fully deployed by this point. In the low-cost case however, TCO parity is achieved in the early 2030s. This would mean that even large rigids, which are one of the most challenging segments from a cost perspective, would be able to transition to zero-emission drivetrains with a greatly reduced level of financial policy support.

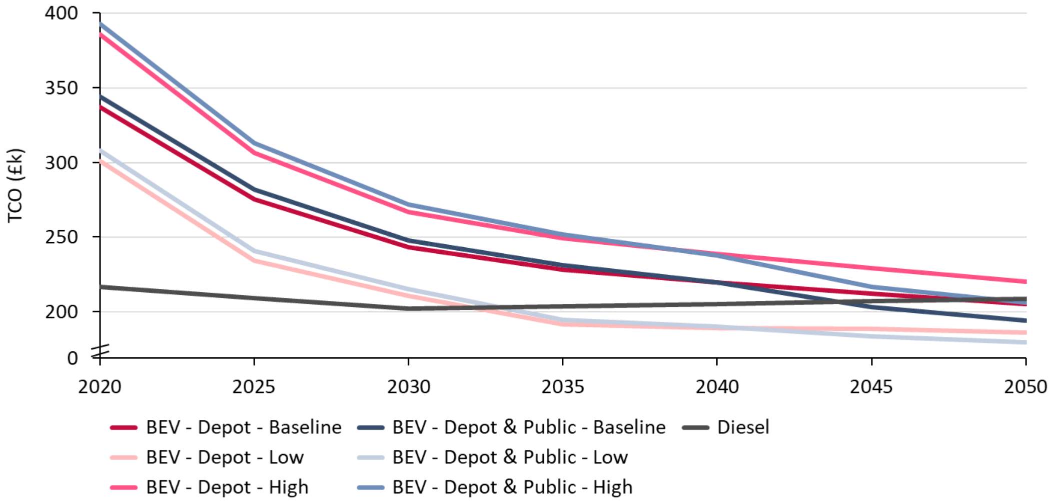


Figure 38: Impact of high and low battery cost scenarios on TCO of selected zero-emission large rigid variants in 2035 (6-year 1st owner lifetime, 53,000 km/y assumed)

Impact of Low Battery Costs on technology mix

Applying these low-cost projections for batteries to Trajectory 4 significantly reduces the volume of FCEV vehicles purchased in the early years, with BEV models dominating throughout. Across all vehicle categories there is almost no impact on the rate of deployment seen in Figure 39 by removing all the annual incentives provided in the baseline case, suggesting that achieving the low cost battery case would drastically reduce the financial policy required to support the uptake of zero-emission HDVs.

For trucks, nearly all diesel sales are removed 5 years earlier, by 2035 and BEVs are suitable for all small and large rigids with a negligible share of FCEV sales. Artics continue to require the longer-range FCEV models in the early years, but once the mega-charger network is deployed these disappear from sales by 2045. For buses and coaches there is no overall change in the speed of adoption of zero-emission models, but the mix changes substantially, with a much greater share of vehicles using mega-chargers. This reflects the high on-board energy storage requirements of both vehicle categories.

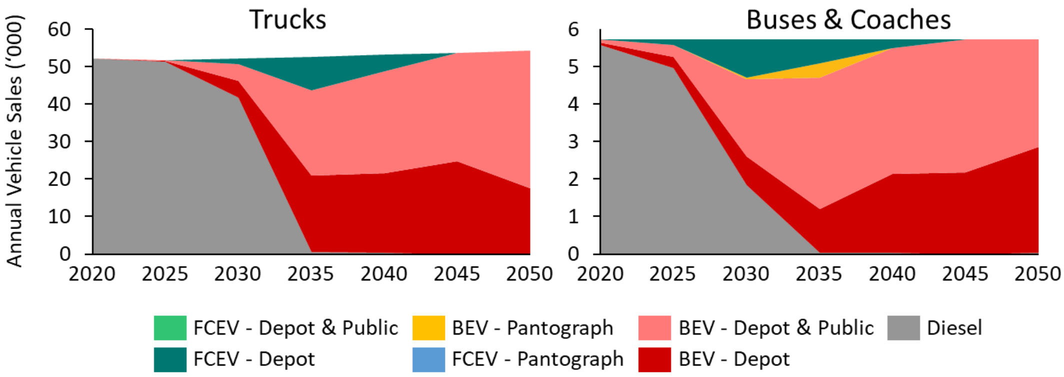


Figure 39: Impact of Low Battery costs on uptake Trajectory 4

Impact of High Battery Costs on technology mix

Figure 40 shows the results of applying the high battery cost scenario, where overall the peak sales for FCEVs is broadly similar to the baseline, though there is a higher use of public refuelling FCEVs that have smaller batteries. FCEVs also maintain more of their share out to 2050 as BEV models are less competitive. Across all HDV segments, BEVs using mega-chargers ultimately have the largest share of sales, but for trucks they are not able to remove the last 15% of sales which remain as diesels.

Within the truck results, the impact on artics is limited, with only a very few diesel sales remaining in 2040 and all sales zero emission by 2045. The mix changes slightly with fewer BEV mega-charger models and a larger share of public refuelling FCEVs during the early years and more depot refuelling FCEVs in the 2050 mix. The biggest impact is on small rigids, where by 2050 roughly a third of sales are still diesel as the otherwise well-suited BEV models remain prohibitively expensive. This impact is less pronounced for large rigids which are able to cost-effectively adopt a larger proportion of FCEVs, but by 2050 they also still have around 15% diesel sales. In practice, for both these segments the challenge here is financial rather than technical and the uptake rates seen in the baseline could be achieved with a higher level of financial policy support.

For buses and coaches that do not receive financial subsidies in the baseline due to the expectation that they will achieve TCO parity relatively quickly, the impact of higher battery costs is muted. Both segments adopt slightly more FCEVs in the early years, and they maintain a higher market share out to 2050. Overall, the high fuel consumption of vehicles in these segments and the lower cost of electricity means that BEV models continue to dominate in 2050 regardless of higher battery costs.

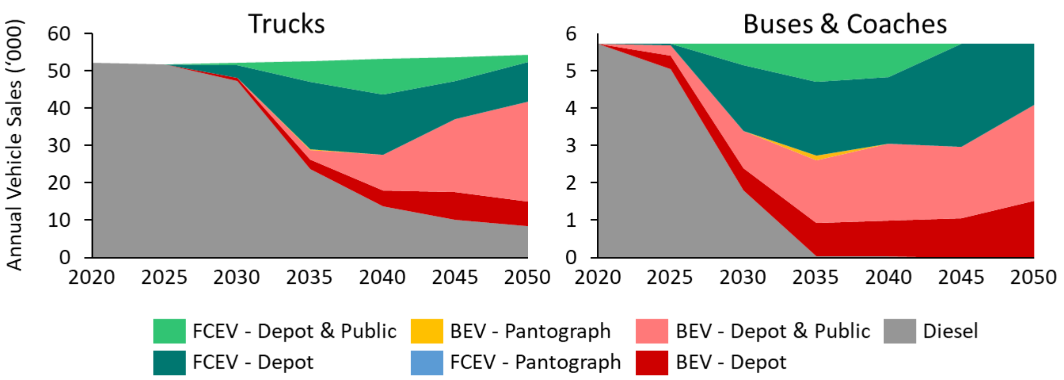


Figure 40: Impact of High Battery costs on uptake Trajectory 4

6.1.3 Fuel Cell Cost Sensitivity

There is a higher level of uncertainty around the future cost of fuel cells than there is for batteries, as they are currently manufactured at significantly lower volumes. When produced at scale, it is expected that fuel cell costs will fall rapidly, but since hydrogen is generally expected to be a higher-cost fuel for zero-emission vehicles than electricity, the viability of hydrogen HDVs as a mass market product is not driven by fuel cell costs alone.

The low cost fuel cell scenario is based on the potential that 'light duty' fuel cells, which several manufacturers such as Toyota and Hyundai plan to begin manufacturing in the 100,000's per year by 2030 for cars and vans, prove to be durable enough for HDVs. It is expected that in this case, the more demanding duty cycles of HDVs will mean that these fuel cells will need replacing multiple times in a vehicle's lifetime. However, since their projected costs could be an order of magnitude lower than the more rugged variants being designed specifically for HDVs this could still represent a lower cost option.

In the high cost fuel cell scenario, 'light duty' fuel cells prove unsuitable for the demands of HDVs. In addition, in response to the higher cost of 'heavy duty' fuel cells, fewer fuel cells are manufactured for the HDV market, increasing their unit costs and adding a premium to the already more expensive fuel cells designed specifically for heavy-duty use.

Impact of Low Fuel Cell Costs on technology mix

Figure 41 shows the impact of the low-cost fuel cell scenario on Trajectory 4. Across all HDV categories there is a drastic change in the mix of technologies purchased, with FCEVs taking a much larger share. This effect is more pronounced for trucks than it is for buses and coaches, but across both groups by 2050 FCEV hold over 50% of sales.

Within the truck category, the impact of low-cost fuel cells is greatest for the rigid trucks. Since these vehicles consume less fuel than artics, buses and coaches, capex is a greater share of TCO, and so lower cost FCEVs overcome the higher cost of hydrogen fuel. By 2050 about two thirds of rigid sales are FCEVs, while in the baseline scenario they make up less than 10%. The results for artics are less different with roughly half of sales in 2050 FCEV compared to 15% in the baseline. Almost all of this difference is made up of a reduced share of BEVs using mega-chargers being replaced by FCEVs using public refuelling to provide the longest-range requirements of artics.

Without any financial policies for zero-emission trucks, diesel sales end in 2045 with the low-cost fuel cell scenario, 5 years later than the baseline. With the same level of subsidies as included in the baseline, 100% zero-emission sales are achieved 5 years earlier in 2035. This suggests that while financial support would still be needed to achieve the 2050 target, the level of support required would be lower than in the baseline.

The impact on buses and coaches is relatively equal, with both vehicle categories adopting more FCEVs that refuel during the day, which mostly displace BEVs using mega-chargers. As with artics where high fuel consumption and lower cost of electricity overcome some of the cost benefits of lower fuel cell costs, BEVs maintain their share better for buses and coaches than they do for rigid trucks.

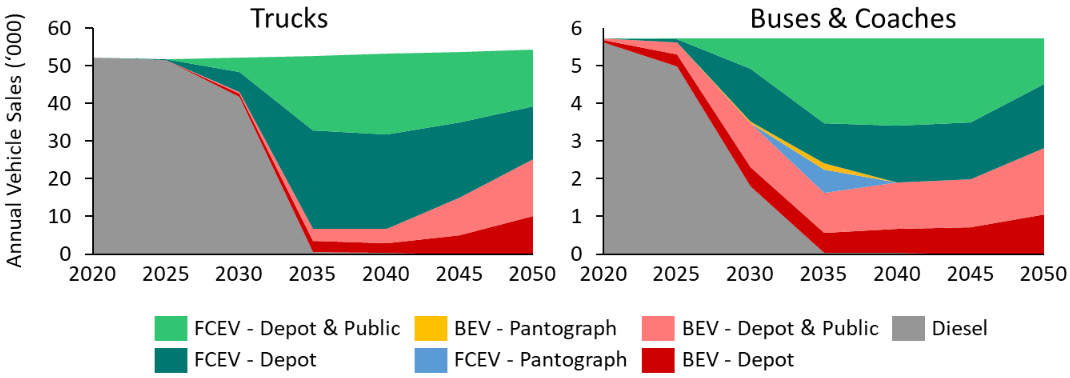


Figure 41: Impact of Low-Cost Fuel Cells on zero-emission Truck and Bus & Coach Uptake in Trajectory 4

Impact of High Fuel Cell Costs on technology mix

The results for the high fuel cell cost sensitivity are similar to the results for low cost batteries. Across all HDV segments, the role of FCEVs in the early years is reduced and BEV models make up almost all sales from 2045 onwards once the mega-charger network is deployed. The overall rate of deployment for zero-emission vehicles is not significantly affected, with only a small number of diesel truck sales remaining in 2040, compared to the baseline where sales end entirely in 2040, and buses and coaches are still able to end diesel sales in 2035. It is the large rigid segment that makes up most of the remaining diesel sales in 2040. The higher cost of fuel cells means that the roughly 10% of longest routes cannot be met cost effectively until 2045 when the mega-charger network is fully available. A small number of artics are also affected in the same way.

Buses would also be affected by this, but the rollout of opportunity chargers for buses is expected to take place ahead of mega-chargers for trucks and coaches, so BEVs carrying out additional daily recharges are more quickly able to cover the longer routes. Despite the increased TCO, coaches are still able to cost-effectively deploy a large number of FCEVs during the early years which are replaced entirely by mega-charger vehicles by 2045. In practice as discussed in Section 5.4.5, mega-chargers may be challenging for coaches to use, and in the case of high fuel cell costs operators may be willing to pay the premium for FCEVs or pantograph vehicles, if this infrastructure were deployed.

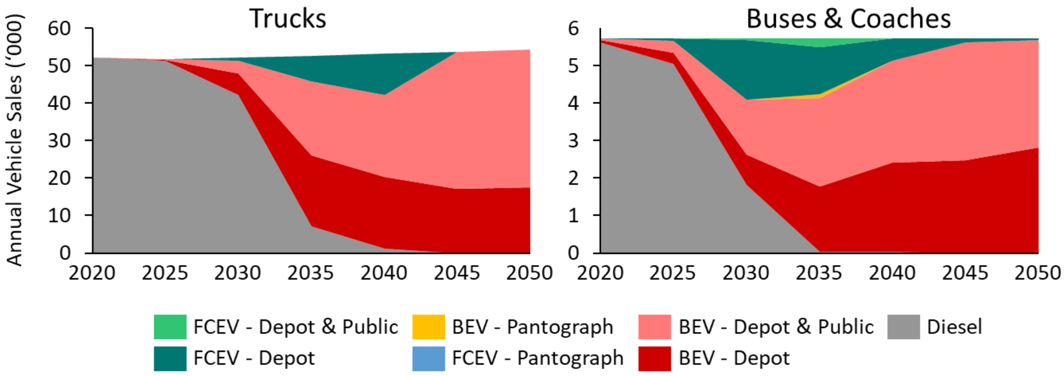


Figure 42: Impact of high cost fuel cells on zero-emission truck and bus & coach uptake in Trajectory 4

6.1.4 Fuel Price

Low Diesel Prices

At time of writing (August 2020), the Covid-19 pandemic has reduced global price of crude oil due to a steep fall in travel demand. This has led to a significant reduction in the pump price of diesel in the UK over the last six months, as shown in Figure 43[12]. Though the price is beginning to rise again, it is still 10% below where it was a year previous. A sustained period of low oil prices could impact on the uptake of ZE HDVs, by reducing the benefit of zero-emission fuels compared to diesel. If low diesel prices persist, additional policy support for zero-emission options may be required, such as a fuel duty uplift to ensure that the cost advantage for zero-emission fuels is maintained.

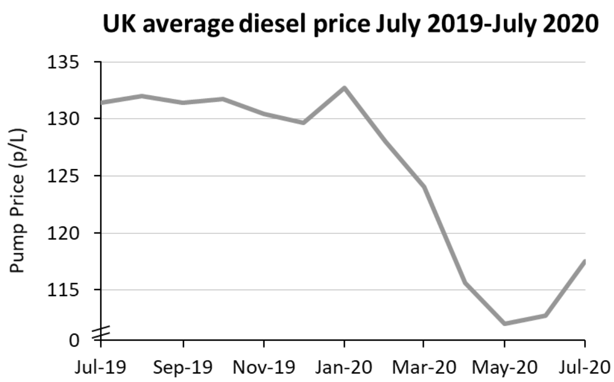


Figure 43: UK historic diesel price at pump

Impact of low diesel prices on technology mix

Figure 44 shows the impact on the results for Trajectory 4 when the diesel price is 20% below the Committee on Climate Change's current expectations every year out to 2050. As can be seen from the charts, there is a major impact on the uptake of zero-emission trucks and a more muted but still significant impact on buses and coaches. For trucks, the sale of zero-emission vehicles never really takes off and from 2045 onwards sales plateau, leaving just over a quarter of all sales diesels. Amongst the zero emission trucks sold, the technology mix is broadly similar to the baseline. For buses and coaches the main impact is to make FCEVs and BEVs using mega-chargers less competitive for the longest routes, leaving a small number of sales in 2035 and delaying the end of diesel sales by 5 years.

[12] Diesel pump prices from: The AA, 2020, UK and overseas petrol and diesel prices - July 2020, https://www.theaa.com/driving-advice/driving-costs/fuel-prices

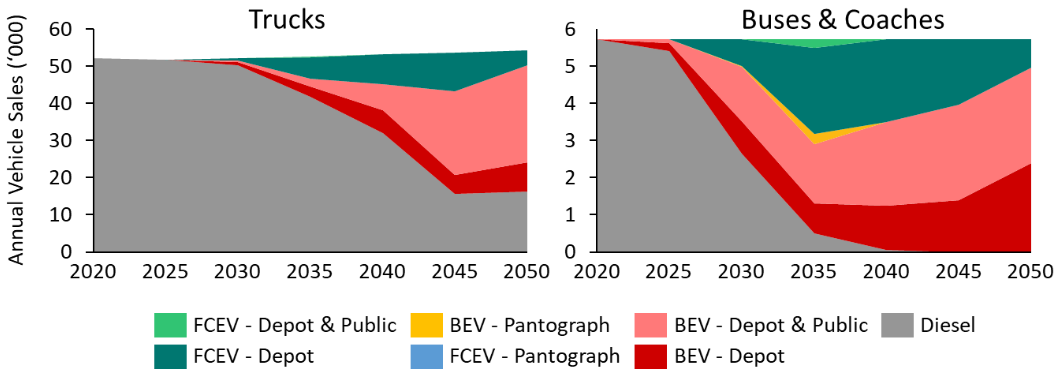


Figure 44 - Impact on the Uptake of ZE HDVs from a 20% Lower Diesel Price

The impact of lower diesel prices on trucks is mostly in the small rigid segment, where the TCO benefits of zero-emission drivetrains are more marginal. In 2035 for the small rigid, the lower diesel price reduces the diesel TCO by just 8%. However, as can be seen in Figure 45, this is enough to ensure that the small rigid BEV using mega-chargers would not achieve diesel parity without a higher level of financial policies being applied. This results in a significant delay in uptake as zero-emission small rigids can meet all range requirements by 2035, at which point the TCO premium becomes the main barrier to adoption. By comparison, although the impact on the comparative TCO is similar for artics, diesel cost parity is achieved 10 years later, the impact on the uptake of zero-emission artics is just a delay in uptake. In the baseline scenario, long range FCEVs help to increase zero-emission vehicle uptake in the early years before mega-charger infrastructure is in place. With low cost diesel these FCEVs are uncompetitive, and diesel artic sales are significantly higher in 2030-40, with sales ending in 2045, 5 years later than in the baseline.

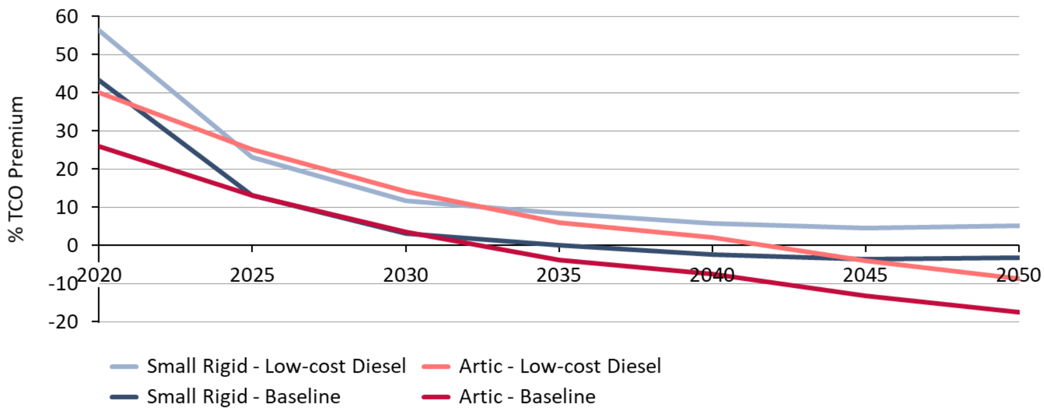


Figure 45 - Impact on TCO premium of small rigids and artics (BEVs using mega-chargers) compared to diesel vehicles under Baseline and Low-Cost diesel scenarios. Financial policies included.

As is the case for artics, the main impact of lower diesel prices on buses is to reduce the share of zero-emission sales in the early years. In 2030, when FCEVs have a range benefit over BEV models, diesels make up a much higher share of sales, displacing FCEVs on the longest routes which are unable to compete with the reduced diesel TCO. By 2035 BEVs refuelling during the day remove the remaining diesels from buses sales, as is the case in the baseline. For coaches, the negative impact on the TCO comparison of FCEVs with diesels leads to around a quarter of sales continuing to be diesel in 2035 and diesels are only completely removed by 2045.

High Electricity Prices

The electricity prices used for in-depot recharging, mega-chargers and ERS are based on the Committee on Climate Change's expected future costs of electricity for these infrastructure options (see Section 5.1 for more detail on fuel prices). These costs are uncertain as many of the refuelling options modelled have never been built on this scale before meaning there are a range of potential barriers to these costs materialising. For example, the very low utilisation of refuelling infrastructure during the sector's early growth phase could lead to higher pricing. To reflect this uncertainty, this sensitivity explores the impact on uptake if electricity prices are 20% higher than in the baseline case in every year from 2020 to 2050.

Impact of high electricity prices on technology mix

As can be seen from Figure 46, more expensive electricity significantly delays the uptake of zero-emission trucks, and has a more limited impact on delaying uptake amongst buses and coaches. It also produces a change in the mix of drivetrains that are adopted, with a lower share of BEVs deployed. For trucks, hydrogen vehicles refuelled in depot maintain their 2035 proportion of sales for longer, and between 2035-2045 public refuelling FCEVs take a small share of the longest-range vehicles. However, this mix of technologies are not capable of displacing diesels fully from sales which persist out to 2050. The higher electricity price does not significantly affect the speed at which diesels are removed from bus and coach sales, but there is a larger proportion of hydrogen vehicles using additional daily refuelling at a HRS. Hydrogen also maintains a slightly larger share of sales out to 2050.

The small rigid category is the most adversely affected by higher electricity prices, due to BEVs typically being best suited to this category. The challenging TCO comparison to diesel also means that with this additional electricity cost, none of the zero-emission options become cheaper than diesel with the level of subsidies applied in this modelling. As a result, diesel sales between 2030 and 2040 are significantly higher for this category with high electricity costs, and 5-10% of sales continue to be diesel by 2050. The impact is similar for large rigids, though since hydrogen would continue to be cheaper than diesel, the higher fuel consumption for rigids allows these vehicles to become competitive with diesel by 2035. However, it is not until 2045 when the mega-charger network is completed that diesel sales end entirely for this segment.

Finally, it is important to note that higher electricity prices do not change the overall shape of the sales graphs and that the long-term cost benefits of BEV is maintained even with the higher electricity prices.

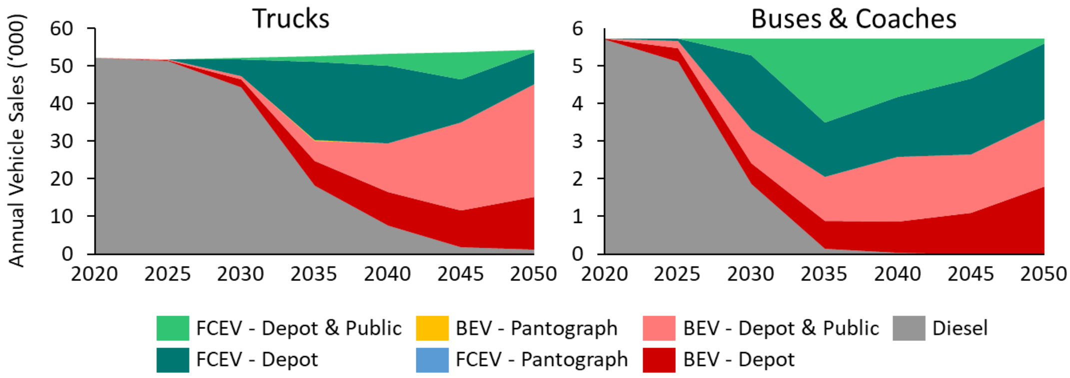


Figure 46 - Impact of Higher Electricity Prices on Uptake of ZE HDVs

High Hydrogen Prices

The hydrogen prices used in the baseline case are based on a scenario where the UK develops significant steam methane reformation (SMR) capacity as the main method for producing hydrogen at scale for use across the economy. This is deployed alongside large-scale carbon capture and storage (CCS) facilities to ensure that most carbon emissions resulting from this process are captured and stored underground. A small proportion of hydrogen (16%) in this scenario is produced through electrolysis from renewable electricity, without producing any emissions.

The scale of the hydrogen production infrastructure implied by this scenario, compared to the little that has been deployed to date, particularly in terms of CCS and electrolyser capacity, means that there is significant uncertainty around the hydrogen prices assumed in this study. To explore the impact of hydrogen prices that are substantially higher than those in the baseline, this sensitivity applies a 20% premium to the hydrogen price used in the baseline.

Impact of high hydrogen prices on technology mix

As can be seen from Figure 47, higher hydrogen prices would almost entirely remove FCEVs from the mix for all HDVs, but would not significantly reduce the overall speed of uptake of zero-emission vehicles. Compared to the results from the high electricity costs in Section 0, high cost hydrogen leads to half as many diesel trucks being sold in 2035 and several times fewer diesel sales in 2040. This is driven by the generally lower TCO of BEV models allowing them to displace the FCEVs that have become too expensive.

The impact of higher cost hydrogen is strongest for artic and large rigid trucks because they are more range constrained in the early years than small rigid trucks which can meet all their range requirements with batteries by 2035. Large rigid diesel sales end in 2045 in this sensitivity, 10 years later than in the baseline, however 90% of sales are zero-emission from 2035 with the longest routes met with diesels until mega-chargers become fully available. In the artic segment diesels are a third of sales in 2035, twice as many as in the baseline, and are still 10% of sales by 2040, suggesting that a significant number would still be on the roads by 2050.

For buses, where recharging infrastructure is fully deployed by 2035, BEV models can displace the FCEVs that would be too expensive with a higher hydrogen price, unlike trucks which are more dependent on them to provide the longest ranges until 2045. In the baseline scenario, FCEVs feature more heavily in coach sales, however with higher hydrogen costs they are able to replace most of these with BEV models and by 2040 only a small proportion of FCEVs are purchased to displace the remaining diesels on the longest routes.

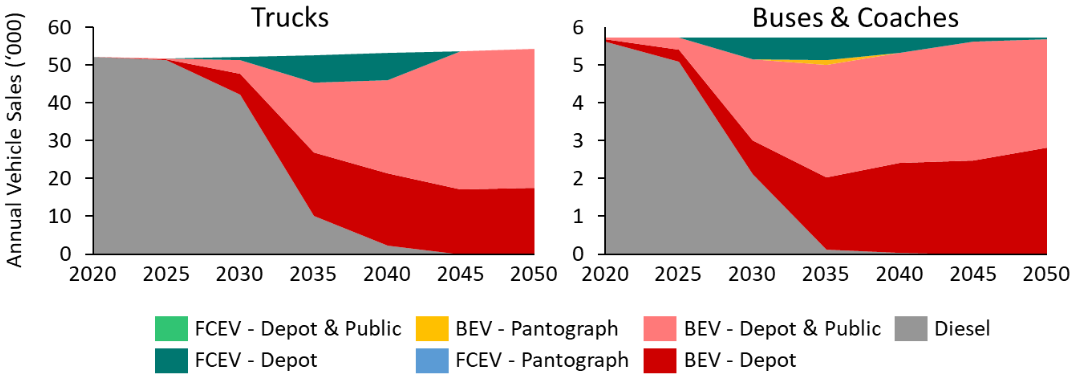


Figure 47 - Impact of Higher Hydrogen Prices on the Uptake of ZE HDVs

6.1.5 Fuel Cell and Battery Replacement Sensitivity

The vehicle costs used to generate the 5 Trajectories in this work only consider the first owner lifetime of the vehicle, which is assumed to be 6 years for the trucks and 8 years for the buses and coaches. The model also assumes that fuel cell and battery replacements will not typically be necessary within these periods. However, since only a limited number of full-scale production models of zero-emission HDVs have been deployed to date and even fewer have been on the roads for 6-8 years, it is unclear whether fuel cell and battery replacements will be necessary within a vehicle's first ownership.

As the most expensive components of zero-emission drivetrains, replacing fuel cells and batteries would represent a substantial additional cost for operators. This sensitivity applies the cost of a new battery or fuel cell to the operator's costs after 5 years of ownership. This means that, for example, the TCO calculation for a vehicle purchased in 2020 includes the price of the required battery size in 2020, as well as the price of an equivalent battery at the projected costs for 2025, when the battery would be replaced. As shown in Figure 48 for a large rigid purchased in 2035, this would add about a quarter to TCO of a BEV vehicle and about a fifth to the TCO of a FCEV model.

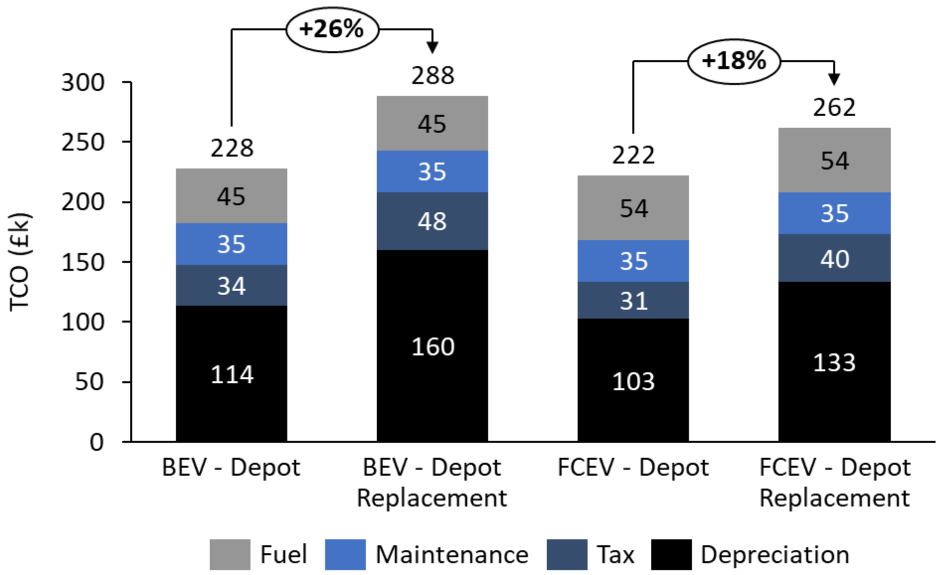


Figure 48: TCO comparison for depot refuelling FCEV and BEV large rigids in 2035 with and without fuel cell and battery replacements (6-year 1st owner lifetime, 53,000 km/y assumed)

Impact of fuel cell and battery replacement on technology mix

Figure 49 shows the impact of an additional fuel cell or battery replacement on Trajectory 4. The impact on trucks is stark, where over half of all sales are still diesel vehicles by 2050. There is a more muted effect on buses and coaches, as the TCO benefits of the cheaper zero-emission fuels mostly continue to outweigh the additional capex costs of the vehicles. The additional costs mean that the full transition to zero-emission drivetrains takes longer, with diesel vehicles only completely disappearing from the sales in 2045 and zero-emission sales growing much more slowly throughout the 2030s.

Within the truck market, artics are the least affected by this significant increase in capex for zero emission drivetrains, though their uptake is significantly delayed by 10-15 years. A small number of diesel sales remain in 2045, and 100% zero-emission sales are achieved by 2050, but this would clearly lead to many diesel vehicles still being on the road well into the 2050s. Artics are able to remove diesels from sales within this period due to their high fuel consumption and significantly lower fuel costs for zero-emission vehicles compared to diesels. The capex for these vehicles finally falls low enough by 2045 that these low fuel costs overcome the additional cost of replacing batteries and fuel cells. For both the rigid truck categories, the larger proportion of capex in the TCOs means that they are unable to achieve TCO parity with diesel by 2050. All zero-emission drivetrain options in these segments continue to be 10-20% more expensive than diesel options and very few are purchased.

For buses, the impact is mostly on reducing the number of zero-emission vehicles that are adopted in the late 2020s and early 2030s, as the sales of diesel vehicles in 2030 are several times higher in the fuel cell and battery replacement costs than in the baseline. These higher costs also lead to slightly fewer FCEV sales over the period, and a larger proportion of BEVs using mega-chargers which need smaller batteries compared to the vehicles that only refuel in depot and therefore need larger batteries. Although the TCO impact of replacing fuel cells and batteries is likely to have a greater impact on the capex of BEV than FCEV models as shown above in Figure 48, for buses this is overcome by the lower cost of electricity compared to hydrogen. As a result, by 2050, BEV models using mega-chargers dominate more strongly than they do in the baseline.

The end of diesel sales for coaches is delayed by 10 years to 2045 with the need for battery and fuel cell replacements. The driver of this change is similar to that for artics, with FCEV options becoming prohibitively expensive in the early years, and a cost-effective long-range option only becoming available in 2045 when mega-chargers are completely rolled out.

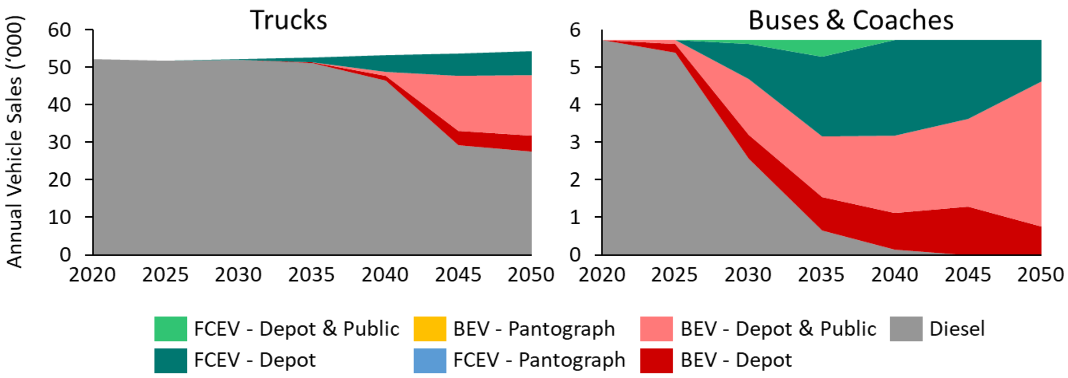


Figure 49: Sensitivity of zero-emission HDV Uptake to the Need for Additional Replacements of Fuel Cells and Batteries

6.1.6 No Public Refuelling

This report presents different uptake trajectories for zero-emission HDVs, where the main differentiator between the scenarios explored is the type of public refuelling infrastructure deployed to support the rollout of these vehicles. The reason for this is that a very small proportion of the infrastructure discussed is already in place for HDVs and it is as yet unclear which option would be the most cost effective to deploy, or most likely to support the fastest rollout of zero-emission vehicles. The large investments involved as well as the need for agreement amongst a wide range of stakeholders to install this equipment at scale across the UK make it difficult to predict whether any one option will emerge as a clear winner, or if different technologies will be deployed to meet particular use cases resulting in a patchwork deployment which may not provide national coverage of any one type of infrastructure.

To explore the potential outcome that no one technology option is able to provide similar national refuelling coverage to that enjoyed by diesel vehicles today, this sensitivity explores the impact of a scenario where no vehicles are able to rely on public refuelling to meet their range requirements.

Impact of no public refuelling infrastructure on technology mix

Figure 50 presents the results for this sensitivity and until 2035 the rate of uptake of zero emission HDVs is practically unchanged compared to the baseline. From 2035 onwards there is a persistent 5-10% of HDV sales that are diesel and are not displaced by a viable zero-emission alternative in the absence of public refuelling. The key difference between these results and the baseline is the substantially larger proportion of FCEVs deployed. Figure 50 includes a breakdown of the FCEV category into the long- and short-range variants that refuel only in depot.

In general, across the HDV results for this sensitivity, the long range FCEVs are suitable for the longest third of routes, while the TCO and range capabilities of the short range FCEV and BEV variants also take a third each, covering the shorter range requirements. For trucks the 2050 growth of BEVs is driven by the small rigid market which flips from a 50% split between FCEVs and BEVs to 100% sales BEV between 2045 and 2050.

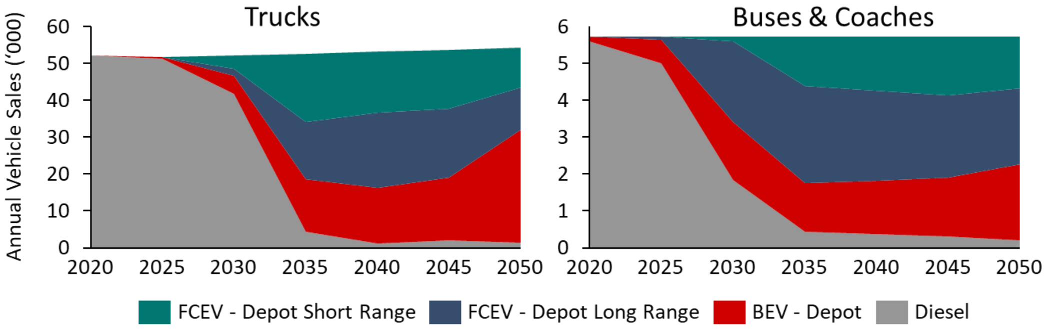


Figure 50 - Impact of no publicly available zero-emission refuelling infrastructure being deployed

This sensitivity is particularly useful for showing the role hydrogen vehicles could play if a full network of public refuelling infrastructure fails to materialise or is not deployed in time to meet the 2050 target. Figure 51 shows the results of this sensitivity if the long-range depot refuelling FCEVs are removed from the technology mix. The results in this case are substantially different to those shown in Figure 50, with a large proportion of diesel HDVs remaining in the mix.

Small and large rigid trucks are largely unaffected by the removal of the long-range option. By 2035 small rigid BEVs are capable of carrying sufficient batteries for all their daily range requirements. For large rigids, the short-range FCEVs and BEVs have almost identical TCOs and range capabilities and these make up an even share of large rigid sales. By 2050 less than 5% of large rigid sales are diesel with no public refuelling and no long-rage FCEV. Artics are the truck category that is most dependent on public refuelling, or vehicles with long-range capabilities. Without either, just over a third of artic sales would still be diesel by 2050.

Figure 51 also shows that long-range zero-emission vehicles would be essential for buses and coaches. Similarly, to the case for artics, meeting the longest third of routes covered by these vehicles with batteries alone would not be possible within the weight limitations of today's vehicles. However, with relatively minor adjustments to the vehicle bodies, sufficient hydrogen tanks could be added, either on the roof or at the rear of the vehicles to cover all these range requirements. As shown in Figure 50, these long-range vehicles would be necessary for a third of buses and coaches if no infrastructure were available for an additional refuel during the day. This is much less likely to occur for buses, as operators are likely to directly manage their own refuelling infrastructure.

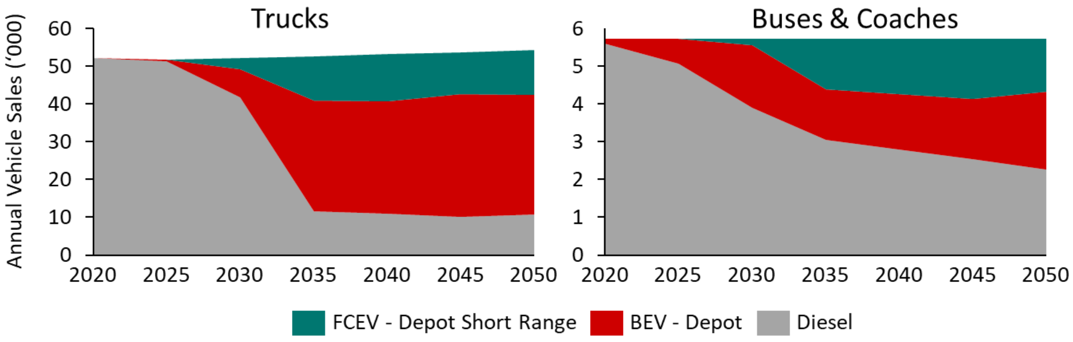


Figure 51: Results of the 'no public refuelling' sensitivity with the long-range depot refuelling FCEV variant removed

7 Required Government Support

The introduction of zero-emission HDVs will require strong policy support to overcome the challenges of high purchase cost, uncertain maintenance requirements and lack of refuelling/recharging infrastructure. Current support for zero-emission HDVs varies significantly between regions and vehicle types. Across the UK all zero-emission trucks can apply for grant support through the plug-in grant scheme. This offers a grant of up to 20% off the purchase price of a new zero-emission vehicle, with a maximum grant of £20,000 for the first 200 trucks sold and a maximum of £8,000 thereafter.

All other targets for the introduction of zero-emission HDVs and the corresponding support is local. For example, London which has the most aggressive targets for the introduction of zero-emission buses aims to phase out all diesel buses by 2037, requiring a major shift to purchasing zero-emission buses in the early 2020s. Many other regions are just beginning to introduce low emission zones and are targeting the removal of pre-Euro VI vehicles from the bus fleet, but most have not yet moved on to planning the transition to zero-emission vehicles.

The policies needed to support the transition of the HDV fleet to zero-emission vehicles will require both vehicle and infrastructure policies. The range of vehicles policies needed is expected to include:

- Large scale commercial demonstrations to provide information for operators about how zero-emission HDVs will work for them.
- Information campaigns to inform HDV operators about zero-emission HDVs.
- Aggregation and clustering of zero-emission HDV orders to encourage supply, reduce costs and facilitate infrastructure rollout.
- National fiscal measures to make zero-emission HDVs more cost competitive.
- Local fiscal and operational measures to make zero-emission HDVs more competitive.
- Support to ensure battery/fuel cell lifetimes meet operators' requirements.
- Flexibility in HDV weight and size restrictions to allow zero-emission powertrain to be packaged on the vehicles.

The range of infrastructure policies needed is expected to include:

- Fiscal support for early infrastructure providers to help overcome the first mover disadvantage of installing infrastructure when the equipment costs are high.
- Planning support to ensure infrastructure can be built to the tight timeframes required.
- Infrastructure such as ERS will only be built once on a particular road meaning the infrastructure operator has a monopoly and could easily over charge operators for the service as vehicle operators have little choice but to use the infrastructure available. Policy oversight will therefore be required on prices to ensure a fair price is set and high prices do not lead to a delay in zero-emission vehicle rollout.

7.1 Recommendations for Government Action

To meet the net-zero target in 2050 the majority of HDVs purchased in 2035-2040 must be zero-emission vehicles. This means that most of the government support required is needed before 2035. Policy support packages will therefore be needed for the next 20 years to support the transition to zero-emission HDVs, this is in-line with what we expect to see for car and vans where policy support started in the early 2010s and will probably need to run till 2030. Table 7 summarises the range of government support packages needed over time.

Table 7: Policy support timeline

Policy Type	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Commercial Vehicle Demonstrations	→	→				
Information Campaign	→	→				
Government Industry Partnership Collating Demand	→	→				
Stimulating Domestic Vehicle Production	→	→	→			
UK Level Tax	Purchase and annual taxation of fossil fuel powered HDV increased by the equivalent of £40 annually →	→	→	→	→	→
	Electricity and hydrogen used for transport exempt from fuel excise duty →	→	→	→	→	→
	Purchase grants →	→	→			
Local Fees and Charges	Exemption from zero-emission zone charges →	→	→	→	→	→
Battery and Fuel Cell Lifetime Guarantee	→	→				
Vehicle Weights and Size Regulation	→	→	→	→	→	→

7.1.1 Fiscal Incentives

A wide range of fiscal incentives will be required to support the transition of the HDV fleet to zero-emission vehicles. These incentives could include; increasing taxation of fossil fuelled powered vehicles, exemption from taxation for zero-emission vehicles and direct payments such as grants for zero-emission vehicles. Table 8 summarises a range of policy options some of which, such as increasing diesel vehicle registration tax, provide new income for government (highlighted green), some, such as zero-emission vehicle purchase grants, will cost government money (highlighted red) and some, such as continuing fuel excise duty only for fossil fuel vehicles, will not cost government any money as changes in income are assumed to be made up through other policies (highlighted black).

It is clear that all the policies both national and local add up to more financial support than is required to reach TCO parity for vehicles in 2035 (2035 is the target year for TCO parity to ensure the vehicle stock is zero-emission by 2050). This means that not all of the policies in Table 8 need to be enacted for the Trajectories presented in Chapter 5 to be achieved. As a result, both national and local government have significant potential capacity to drive the transition and if one area of government is not moving quickly enough this slack can be covered by more ambitious policies from other areas of government. The assumptions behind the policies in Table 8 are given in the rest of this chapter.

Table 8: Value of policy options to first vehicle owner in 2035 (first ownership period trucks = 6 years. Bus and Coach = 8 years), in GBP

Incentive	Small Rigid	Large Rigid	Articulated	Bus	Coach
Exemption from increase in purchase tax	600	600	600	600	600
Exemption from increase in VED	3,600	3,600	3,600	3,600	3,600
Exemption from fuel excise duty	21,000	40,000	95,000	90,000	90,000
Zero-emission vehicle purchase grant	15,000	15,000	0	0	0
Exemption from zero-emission zone charges in towns and cities	13,500	6,000	3,000	16,000	12,000
Total (£)	**53,700**	**65,200**	**102,200**	**110,200**	**106,200**
Total Required for TCO Parity in 2035 for					
Trajectory 1 (£)	41,600	66,100	114,300	90,000	101,000
Trajectory 2 (£)	41,400	64,700	97,900	90,000	90,000
Trajectory 3 (£)	41,100	67,000	97,900	90,000	90,000
Trajectory 4 (£)	41,600	67,000	108,600	90,000	90,000
Trajectory 5 (£)	41,600	67,000	109,400	90,000	100,600

UK Tax and Incentives

This work assumes the continuation of the plug-in truck grant which is currently set at £8,000 per vehicle. The results of this analysis suggest that this level of support is sufficient for vehicles operating in urban areas if most major urban regions introduce emission charging zones in the 2020s. However, for trucks moving mostly outside of urban areas additional policy support will be required in the early years. This could be achieved by increasing the grant to £15,000 per vehicle or by introducing increased taxation on the longer range inter-urban vehicles, for example by, increased diesel duty or road taxes for diesel vehicles on motorways. For this work we assume the grants are continued out to 2030 for Artics and 2035 for Rigids after which they are gradually removed.

However, this alone is not sufficient to provide the financial support needed for the HDV sector to meet the 2050 net-zero target. The first additional tax policy option is a gradual increase in the taxation of diesel HDVs. This sends out a clear message that the cost to use diesel vehicles will always increase in the future and that the UK government is committed to the complete phase out of these vehicles. The tax increase is assumed to be equivalent to the registration tax increasing by £40 a year and the annual VED tax increasing by £40 per year. This means that the registration tax for an HDV will increase from the flat rate of £55 today to £655 in 2035. Annual tax will also increase by £600 between now and 2035 but because VED is paid multiple times in a vehicle life it will have a more significant impact on operators. For example, a small rigid truck today will pay approximately £300 tax a year or £1,800 for the first owner assuming a 6-year ownership period. By 2035 this will increase to £900 per year or £5,400 for the first owner. Zero-emission HDV would be exempt from these tax increases and continue to pay today's tax rates in the future.

Another policy option to provide financial support to zero-emission HDV is maintaining fuel excise duty on diesel fuel while exempting zero-emission fuels. This would require no action on the government's part as this reflects the situation today where zero-emission fuels are not taxed in the same way as diesel. This situation has arisen because adding excise duty to electricity used for road transport is very challenging as users can easily plug electric cars into household electricity sockets therefore making it difficult to differentiate between domestic and transport electricity demand. Assuming the government needs to recuperate lost earnings from excise duty as transport decarbonises, we assume a new tax must be introduced. This could be an increase in VED but could be much more effective at shaping transport demand if it is tied to the amount the vehicle is used (as is the case for fuel duty). One option for this is road user charging which would allow government to recover lost income from fuel duty, while also shaping transport demand as road user charging can include different per km charges for different vehicle sizes, road types, time of day and user type. This would allow government to maintain income from transport, control transport demand and maintain a cost benefit for zero-emission vehicles. To maintain current government income this new tax system would need to be applied to polluting and zero-emission vehicles and is therefore not explicitly modelled here.

Local Incentives

Over the last year many local governments have taken a forward position on climate change, declaring a climate emergency and setting more ambitious climate targets than those agreed at a UK level. This suggests local policies will have a very important role to play in shaping the uptake and use of zero-emission HDVs. With the local net-zero climate targets announced to date, approximately 40% of trucks, buses and coaches (see Table 9 and Figure 52) have a depot in a region with a local net-zero climate target of 2030, with a significant number of additional HDVs expected to have depots outside of these regions but travel into/through these regions on a regular basis.

Table 9: Proportion of zero-emission HDV fleet impacted by local climate targets

Target	Number of Trucks	% of Trucks	Cumulative % of Trucks	Number of Buses and Coaches	% of Buses and Coaches	Cumulative % of Buses and Coaches
2025	14,300	3%	3%	3,664	2%	2%
2030	194,250	37%	40%	66,286	41%	43%
2035	-	0%	40%	-	0%	43%
2040	14,127	3%	43%	5,881	4%	47%
2045	27,036	5%	48%	10,888	7%	54%
2050	262,488	50%	100% National Target	70,480	44%	100% National Target

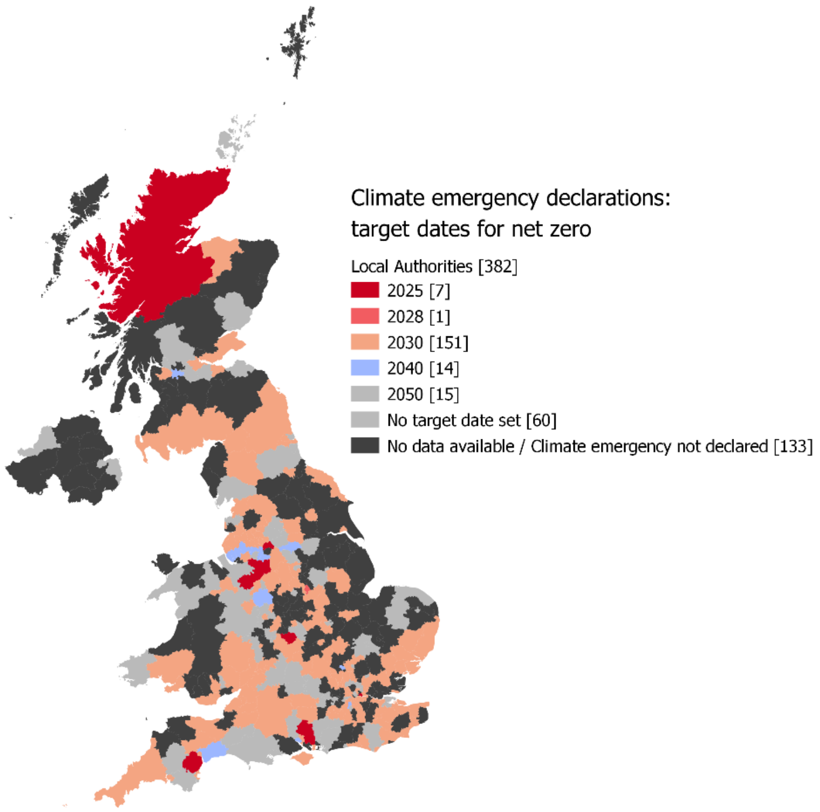


Figure 52: Map of local climate change targets (EE mapping of data from https://www.climateemergency.uk/blog/list-of-councils/ , correct as of March 2020)

To meet these climate targets local government will need to introduce a range of policies to fiscally incentivise zero-emission HDVs and disincentivise or restrict fossil fuel powered vehicles. Local policies that together could provide significant support for zero-emission HDVs include:

- Only procure zero-emission HDVs for local government fleets (bin lorries etc.).
- Only allow zero-emission vehicles on tendered bus routes.
- Zero-emission zones with penalties for non-compliant vehicles. The Low Emission Zone and Ultra Low Emission Zone in London currently charge £100 a day for non-compliant HDVs. However, this level of penalty is not necessary to drive the level of change needed. A wider zero-emission zone with a lower penalty (approximately £10 per day) would have an impact on a greater number of vehicles and would be sufficient to help make zero-emission vehicles TCO competitive with diesel.
- Setting up zero-emission only parking spaces for delivery trucks.

7.1.2 Commercial Vehicle Demonstrations

Commercial vehicle demonstrations are not required for zero-emission buses as thousands of zero-emission buses are in operation around Europe, including in the UK, and the lessons learned from these experiences can be gathered through conversations with those involved[13]. However, there is not this same experience with zero-emission trucks and coaches, and this may make some operators unsure about the suitability of zero-emission vehicles for their operation. The truck market is also very diverse with different operators using the vehicles in very different ways. This further complicates the process of providing useful lessons learned from a demonstration to other operators.

Zero-emission trucks and coaches have been developed by vehicle OEMs and are currently being trialled with a small number of customers. We would advise against further small scale (1s to 10s of vehicles) trials of zero-emission trucks and coaches in the UK for four main reasons:

1. Meeting the 2050 net-zero target requires ambitious programs of zero-emission vehicle deployment. Small scale trials are not in keeping with the size of the 2050 net-zero challenge.
2. Refuelling/recharging infrastructure is very expensive. Installing infrastructure for a very small number of vehicles make the fuel very expensive and the business case unappealing for fuel providers and vehicle operators. This leads to everyone assuming that the business case for zero-emission vehicles is not yet viable, delaying investment off the back of the trial.
3. Trials often suffer from expensive vehicle maintenance and delays in getting vehicles fixed. This is because there are insufficient vehicles to warrant a dedicated maintenance team and replacement parts often require production of one-off parts. Disappointing maintenance experiences lead to poor feedback from operators delaying the subsequent rollout of zero-emission vehicles.
4. Trials often see vehicles used differently to real-world operation reducing the useful lessons learned. Trials are also already being completed by the OEMs to ensure the vehicles are fit for purpose. Repeating this process will therefore lead to little additional benefit.

Instead of small-scale vehicle trials we propose large-scale commercial demonstrations where 100s of vehicles are put into everyday use with multiple operators across the UK over a period of 1-2 years. This will provide:

1. A clear signal that the UK plans to transition the HDV fleet to zero-emission vehicles in-line with meeting the 2050 net-zero target.

[13] The number of FCEV buses is much smaller than BEV buses. The FCEV buses in operation have been rolled out through funded projects, the findings of which will be shared.

2. Much more useful lessons learned from real-world operation by multiple operators. This broader experience will mean that data and experience that are relevant to a much larger proportion of the UK HDV fleet is collected.
3. By setting up the demonstration with clusters of vehicles across the UK it will be possible to ensure refuelling/recharging infrastructure is well utilised from day one. This will help fuel providers to offer a competitive fuel price making the business case for zero-emission vehicle much more attractive to vehicle operators.

Setting up and running the commercial vehicle demonstration is a large undertaking. Planning the demonstration should start immediately as it will take 1-2 years to source vehicles, and delivery of this number of zero-emission HDVs is likely to take time and be delayed as production capacity is built up. It is also likely to take 1-2 years to find operators willing to take part in the trial and set up refuelling/recharging infrastructure in/close to their depot. The demonstration organiser should aim to have the first vehicles in operation by 2023 with all vehicles in operation by 2025.

7.1.3 Information Sharing Campaign

The outcome of the commercial demonstration should be a detailed information campaign that shares the findings with HDV operators across the UK. This is very important as views about the suitability of zero-emission HDV could seriously impact when zero-emission HDV are considered in operators buying options and therefore the early uptake rate. The commercial demonstration will not be able to demonstrate a zero-emission HDV under all circumstances, making it very challenging to provide tailored information to all operators. This could be overcome by using the findings of the demonstration to develop a tool to calculate range suitability and TCO payback (or update an existing tool, such as the LoCity Commercial Vehicle Finder). The tool could use an individual operators operating profile by making use of speed profiles taken from telematics systems installed on most vehicles. In this way operators could have tailored information from the tool with the knowledge that the tool inputs (fuel consumption, battery degradation etc.) are confirmed by real-world experience.

Case Study - LoCity Operators Views to ULEV[14]

Operators' views of low/zero emission vehicles can have a major impact on the number of operators considering low/zero emission vehicles when making a vehicle purchase. The results of the van and truck operators views to ULEV study conducted by LoCity demonstrate how many operators consider ULEV trucks to be unsuitable for their operation without sufficient evidence to make the decision (this study interviewed 200 operators making this research the most comprehensive on this subject in the UK). Figure 53 shows that only 43% (the positive groups in green and the "sceptic having done research group" in pale red) of fleets have conducted enough research to understand if ULEVs are a viable option for them. This suggests a strong need for reliable information and education to increase the number of fleets considering ULEVs. The results also show that there are currently more fleets with a positive outlook on using ULEVs than there are ULEV being supplied by current HGV manufacturers suggesting supply constraint is an issue.

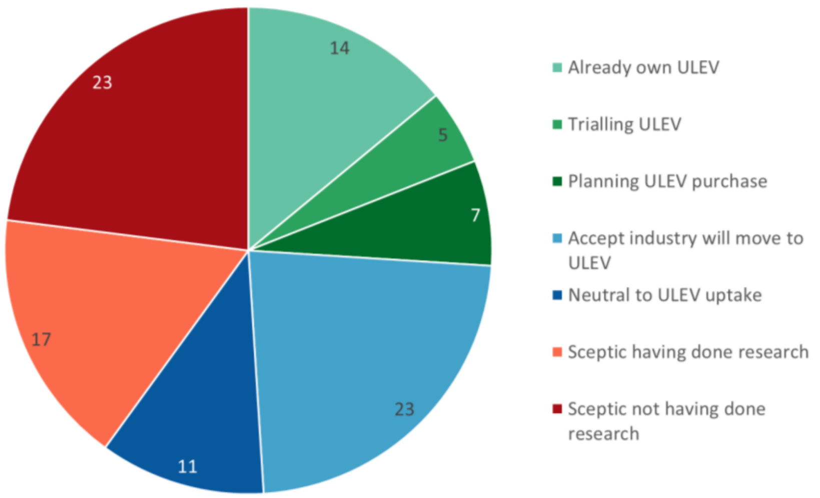


Figure 53: Fleet operators stated views on ULEVs, sample size = 200, 2016

7.1.4 Ensuring Zero-Emission HDV Supply by Collating Orders

The limited supply of zero-emission trucks and coaches will hamper uptake of these vehicles over the next 10 years. Small orders of zero-emission vehicles from multiple operators will not be sufficient to encourage OEMs to build up supply capacity quickly. This can be overcome by large guaranteed orders which can allow OEMs to invest early in zero-emission production capacity. Collating orders across multiple operators can also help to form clusters (areas with high numbers of zero-emission HDV in use) which can make the business case for public refuelling infrastructure viable and accelerating infrastructure rollout. There is therefore a need for an organisation to support the rollout of zero-emission HDV over the next ten years. This organisation will:

1. Collate orders across multiple operators within clusters
2. Approach OEMs to offer guaranteed order volumes if specific vehicle specifications and timescale can be met

[14] LoCity, 2016, How can LoCity increase operator uptake of Ultra Low Emission Vehicles, https://locity.org.uk/wp-content/uploads/2016/05/Final-Report-Databuild1-.compressed.pdf

3. Agree competitive vehicle prices through high volume agreements
4. Liaise with infrastructure providers to ensure infrastructure is installed alongside the introduction of the zero-emission HDVs

<u>Case Study – H2 Energy/Hyundai partnership in Switzerland</u>

In Switzerland the "H2 Mobility Switzerland Association", which represents several key logistics companies, wanted a zero-emission HGV that met its members' needs. Unable to find anything on the market the group, represented by H2 Energy, sought a vehicle manufacturer who would develop a new zero-emission HGV for this market. This resulted in H2 Energy forming a joint venture with Hyundai to supply 1,600 hydrogen HGVs in Switzerland between 2020 and 2025. The joint venture between H2 Energy and Hyundai will organise or supply hydrogen production (H2 Energy), stations (H2 Energy) and vehicles (Hyundai) offering fleet user's vehicles at a fixed per km charge with no high capital cost investments.

7.1.5 Stimulating Domestic Production

The UK has a small number of zero-emission HDV manufacturers such as Alexander Dennis and Wrightbus, who produce both battery electric and fuel cell buses. However, unlike the car market which relies on large volumes and production automation to provide competitively priced products, the HDV market is low volume production and relies on more manual construction and finishing. This means that it is much easier for small-scale companies to produce a price competitive product in the HDV market than the LDV market. The UK should take advantage of this and the wealth of experience already in existence in small engineering companies working on zero-emission powertrains in the UK to support domestic zero-emission vehicle production. This will help the UK to quickly rollout zero-emission HDVs in the 2020s/early 2030s when OEM production volumes are limited and could offer the opportunity for a number of small UK based engineering firms to grow and offer products for export to other countries in Europe with strong climate targets.

7.1.6 Infrastructure

The installation of major infrastructure such as roads, railway lines or a new HDV public refuelling network requires an overall strategy and central planning to ensure the infrastructure is built when and where it provides the greatest benefit. As it is unlikely that a single industry group will own and operate all the HDV public refuelling infrastructure in the UK, it will be necessary for government to take a leading role in planning the infrastructure rollout across different industry groups involved.

Early investment in infrastructure is very challenging because building a refuelling site early, when the CAPEX costs are high, means selling the fuel at a high price for the lifetime of the refuelling/recharging site. If a competitor comes along later and builds a second refuelling site with a lower CAPEX, the competitor can then offer fuel at a lower price, removing demand for fuel from the first site. This first mover disadvantage can be overcome by providing CAPEX grants to early infrastructure projects to make the CAPEX faced by industry similar to the CAPEX of expected future sites or industry groups can be given a geographical monopoly preventing competitors from building refuelling sites nearby and undercutting prices.

Whether industry groups are given geographical monopolies or not some infrastructure such as ERS naturally leads to a monopoly in a region because once built it is not possible to build a competing infrastructure along the same road network. As this is a monopoly, strict government set price controls will be required to ensure a fair fuel price is offered to vehicle operators.

7.1.7 Battery and Fuel Cell Lifetime Guarantees

The lifetime of batteries and fuel cells used in HDV is currently uncertain. This means that vehicle operators could face a large additional cost for battery or fuel cell replacements at some point during the vehicle's lifetime. Depending on how long the battery or fuel cell lasts this could results in a large cost to the operator to have the battery or fuel cell replaced or could result in the vehicle being worthless when it comes to be sold on the second hand market. This uncertainty will remain for the next 10-15 years until a generation of zero-emission HDVs have performed in real-world operation for a full vehicle lifetime. At the moment this uncertainty is being overcome by HDV OEMs offering the vehicles through a leasing package. This places the risk on the OEM not on the vehicle operator. The problem with this situation is that OEMs are likely to move back to a vehicle purchase model before batteries/fuel cells are fully proven and OEMs will pass some of the cost of the risk onto operators through the leasing charges. Policy will be needed to ensure battery/fuel cell lifetime risks do not lead to significant additional costs for operators resulting in reduced zero-emission HDV uptake. The policy options that could be employed to overcome this issue include:

1. Require battery and fuel cell guarantees from OEMs before vehicles become eligible for grants and tax breaks. It is suggested this policy is employed in all cases, but policy makers must be careful that this stipulation does not prevent small domestic suppliers from competing in the zero-emission HDV production market.
2. Offer grants/loans to help cover the cost of battery or fuel cell replacements. In this case if the battery or fuel cell does not need to be replaced then there would be no policy cost. However, this would not cover the full cost of the replacement so operators would still need to find the capital to cover most of the replacement costs.
3. Offer resale price guarantee so that people purchasing a new zero-emission vehicle know they will receive at least X% of its value after Z number of years. Most of this value should be covered by the second owner purchasing the vehicle and the government could guarantee to make up the difference.
4. Fund research and testing into battery and fuel cell degradation under HDV operation profiles.
5. Support second life applications for batteries to increase their second-hand value and reducing the net cost of a battery replacement.

7.1.8 Weights and Size Regulation

EU regulation 2019/1242 sets out the new CO_2 regulations for HDVs out to 2030. This regulation includes a clause to allow zero-emission vehicles to exceed their regulation weight limit by the additional mass of the zero-emission powertrain with a maximum additional weight of 2 tonnes. Discussions with the Department for Transport suggest that this proposal will be carried across into UK law and this forms part of our base assumptions for the modelling work conducted in this report.

This analysis also assumes that the length of long-haul HGVs is increased by 1 meter to allow for improved aerodynamic features and the packaging of larger batteries and hydrogen tanks onto the tractor unit.

8 Conclusions

BEVs dominate in 2050

- As costs fall, BEVs are likely to be the preferred technology for lighter and shorter-range vehicles
- BEVs are technically capable of serving the longest routes once mega-chargers are available. Vehicles making use of this infrastructure will likely have substantially cheaper TCOs than other drivetrain options.
- Deploying only BEVs would likely delay the overall speed of rollout for zero-emission HDVs as they are more range limited in the early years than hydrogen vehicles.
- The BEV results are sensitive to several factors, particularly lower fuel cell costs and requirements for battery replacement, however for high mileage vehicles the low cost of electricity is likely to outweigh these challenges by 2050.

Hydrogen is important in the early years

- Across all vehicle types, in the early years before public refuelling is available, FCEVs make up a large proportion of sales due to their greater independent range.
- If hydrogen vehicles are not deployed or are more expensive than expected this will likely slow the transition to zero-emission HDVs in the early years.
- Since hydrogen vehicles have an advantage in the early years, they may produce ‘technology lock-in’ if operators invest early in the infrastructure and vehicles, reducing the benefits of BEV models later on.
- Certain companies such as coach operators may be willing to pay a premium for the additional flexibility afforded by hydrogen.

ERS does not take a sufficient share to justify infrastructure

- Vehicles using an ERS do not feature significantly in the results, primarily because the electricity price from such a network modelled in this work is higher than other electric and hydrogen options.
- This modelling does not capture some of the operational benefits of an ERS that would allow vehicles to charge on the move and overcome some of the challenges of stationary mega-charging.
- However, such a system’s success would be dependent on a high level of utilisation and this work demonstrates that there are multiple viable alternatives which could be deployed piecemeal ahead of an ERS and may limit the number of vehicles making use of such a system once ready.

All options should continue to be supported as technologies mature

- Current evidence is not strong enough to pick technology winner
- Supporting all options should include ‘supported deployments’ of vehicles and infrastructure to build confidence
- Lower mileage vehicles are likely to require more financial support as they benefit less from the lower cost of zero-emission fuels compared to diesel.
- BEVs and FCEVs can have complimentary advantages with BEVs generally cheaper but FCEVs more applicable to challenging use cases.
- ERS is not a necessary infrastructure option and involves risks due to requiring national coordination and high utilisation to be deployed effectively. It should still be demonstrated in the short term as alternative infrastructure deployment and costs

are also uncertain, and it would be beneficial to continue to have multiple options in development.

Low cost of ZE fuels likely to be a driver for adoption of ZE HDVs

- Low zero-emission fuel costs incentivise deployment of vehicles for high-mileage applications, which might otherwise be the last to decarbonise.
- Desire to maximise mileage of capitally expensive zero-emission vehicles may increase attractiveness of hydrogen which can refuel more quickly.

FCEVs may offer reduced barriers for operators

- Low-cost electricity provides an advantage for BEVs that can recharge overnight in depot. On high mileage applications where an additional daily recharge is necessary, these low costs may continue to outweigh the operational complexity of aligning driver breaks with extended stops to recharge.
- For some applications, FCEVs offer the only practical and cost-effective option that is capable of ranges of up to 800km that would be required for high mileage vehicles to refuel only in depot. Since depot-based refuelling is currently most common for operators, hydrogen could be a more direct replacement for existing technologies.

9 Appendices

9.1 Methodology to Model Zero-Emission HDV Uptake Trajectories

The model starts by looking at the zero-emission powertrain packaging constraints for each vehicle size and year. This is completed once at the beginning of the model. The model then selects a subset of the available powertrain options based on the trajectory being studied. The core of the model, demonstrated in Table 10, then calculates the range suitability of every zero-emission powertrain option, for every vehicle size, in every year. This is used to filter the total number of HDV sales down to the number where a zero-emission vehicle could be considered as a purchase option. The outcome of the Range Suitability Filter is passed to the TCO Suitability Filter where the number of zero-emission vehicles considered for purchase is further reduced based on the relative TCO between each zero-emission powertrain option and diesel.

At the end of the TCO Suitability Filter the model has calculated the suitability of every powertrain option, for every vehicle size, in every year. The final section of the model calculates what mix of zero-emission powertrains will be selected. To do this, within each powertrain, vehicle size and year the model orders the powertrains from the lowest TCO to the highest and works out if the more expensive powertrains offer greater range suitability than the cheaper options. Finally, the powertrain mix is selected, this works by selecting all vehicles to make it through the earlier filters for the powertrain with the cheapest TCO. For the more expensive options only a proportion of the vehicles to make it through the earlier filters are selected, this is calculated based on the fraction of additional range suitability offered relative to the total range suitability of that powertrain.

Once a final zero-emission powertrain mix is calculated it is tested against the OEM supply constraint curve to ensure the total number of zero-emission vehicles sold in that year do not exceed the curve. If it does then the sales of zero-emission vehicles are scaled down to hit the curve in their existing zero-emission powertrain proportions.

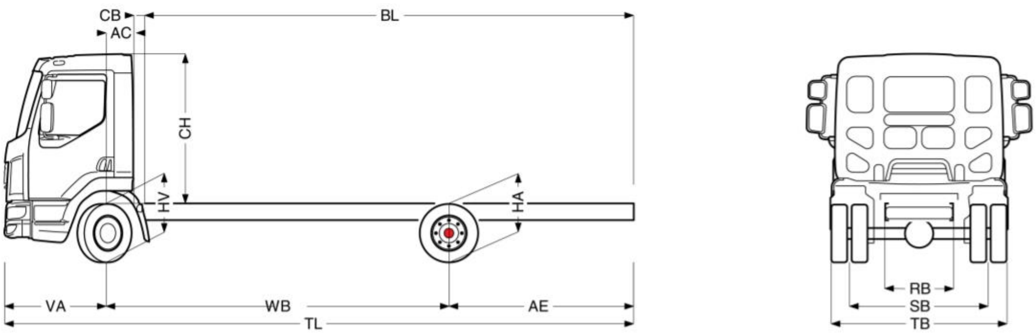
Table 10: Example calculation method for one year and vehicle size in one trajectory (using dummy data)

Modelling Steps	BEV depot	BEV depot & mega-charger	BEV depot & ERS refuelling	FCEV depot	FCEV depot & public HRS	FCEV depot & ERS refuelling
Annual Sales for all Small Rigids in 2040	100					
Step 3. Range Suitability Filter Outcome	50%	75%	90%	70%	100%	100%
Number of Zero-Emission Vehicles Taken Forward	50	75	90	70	100	100
Step 5. TCO Suitability Filter Outcome	100%	30%	20%	80%	15%	5%
Number of Zero-Emission Vehicle Taken Forward	50	23	18	56	15	5
Step 6. TCO Ranking	1st	3rd	4th	2nd	5th	6th
Step 7. Additional Range Suitability Offered	50%	5%	15%	20%	10%	0%
Step 8. Zero-Emission Vehicle Option Selection	All vehicles carried forward	Proportion of vehicles carried forward based on additional range offered	Proportion of vehicles carried forward based on additional range offered	Proportion of vehicles carried forward based on additional range offered	Proportion of vehicles carried forward based on additional range offered	No vehicles carried forward

Number of Zero-Emission Vehicle Taken Forward	50	2	3	16	2	0
Step 9. OEM Supply Constraints	If total zero-emission sales across powertrain types exceed the OEM supply in a given year, then the number of zero-emission vehicles is capped at the OEM supply limit. Proportion of zero-emission vehicle is maintained from Step 8					

9.1.1 Step 1. Modelling Powertrain Packaging Constraints

The packaging of zero-emission powertrains is constrained in terms of the volume and mass available on the vehicle. The volume available for the zero-emission powertrain has been assessed by studying technical drawings of existing diesel and zero-emission HDVs. An example truck technical drawing of the type used in this analysis is shown in Figure 54. This provides details of the dimensions of the vehicle that can be used to assess the space available for powertrain packaging.



	Wheelbase - AE		Unladen weight⁴⁾			Gross Carrying Capacity			Variable dimensions									
	WB	AE⁵⁾	Front	Rear	Total	Front	Rear	Total	AC	CB⁶⁾	CH⁷⁾	BL⁸⁾	BL	TL	HA⁹⁾	HA¹⁰⁾	TK ¹¹⁾	TW¹²⁾
DAY CAB	3.05	1.80	2423	872	3295	1177	4128	4205	0.33	0.12	1.84	3.50	5.08	6.13	0.91	0.79	10.55	11.88
	3.15	1.62	2430	860	3290	1170	4140	4210	0.33	0.12	1.84	3.65	5.29	6.05	0.91	0.79	10.79	12.13
	3.55	1.87	2443	885	3328	1157	4115	4172	0.33	0.12	1.84	4.24	6.10	6.70	0.91	0.79	11.75	13.12
	3.90	2.12	2448	898	3346	1152	4102	4154	0.33	0.12	1.84	4.74	6.80	7.30	0.91	0.79	12.61	13.99
	4.30	2.32	2457	911	3368	1143	4089	4132	0.33	0.12	1.84	5.32	7.61	7.90	0.91	0.79	13.58	14.99
	4.65	2.65	2461	933	3394	1139	4067	4106	0.33	0.12	1.84	5.83	8.31	8.58	0.91	0.79	14.44	15.86
	5.00	2.72	2473	941	3414	1127	4059	4086	0.33	0.12	1.84	6.35	9.02	9.00	0.91	0.80	15.30	16.73

OTHER DIMENSIONS VA: 1.28 HV¹³⁾: 0.79 HV¹⁴⁾: 0.75 RB: 0.86 SB: 1.74 TB¹⁵⁾: 2.20

Figure 54: Example truck technical drawing with dimensions[15]

As summarised in Table 11, trucks have space to store batteries or hydrogen fuel tanks, either side of the chassis rail, where the diesel tank currently sits, between the chassis rails and in the old engine bay. For the different size of trucks different areas have been utilised based on what is assessed to be most suitable. In every case some areas are left empty for brake systems, battery management systems, fuel cells etc. For example, in the articulated trucks batteries/hydrogen fuel tanks are located in the engine bay and down the centre of the vehicle between the chassis rails, however only a third of this space is used for batteries/hydrogen tanks allowing the rest to be used for other key components. Where

[15] DAF, 2019, Specification Sheet, https://www.daf.co.uk/api/feature/specsheet/open?container=60cab380-b034-4986-9f6f-eed71775fe14&filename=TSGBEN016F2602AAAA202017.pdf

possible the assumptions are checked against real-world zero-emission vehicles. For example, the Nikola / Iveco 2 axle artic truck, announced for release in Europe in 2021, will have a 720kWh battery[16], our approach on the same size vehicles assumes 711kWh of batteries can be packaged onto the vehicle in 2020.

Table 11: Summary of truck battery/hydrogen tank storage sites (Green = considered for both batteries and hydrogen tanks. Orange = only considered for batteries. Yellow = only considered for hydrogen tanks. Clear = not considered)

Storage Space	2 axle Rigid	3 axle Rigid	4 axle Rigid	2 axle Artic	3 axle Artic
Between the wheels either side of the chassis rail	[green]	[green]	[green]	[green]	[green]
Between the wheels between the chassis rails			[green]	[green]	[green]
Behind the back wheel either side of the chassis rail	[green]	[green]			
Behind the back wheel between the chassis rails					
Engine bay			[green]	[green]	[green]

For buses and coaches, equivalent technical drawings have been used, along with the packaging design of existing zero-emission vehicles, to assess the volume available for packaging the powertrain. Table 12 summarises the areas of the vehicle considered for packaging batteries and hydrogen tanks.

[16] Transport Topics, 2019, Nikola Battery-Electric Truck Slated for Europe in 2021, https://www.ttnews.com/articles/iveco-nikola-begin-work-battery-electric-truck

Table 12: Summary of bus and coach battery/hydrogen tank storage sites (Green = considered for both batteries and hydrogen tanks. Orange = only considered for batteries. Yellow = only considered for hydrogen tanks. Clear = not considered)

Storage Space	Single Decker Bus	Double Decker Bus	Coach
Under downstairs seats			
Engine bay			
Up the back of the vehicle			
On the roof			
Storage racks			

The other factor impacting the size of the zero-emission powertrain is the mass restrictions. The loaded mass restrictions for HDVs are set by DfT and are based on the number of axles on the vehicle. For example, a 3-axle rigid truck is allowed to have a total weight of vehicle plus goods of 26 tonnes. These mass restrictions mean that if a zero-emission powertrain weights more than the diesel powertrain it replaces then an operator switching from a diesel vehicle to a zero-emission vehicle will see a drop in goods/passengers that can be carried. *This analysis assumes that the transition to zero-emission vehicles should not reduce the operator's payload, restricting the mass of the zero-emission powertrain to that of the diesel powertrain in replaces*. However, it is expected that DfT will change policy to provide zero-emission HDV with additional mass allowances. The assumptions used in this work for the mass allowance of the zero-emission powertrains are:

- For trucks the zero-emission powertrain is assumed to have an allowable mass equal to the diesel powertrain plus up to 2 tonnes (discussions with DfT suggest it is very likely that an additional 2 tonne mass allowance for zero emission trucks will be introduced in the UK).
- For 2 axle buses and coaches, assumed to be the majority of the market, the regulated weight was increased from 18 tonnes to 19.5 tonnes in 2017, for all powertrain types, to allow for additional features such as wheelchair ramps and the heavier aftertreatment systems needed in EURO VI diesel vehicles. It is assumed only 0.5 tonnes of this increase is needed for non-powertrain features and that 1 tonne can be utilised by the powertrain, meaning the zero-emission powertrain can equal the mass of the diesel powertrain plus 1 tonne.

The final factor considered is improvements in battery and hydrogen storage technology over time. For batteries, this analysis only considered the improvements expected in the volumetric and gravimetric densities of lithium ion batteries. For hydrogen, it is assumed storage is currently in steel tanks and will transition to carbon fibre tanks over time. In both cases, this is relatively conservative as it does not consider the impact of new battery/hydrogen storage technologies currently in the research stage that could become market products over the next 10-20 years.

The packaging constraints modelling considers the volume and mass available to package the zero-emission powertrain and the range needed for a particular vehicle size by operators. The zero-emission powertrain is then sized to be within the volume and mass constraints while meeting as much of the required range as possible. Up to 2030 the size of the battery/hydrogen tanks is constrained further to reflect the current situation where OEMs are producing zero-emission HDVs with less than the maximum energy storage for a vehicle of that size to bring down the purchase costs.

9.1.2 Step 2. Powertrain and Refuelling Option Filter

Before any trajectory analysis takes place in the model, zero-emission powertrain and refuelling options that are not included in a particular trajectory are removed from the model choice options. Table 4 summarises the different powertrain and refuelling options considered in each trajectory. Although Trajectory 4 considers all powertrain/refuelling options, government support for minor refuelling options is only expected in the early years when the decision over which are the best options to pursue is unclear. Therefore, powertrain/refuelling options that only capture a minor proportion of the market by 2035 are assumed to stop expanding their market share after 2035 in Trajectory 4 as government support for the rollout of this refuelling infrastructure is removed.

9.1.3 Step 3. Range Suitability Filter

The packaging constraints modelling outputs the amount of energy stored on a vehicle of a given size. Not all 100% of this energy is available for driving the vehicle and the same amount of energy will not result in the same range every day due to weather effects. We therefore calculate the range based on a proportion of the total energy available as follows:

- **Small Rigids BEV** – Range calculated from 70% of total energy storage
- **All Other BEV** – Range calculated from 60% of total energy storage
- **All FCEV REEV** – Range calculated from 70% of hydrogen energy storage and 80% of battery energy storage
- **All FCEV** – Range calculated from 70% of hydrogen energy storage

The remaining proportion of the energy stored is used for:

- the non-usable portion of the battery energy. Using the full 0% to 100% window accelerates the battery degradation and full power is not available at low State of Charge. The vehicle is therefore excluded from using the highest and lowest proportion of the battery SOC
- energy remaining in the vehicle when it arrives at its destination
- battery degradation over time
- for the larger BEVs, additional allowance for battery degradation caused by frequent mega-charging
- reserves to cover high fuel consumption days caused by carrying especially heavy loads or bad weather.

The energy available for propelling the vehicle is then converted into a vehicle range based on the average fuel consumption for a particular vehicle size, in each year.

Once a vehicle range has been calculated for each powertrain type and vehicle size, in a given year, it is compared to the daily range requirements of vehicles today to assess the range suitability. The range suitability (the proportion of vehicles in the fleet today for which that range would cover their daily range requirements) is used to filter the number of HDV sold in each year, in each vehicle size to give the total number of HDV purchases where a zero-emission option could be considered, this is done for each powertrain option simultaneously without selecting a winner. This result is then passed on to the TCO Suitability Filter for further filtering. For example, if 100 small rigid trucks are projected to be sold in a given year and the zero-emission range suitability of BEV with depot recharging is 50% and the range suitability of FCEV REEV with depot plus public HRS refuelling is 100% then 50 BEV with depot recharging and 100 FCEV REEV with depot plus public HRS refuelling are passed onto the TCO Suitability Filter.

The daily range requirement of vehicles today has been assessed based on several sources including telematics tracking data, interviews with vehicle operators and interviews with vehicle OEMs. For trucks, the daily range required has been assessed based on telematics data, which uses on-board data loggers to track information about the vehicle such as time, speed and location. Element Energy completed a project for the Energy Technologies Institute in 2017-2018 which involved tracking 10,000 trucks in the UK over a three-month period[17]. The findings of this research gave detailed information about the daily range requirements of trucks by truck size and business type. The daily range required for buses and coaches has been assessed based on interviews with vehicle operators and OEMs conducted in 2020. The daily range requirement curves used in this analysis are presented in Figure 55. The model is designed to understand new purchasing decisions and so these curves are designed to represent the range requirements of new vehicles, which are often much higher than the fleet average as older vehicles are driven much shorter mileages.

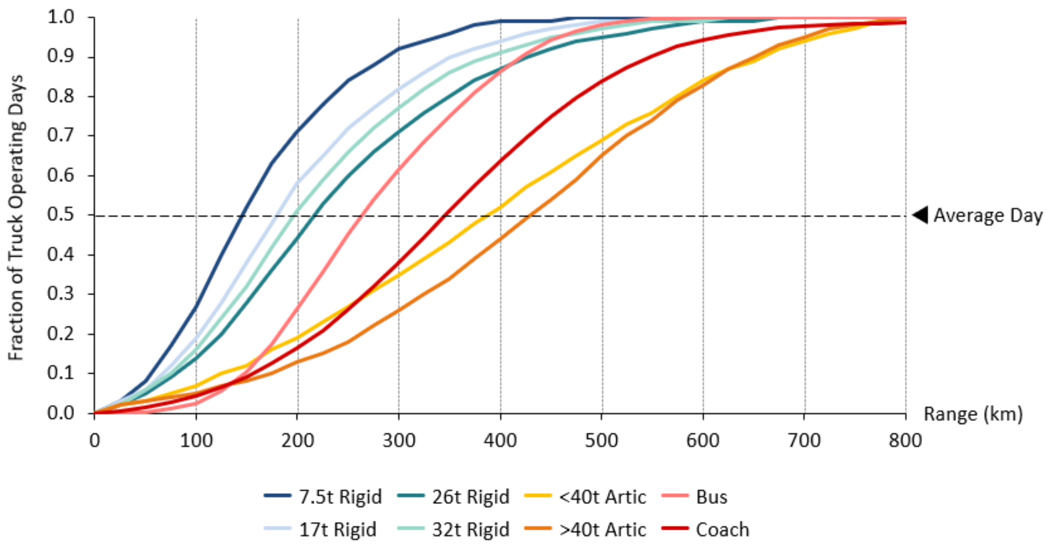


Figure 55: Daily range requirement of HDVs by vehicle size

The size of the battery/hydrogen tanks, and therefore the range suitability, up to and including 2030, is reduced in this analysis to reflect the current market where smaller powertrains are being installed on HDVs to reduce the price. This means the vehicle has a lower range suitability but because it has a more competitive TCO it is appealing to more operators than a vehicle with a very high range and a very high price.

The final factor effecting the range suitability is the rollout of zero-emission public refuelling infrastructure. The rollout of this infrastructure is summarised in Figure 56. With a complete

[17] Element Energy for The Energy Technologies Institute, 2018, Report on Telematics data analysis and truck performance algorithms, https://www.eti.co.uk/programmes/transport-hdv/element-energy-to-deliver-new-eti-project-to-increase-understanding-of-hdv-operations

mega-charger or HRS public infrastructure network it is assumed that truck and coach drivers will drive for their full driving time between breaks (4.5 hours) and then stop to refuel. This means the vehicle must be able to cover 400km between refuelling events. With a complete ERS network it is assumed that trucks and coaches can refuel as they travel along the strategic road network. The vehicle then requires sufficient range to travel off the strategic road network to a destination and back again. Based on the strategic road network coverage of the UK and the size of the UK it is assumed that 300km independent range is sufficient for ERS vehicles. The range required by trucks and coaches, while the public refuelling network is being completed is calculated as the weight average of the required range without a refuelling network and the required range with a refuelling network weighted by the percentage of the refuelling network completed.

For trucks the rollout a zero-emission depot and public infrastructure has been assessed in the aforementioned study by Ricardo for the CCC. This study set out the completion of the infrastructure between 2020 and 2060. Assuming that the later infrastructure is mostly depot infrastructure, and public sites in more remote locations, a new base truck public infrastructure curve for Trajectory 1-4 (light green line in Figure 56) has been developed that follows the Ricardo rollout until it reaches its peak build rate and then continues this build rate until the public infrastructure is complete. For trajectory 5, a more ambitious scenario is considered where the infrastructure is completed 5 years ahead of the base case (dark green line in Figure 56). Coaches are assumed to use the same public refuelling infrastructure as trucks for this analysis.

The zero-emission bus market is in a more advanced position than trucks or coaches and benefits from a greater ability to rely solely on depot refuelling. Where non-depot bus refuelling is needed the smaller scale and the fact that regional refuelling networks rather than national refuelling networks is needed means that the infrastructure could be completed much earlier. This is reflected in the more ambitious non-depot refuelling rollout rates for buses in Figure 56.

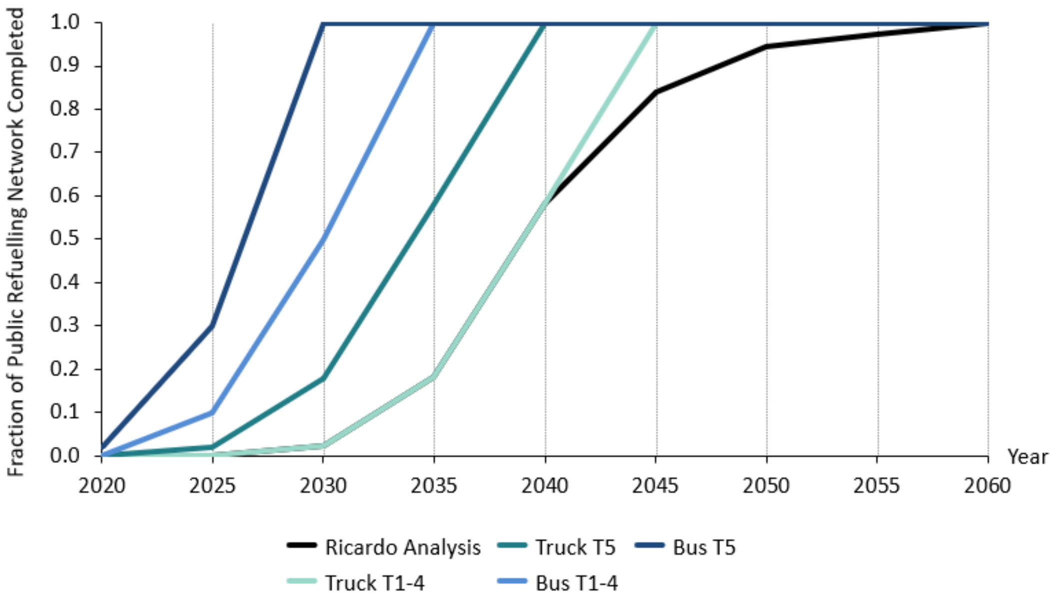


Figure 56: Zero-emission refuelling infrastructure rollout

As an example, Figure 57 demonstrates the range suitability of a zero-emission 44t articulated truck. Between 2020 and 2030 the range suitability of the different powertrain options increases as the size of the battery/hydrogen tanks increase and as the battery/hydrogen tank energy density improves. By 2030 the hydrogen vehicle has 400km of independent range and can start to make use of the growing public refuelling network. The range suitability increases as the public network is built out until the network is complete in 2045, when range suitability reaches 100%. The battery vehicle does not have 400km of independent range until 2040 and can therefore not make effective use of the public refuelling network in driver break periods. The range suitability of the battery truck increases between 2030 and 2040 as the energy density of batteries improves but it is not until the vehicle can make effective use of the public refuelling network that the range suitability of the battery truck significantly increases.

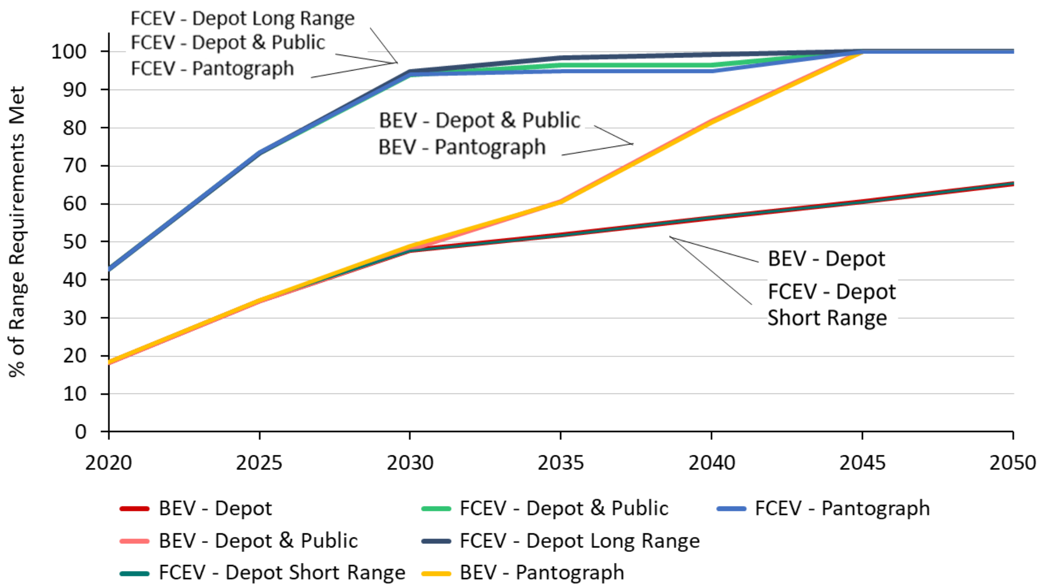


Figure 57: Range suitability of a zero-emission artic truck in Trajectory 4

Disruption to Future Range Requirements

This work also considered future technologies and changes to behaviour that could affect travel demand and range suitability in the future. The factors analysed and their potential impact on travel are summarised in Table 13.

Table 13: Impact of disruptive technology/behaviour on range requirements (Dark Green = Large positive impact. Light Green = Small positive impact. Grey = No impact. Light Orange = Small negative impact. Dark Orange = Large negative impact)

Disruptive Technology / Behaviour	Wider Impact	Impact on Daily Range Requirements/Suitability
Mobility as a Service, Liveable Cities policies and local net-zero climate targets	Greater reliance on public transport. Increased demand for buses and coaches resulting in increases in the fleet sizes	No impact on the daily range required or range suitability of individual new buses and coaches. Increases in demand met by growth in stock
Midday public refuelling	Requires the rollout of a large refuelling network to ensure refuelling sites are available when vehicles stop for the drivers break	Significantly reduces the range a zero-emission vehicle has to complete in one go to be suitable
Battery swapping	Requires the rollout of a large battery swapping network to ensure sites are available when vehicles stop for the drivers break	Significantly reduces the range a zero-emission vehicle has to complete in one go to be suitable
Shift to greater use of rail freight	Shifting goods moved over 300km to rail can help to reduce emissions and avoid the longest journeys. Reducing the size of the truck stock and its emissions	Analysis of DfT truck survey data suggest removing days with individual long trips slightly shortens the average distance covered in a day. However, pushes to increase truck utilisation are likely to maintain long truck daily distances by using the vehicle to cover many shorter trips in one day
Vehicle leasing	Reduces the capital cost barrier to zero-emission HDV purchase	Makes vehicles with large energy storage and high capital costs more accessible, making range suitable vehicles an option for more operators
Changes in vehicle sizes chosen by operators	Many operators choose to use 44t articulated trucks when 40t articulated trucks or 44t rigid trucks with a draw bar	Improves the packaging space on the vehicle helping to increase the range suitability

	trailer could be suitable	
Energy storage in truck trailers	The value of trailers would increase significantly, and they would need to be carefully planned into the operating schedule	Energy storage on the trailer could increase the vehicle range improving its suitability. This could also help to improve the flexibility of vehicles. For example, if the UK built an HRS network and France built a mega-charger network, a FCEV REEV using HRS in the UK could travel to France if battery storage is included in the trailer
Connected and Autonomous Vehicles (CAV)	Increases the utilisation potential of each HDV. Reduces HDV operating costs leading to increased demand	Without drivers driving/rest regulations controlling the time/distance that can be covered in a day, the daily range required could significantly increase.
Physical Internet	Improves the matching of goods to trucks helping to increase the loading factor of each truck and reducing the total truck km travelled and number of trucks needed in the fleet	Likely to shift the range suitability curve towards higher mileages. Increased vehicle loading will increase the fuel consumption and reduce the range suitability
Freight as a Service	Improves the matching of goods to trucks helping to increase the loading factor of each truck and reducing the total truck km travelled and number of trucks needed in the fleet	Likely to shift the range suitability curve towards higher mileages. Increased vehicle loading will increase the fuel consumption and reduce the range suitability
Last mile drone goods deliveries	Reduced km travelled by vans and small trucks doing last mile deliveries resulting in a shrinking of the small rigid truck fleet	Remaining small rigid trucks likely to be those doing longer routes shifting the range suitability curve towards the higher mileages

All of the disruptive technologies/behaviours set out in Table 13 have the potential to impact emissions from the HDV sector. In many cases the changes will impact the size of the fleet needed and the total km travelled by the fleet. These changes have great potential to impact total HDV emissions but are not considered in detail in this work as they will not accelerate/decelerate the introduction of zero-emission HDV by impacting their suitability to operators. The changes that do have the potential to significantly change zero-emission vehicle suitability are:

- Midday refuelling, this is so important to making zero-emission vehicles viable for long-haul vehicles that it has been included as a base assumption in this analysis (removing this option is explored in the sensitivities in Chapter 6).
- A shift to using less space constrained vehicles (e.g. rigid trucks with draw-bar trailers or placing energy storage on trailers) is discussed in the sensitivities in Chapter 6.
- Connected and Autonomous Vehicles. For CAVs, daily range requirements no longer have meaning. The vehicles will be operated as many hours of the day as possible and as the introduction of CAVs is likely to be paired with the automation of warehouses these assets could be running 24/7. In this case, uptime becomes the most important factor. For refuelling, this means short refuelling times are key. Operators of CAVs are therefore likely to prefer ERS or hydrogen vehicles. The number of CAV HDVs expected to be on the road in 2030-2035, when zero-emission HDV take off, is expected to be small (10% of bus sales and 3% of truck sales are expected to be fully autonomous in 2035[18]), but operators must choose the right zero-emission refuelling infrastructure at this time to remain competitive in a CAV dominated market in the 2040s-2050s.
- Freight optimisation, this will result in a shift in the range suitability curve towards higher mileages. Given that in this work all zero-emission vehicles in a particular vehicle class are designed to meet the range needs of the longest-range vehicle in that class this change should not impact the findings in this study.

9.1.4 Step 4. Total Cost of Ownership Analysis

The model analyses the TCO of each vehicle and drivetrain option in each 5-year period, to determine how attractive the zero-emission options might be to a fleet purchaser at that point. The TCO calculations include all factors that might differentiate the costs between the drivetrain options, such as capex and fuel costs, but does not include costs that would apply equally to all vehicle types such as driver salaries. The vehicle TCOs also take account of the different refuelling infrastructure costs, which are captured in the fuel prices depending on the refuelling option used.

Diesel Baseline

In order to assess the decisions a vehicle purchaser might make between different drivetrain options it was necessary to develop a diesel baseline. This involved projecting the future costs of owning a diesel vehicle, including the expected increasing cost of diesel fuel and increasing capex due to efficiency improvement requirements, which are both to some extent offset by improved vehicle efficiency leading to lower fuel consumption. The diesel baseline is then used in the TCO filtering stage to calculate the difference in cost between the ZE and diesel options, assuming that only a very limited number of operators would choose to purchase a ZE option before they achieve at least parity with the cost of a diesel vehicle.

Since there are very few ZE HDVs other than buses on the roads today, the diesel baseline is also used to project costs for ZE vehicles. From the diesel baseline, the cost of the core

[18] Element Energy analysis for the Transport Systems Catapult, 2017, Market forecast for connected and autonomous vehicles, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf

diesel drivetrain components such as the diesel engine and fuel tank are subtracted to provide a 'vehicle glider' cost for each vehicle type. This consists of the basic structure of the vehicle, the cab and the wheels which are unlikely to vary between ZE and diesel vehicles. To project the future costs of ZE vehicles, the costs of the various components of the drivetrains are then added to the glider cost, with the size of components based on the diesel components they replace – for example the electric motor's power requirement for each vehicle size is based on a typical diesel engine size for that vehicle type.

There is a wide range of prices for each category of vehicle, reflecting their different manufacturers and body designs. In each vehicle category we have selected a price that is in the middle of this range to represent the baseline, and best reflect the difference in vehicle costs between the vehicle categories rather than the variety of potential vehicle costs within each category. Ultimately it is the relative difference of the ZE drivetrain costs to the diesel baseline that is important for this analysis rather than the specific value chosen for the baseline in each category.

Capex and Depreciation

Figure 58 shows as an example the depreciation calculation for a BEV Large Rigid from the perspective of the first owner, who is assumed to operate the vehicle for 6 years before selling it on the second-hand market. This includes calculating the total capex associated with purchasing the vehicle, built up from the vehicle glider with costs for all the main electric drivetrain components such as the battery and electric motor added to it. For the other vehicle types analysed, this is where the cost of components such as fuel cells and pantographs would also be added to calculate the total cost of those vehicles. The vehicle costs include a manufacturer profit margin and therefore represent the full vehicle sale prices that operators would need to choose between in each 5-year period. At the end of its first owner lifetime, the vehicle is assumed to have a 'residual value' similar to that of existing diesel vehicles, depending on the mileage it has covered[19]. This is deducted from the capex as it will be recovered by the owner when the vehicle is sold, leaving the total cost to the first owner from purchasing the vehicle captured as the 'depreciation' of the vehicle's residual value compared to its new price.

The depreciation of zero-emission HDVs is treated the same as for diesel vehicles in this report. In the early years this is unlikely to be true as the full lifetime of the batteries and fuel cells are very uncertain, and this will impact their resale value. However, as discussed in Chapter 7 this will only be an issue in the early years of the zero-emission HDV market and is best corrected through tailored policy. There is also significant uncertainty about the future resale value of diesel HDVs. As governments around the world increase their climate change ambition the large stock of diesel HDVs could increasingly become unwanted assets with decreasing resale value. Given the large uncertainty in both the diesel and zero-emission HDV depreciation this report treats them as equal to avoid skewing the results based on an input with high uncertainty.

[19] Based on Kleiner & Friedrich, 2017, Maintenance & Repair Cost Calculation and Assessment of Resale Value for Different Alternative Commercial Vehicle Powertrain Technologies, https://elib.dlr.de/114666/1/EVS30_Paper_Trucks_M%26R_Resale_Florian%20Kleiner_uploaded_update.pdf

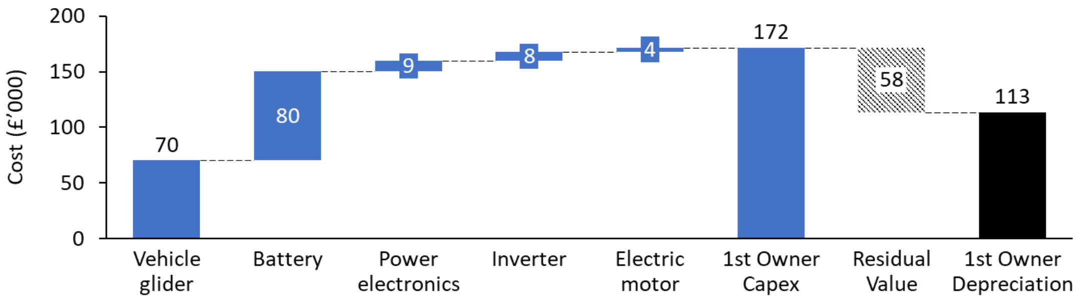


Figure 58: Capex components for a Large Rigid BEV in 2035

Battery cost scenarios

There is currently a large degree of uncertainty around the current and future cost of batteries for HDVs. This stems from the range of different scales at which batteries are used by manufacturers of electric HDVs around the world. Companies in China for example are already producing electric trucks and buses at scale, while European manufacturers are beginning to produce battery electric buses, but the number of trucks produced is still very low. While for batteries used in LDVs, costs have been falling rapidly over the last decade, the costs for battery packs used in HDVs are significantly higher, for several reasons:

- The packs tend to use different lithium-ion cell variants which means that developments for LDVs do not necessarily translate into the HDV sector. For example, batteries for HDVs face much more challenging charging cycles than those for LDVs, and the vehicles themselves are not as space constrained which has led many manufacturers to prioritise longevity over energy density when selecting battery chemistries[20].
- Even if using the same battery cell technology, the current volume of orders for HDVs are very small, and so do not achieve the same pricing.
- The smaller manufacturing volumes also mean that the packing of cells into a battery pack is much less automated. The variety of HDV configurations being larger and the general market size being an order of magnitude smaller than for LDVs also suggest it will be unlikely that the same level of pack manufacturing efficiency achieved for LDVs will be seen in HDVs.

Figure 59 shows the three battery cost scenarios used in the modelling to explore the range of potential future battery costs. The 2019 projected cost for car batteries from Bloomberg New Energy Finance (BNEF) are also shown to provide a comparison between the expected cost of batteries for HDVs and those used in the LDV sector. The descriptions below provide some further background to the sources for the numbers shown.

[20] This has led to the use of cells with lithium titanate oxide anodes (more expensive on £/kWh bases, very long life, significantly lower energy density, can withstand very high charging rates thus suitable for buses doing flash charging) and cells with lithium-ion phosphate cathodes (slightly lower energy density than nickel based cathode cells, but safer and cheaper; the main production output of Chinese factories hence the dominance in the bus market as China is the largest e-bus market)

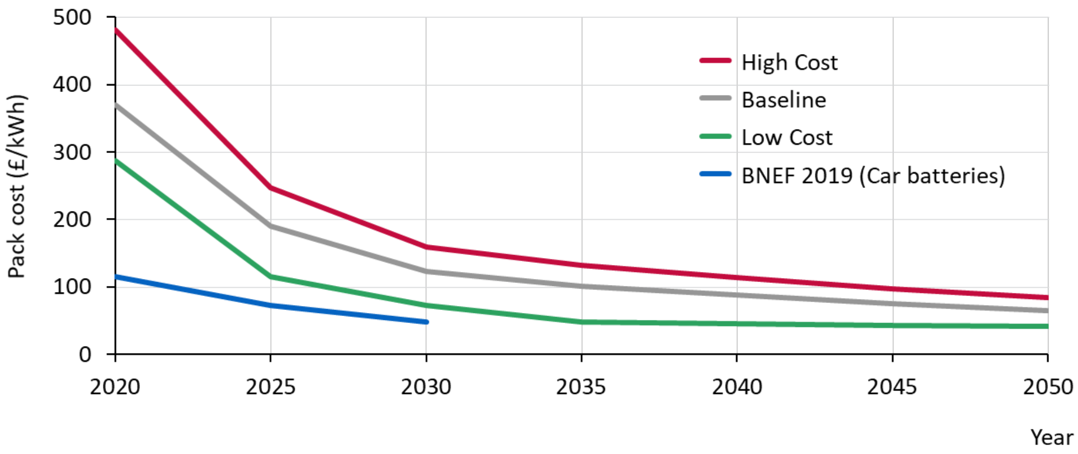


Figure 59: Battery Cost Scenarios

Baseline Scenario

The costs in this scenario are based on an in-depth, bottom-up analysis of battery component costs in the LDV sector[21], where there is far greater data availability than for batteries in HDVs. The historical cost reductions have also been observed over a longer period and there is greater certainty about the potential for these costs to fall in future. The cost reductions projected in this work are more conservative than those from BNEF which is in part due to the different methodologies used. The BNEF projections are based on historical prices for batteries bought in each year and apply a learning rate to project future costs. The price that batteries are sold at may not be a good indicator of the costs to produce them, as manufacturers may under-price their products in order to increase their market share. The bottom-up approach looks at the underlying cost of materials and improvements in manufacturing processes which are likely to better reflect the true cost to produce batteries.

The costs calculated in this bottom-up analysis for LDVs have been adjusted to reflect the expected higher costs for battery used in heavy duty vehicles:

- The curve has been delayed by 5-years to reflect comments from heavy duty battery electric vehicle manufacturers reported by the California Air Resources Board[22]
- Costs for 2020 have been adjusted upwards to reflect the cost of batteries used in large-scale production BEV buses today, based on discussions with OEMs. Costs in 2025 have also been adjusted upwards slightly to reflect these higher costs.

High Cost Scenario

This scenario adds a permanent 30% price premium to the baseline scenario to reflect:

- The wide range of battery costs today – our analysis of a range of battery electric buses on sale in Europe suggests that some are using batteries that cost in excess of £500/kWh.
- The possibility that due to the different cycling and packaging requirements of batteries for HDVs, they may always require different chemistries to those used in

[21] Element Energy analysis for ETI CVEI project 2015-2019
[22] California Air Resources Board, 2019, *Advanced Clean Trucks – Total Cost of Ownership Discussion Document*, https://ww2.arb.ca.gov/sites/default/files/2019-02/190225tco_0.pdf

LDVs and therefore will never be able to benefit fully from the cost down curve expected for LDV batteries.

Low Cost Scenario

This cost curve delays the Bloomberg battery cost projection for light duty vehicles by 5 years and reflects the top end of ambition for the falling cost of batteries for HDVs:

- This represents the potential for companies such as Tesla to demonstrate that there are no real barriers to applying the same LDV battery technology in HDVs and that the costs reductions achieved there could be directly applied to costs for HDVs.
- The Bloomberg numbers are only forecast until 2030 (in the low-cost scenario, with the 5-year delay for HDV batteries, Bloomberg's 2030 figure is achieved in 2035), so a 1% price reduction per year is assumed beyond 2035.

Fuel Cell cost scenarios

As with batteries there is a wide range of potential future costs for fuel cells. Since they are a large component of the upfront cost of the vehicles that use them, three cost scenarios have been developed to explore the impact these possible future costs could have on the uptake of hydrogen vehicles. Much of this uncertainty is based on the difference between the 'light duty' fuel cells which are being developed primarily for cars and vans by manufacturers such as Toyota and Hyundai and the 'heavy duty' stacks from companies such as Ballard Power. As with batteries, the duty cycles are much more challenging for HDVs designed to operate for many hours a day and cover higher annual distances, and some argue that they therefore need more ruggedized fuel cells than those developed for LDVs. However, the market for light duty cells could be orders of magnitude larger which would bring costs down so low that they could prove cost effective in HDVs even if multiple replacements are required during the vehicle's lifetime.

Difference between prices and costs for fuel cells

Figure 60 shows the fuel cell cost scenarios used in the modelling, where 'cost' here means the cost to manufacturers of HDVs who will typically not produce fuel cells in-house and will need to purchase them from the companies that do. In this sense the cost to HDV manufacturers is actually the 'price' of the fuel cells, including a mark-up for whoever makes them. The gap between the cost to produce fuel cells and their sale price is a major source of uncertainty in assessing the cost of fuel cells. The US Department of Energy (DoE) conducts analysis of fuel cell production costs and these are plotted alongside the fuel cell cost scenarios in Figure 60 to demonstrate the difference between the cost per kW of fuel cells used in vehicles in this modelling and the cost to produce them at different scales[23]. Towards 2050 as the scale of production increases, the price that HDV manufacturers pay for fuel cells is expected to converge with the production costs as volumes increase and fuel cell manufacturers are able to recover their development costs over a large quantity of products.

[23] Strategic Analysis, 2018, Fuel Cell Truck System Cost Analysis, https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-truck-workshop-2018-10-james.pdf

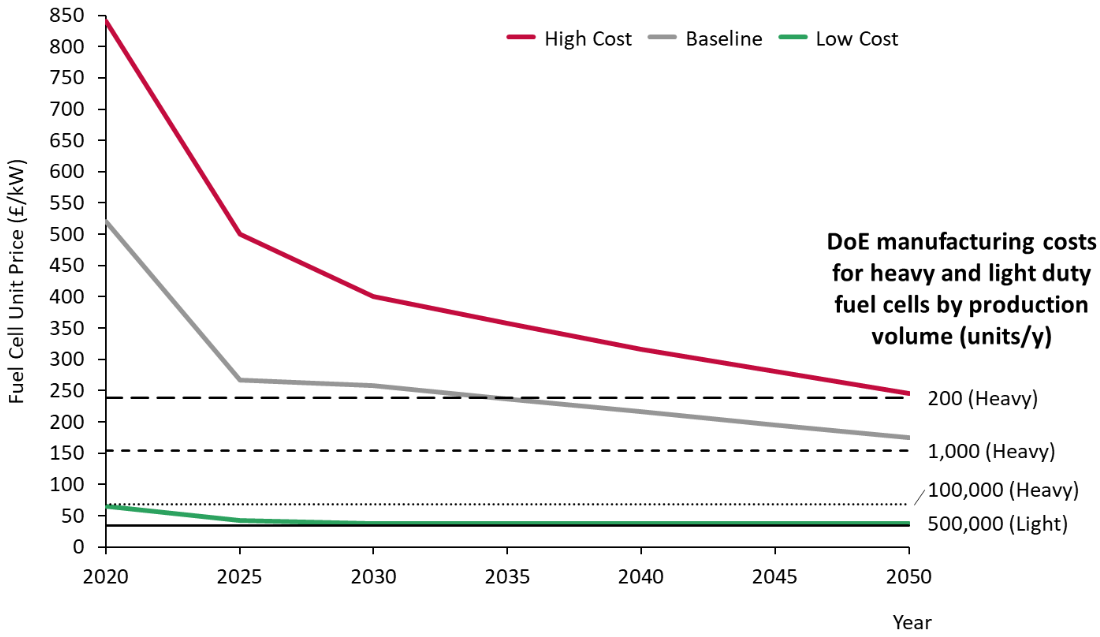


Figure 60 - Fuel Cell Cost Scenarios

<u>Baseline Scenario:</u>

The fuel cell costs in the baseline assume that light duty fuel cells are not sufficient for heavy duty applications, and manufacturers of HDVs are forced to purchase the more expensive and lower volume 'heavy duty' variants. Achieving this cost curve assumes that at least one European OEM will begin producing around 1,000 hydrogen HDVs per year during the 2030s, increasing the scale of orders and bringing down the purchase price from the fuel cell manufacturer. Beyond 2030 fuel cell production volumes grow but the costs fall more slowly, reflecting the diminishing returns from greater scale.

<u>High Cost Scenario:</u>

The 2020 value for this scenario reflects fuel cell prices that have been observed in European deployment projects of heavy-duty hydrogen vehicles. These prices are higher than the baseline which reflects expectations within the industry that manufacturers will seek to 'front load' the recovery of technology development costs in the early years. The objective of this is to recover technology development costs as quickly as possible with early deployments to offset the risk that future demand does not materialise.

This scenario assumes that production volumes for hydrogen powered HDVs ramp up slowly, with early production focussing on pure battery electric vehicles. As a result, fuel cell costs for the low number of hydrogen vehicles produced remain high as manufacturers aim to achieve returns on their investments on the basis of lower sales.

<u>Low Cost Scenario:</u>

In the Low-Cost scenario, manufacturers such as Hyundai and Toyota follow through with their announced plans to expand fuel cell production into the hundreds of thousands a year[24]. This brings the unit price for fuel cells bought by HDV manufacturers down close to

[24] Hyundai, 2019, Current Status of Hyundai's FCEV Development, https://cita2019.citainsp.org/wp-content/uploads/2019/03/%E2%98%8520190403_Hyundai-Motor-Group_-Current-status-of-Hyundai_s-FCEV-development-1690.pdf

the DoE's expected light duty fuel cell manufacturing costs, with just a small profit margin due to the high volume of production.

The lower hours of operation that light duty fuel cells are designed for (ca. 5,000 hours compared to around 40,000 hours for heavy duty cells), means that multiple replacements are likely to be required during a vehicle's lifetime. These additional costs are included in the modelling as maintenance costs and are calculated on the basis of the assumed hours of operation for each vehicle type. The higher mileage vehicles such as Artics and Coaches require 1 or 2 light duty fuel cell replacements during the first owner lifetime (meaning their first owner TCO accounts for the costs of 2 or 3 fuel cells, including the one they are originally purchased with). Labour costs are assumed to be 20% of the cost of the fuel cell and even with these factors considered, light duty fuel cells represent the lowest cost scenario for hydrogen HDVs.

The impact of falling ZE component costs

All the future cost scenarios for fuel cells and batteries assume that costs will fall to varying degrees, driven by technology improvements and economies of scale. The impact of these falling costs can be seen in Figure 61, where today's ZE vehicles have a depreciation cost that is several times higher than current diesel vehicles. However, over time as diesel vehicles face ever more stringent efficiency and emissions regulations, it is expected that their costs will rise slightly. For the ZE drivetrains, the costs fall dramatically over the period, driven by economies of scale and technological improvements. By 2050, the depreciation cost premium for ZE options has fallen to 20-30% of diesel drivetrains. Despite the fact that this chart shows that ZE drivetrains are unlikely to achieve parity with diesel in terms of their upfront costs, their lower fuel costs ensure that over their lifetime the TCO can fall below that of diesels.

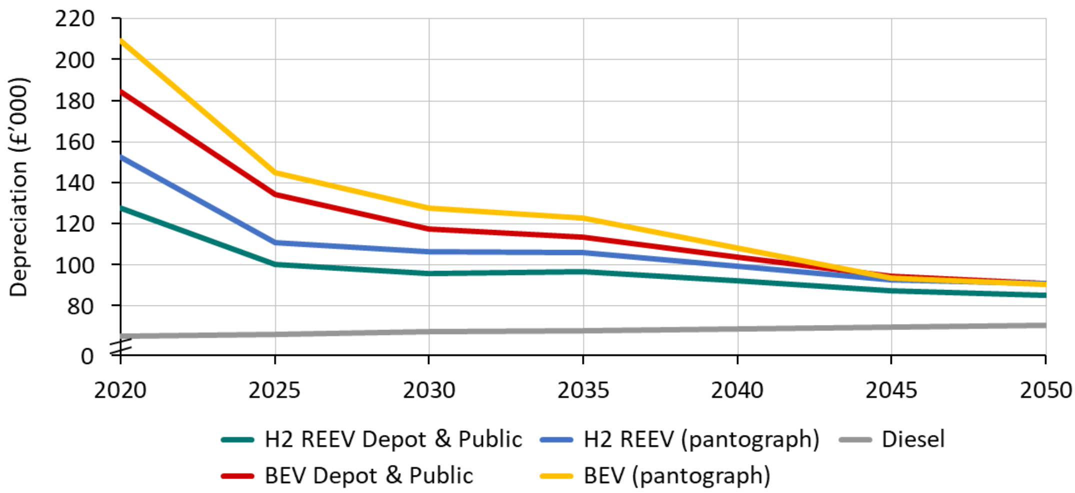


Figure 61 – Vehicle depreciation cost comparison between diesel and ZE drivetrains 2020-2050. Note: the depreciation for some ZE drivetrains appears to increase between 2030 and 2035. This is an outcome of battery and fuel cell costs falling and on-board storage size increasing in order to achieve additional range.

Lifetime Fuel Costs

A major differentiator between ZE and diesel options is the cost of fuel (a table of the fuel costs assumed in the modelling can be found in the appendix). Analysis of future fuel costs was not within the scope of this project. These costs have been supplied by the CCC based on their analysis of fuel use across the economy. A 20% mark-up was applied to ZE fuels from public infrastructure to reflect the expected profit margin required for installers and operators.

Figure 62 shows the lifetime fuel costs for a Large Rigid by year of purchase for all the drivetrain options considered in this report. As can be seen, by 2035 hydrogen is expected to become a cheaper fuel than diesel, at which point each additional kilometre driven will improve the overall TCO comparison with diesel. All the pure electric options have fuel costs that are around 40% cheaper than diesel from 2020, and this improves to be about 50-60% cheaper by 2050. This means that from the start the higher capex of battery electric vehicles is offset by the far lower cost of fuel compared to diesel vehicles. Though there is little difference overall between fuel costs of the pure electric options, the ERS option emerges as the highest cost electric option, due to the higher infrastructure costs compared to Mega-chargers or in-depot chargers that will need to be recovered by the installers and operators. The difference in fuel cost between electric and hydrogen vehicles is also clear, so that ultimately by 2050 when the capex of the ZE options shown in Figure 61 are all within a few percent, the electric options are likely to be a significantly cheaper option on a TCO-basis than the hydrogen vehicles.

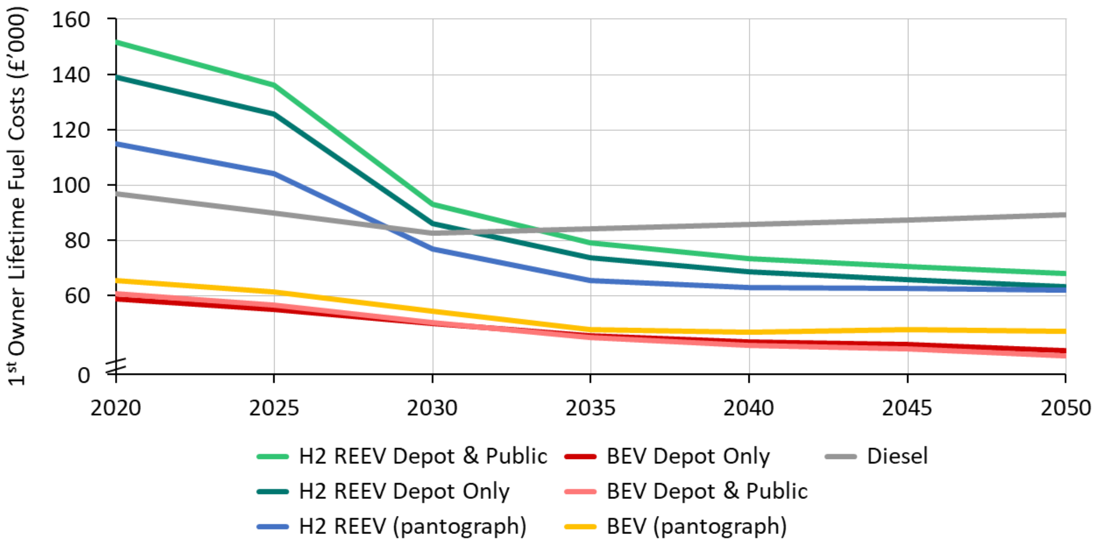


Figure 62 - Comparison of lifetime fuel costs for ZE and diesel Large Rigids by year of purchase (6-year 1st owner lifetime and 53,000km/y assumed)

TCO Calculation

Figure 63 illustrates how the depreciation and lifetime fuel costs are brought together to calculate the TCO of each vehicle in each 5-year period. The depreciation cost is brought over from the capex calculations shown in Figure 58. The cost of capital is added here for clarity, but is calculated based on the total upfront cost of the vehicle, shown as '1st Owner Capex' in Figure 58 and is assumed to be borrowed at a rate of 5%. Maintenance costs are calculated based on a cost per kilometre depending on the vehicle type. Taxes are assumed to remain constant at the levels currently applied to ZE HDVs.

The incentives shown here do not reflect current or planned policies but are an outcome of the modelling. The incentives are calculated to make the lowest-cost option in each Trajectory achieve TCO parity with diesel in 2035. The same level of incentive is applied to all ZE options and is flat for the years from 2020-2035 and then falls to zero in 2045 for all trajectories, except Trajectory 1 where the sustained higher cost of hydrogen vehicles and fuel means that policy support is required until 2050.

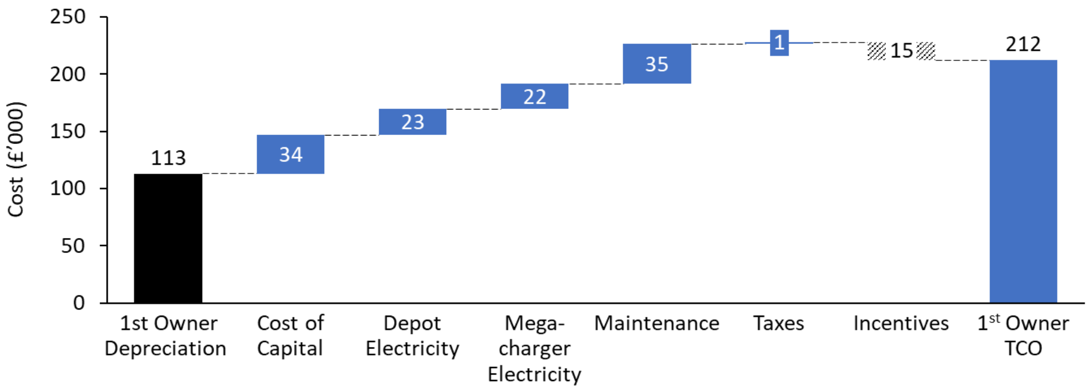


Figure 63 - TCO Components of a Large Rigid BEV Using depot and Mega-charger electricity in 2035 (assumes 6-year 1st owner lifetime and 53,000km/y) – includes £15,000 of incentives required to achieve diesel TCO parity in 2035 (based on modelling rather than announced or planned policies)

9.1.5 Step 5. TCO Suitability Filter

Once the Range Suitability Filter has calculated the proportion of HDV purchases where a zero-emission vehicle is a viable option, and the model has calculated the TCO of all zero-emission powertrain options (with policy incentives), the TCO Suitability Filter further reduces the number of zero-emission vehicle sales taken forward in the model. The TCO suitability is assessed based on the relative TCO of a diesel and a zero-emission vehicle for each powertrain type, vehicle size class and year. Different proportions of operators are then assumed to consider purchasing a zero-emission vehicle dependent on its relative TCO, the relationship between relative TCO and the proportion of operators assumed to consider a zero-emission vehicle is summarised in Table 14. These assumptions are based on interviews conducted with fleets about their interest in ZE HDVs and willingness to accept a higher TCO.

The percentage from the right-hand column of Table 14 is applied to the vehicles passing the Range Suitability Filter to decide the number of vehicles passing to the next stage. For example, if 100 small rigid trucks are projected to be sold in a given year and the zero-emission range suitability of BEV with depot recharging is 50% then 50 vehicles are passed onto the TCO Suitability Filter. If this filter is also 50% then 25 BEVs with depot recharging are passed on to the next stage which decides which mix zero-emission vehicles are purchased.

Table 14: Relative TCO to diesel vehicles and the impact on the percentage of operators considering a zero-emission vehicle purchase

Relative TCO (% Increase TCO between in Diesel and Zero-Emission Option, Including Policy Incentives)	% of Zero-Emission Vehicles Passing the TCO Filter (%)
0 or less	100
5	30
10	5
15	3
20	1
Greater than 20	0

The proportion of operators willing to consider an increase in their vehicle TCO in Table 14 is relatively high. The reason for this is that it will very quickly become the case, over the next 10-15 years, that operating a zero-emission fleet becomes a necessary part of doing business, and so these decisions will not be based on TCO alone. Drivers for this change will include the businesses public image with some customers demanding strict emission targets from HDV operators. Other factors include the local government net-zero targets[25], which are likely to lead to restricted assess for fossil fuel powered fleets across many regions of the UK.

9.1.6 Step 6, 7, 8. Zero-Emission Powertrain/Refuelling Option Selection

The outcome of the Range and TCO Suitability Filters is a proportion of HDV sales in each year and in each vehicle size where a zero-emission vehicle could be considered for purchase. The filtering process does not consider which zero-emission powertrain will be purchased and so the range and TCO suitability filter is conducted separately on every zero-emission powertrain and refuelling option.

This section of the model decides what the final sales mix of zero-emission powertrains and refuelling options should be. To do this the zero-emission powertrain options for each vehicle size and year are ranked from the lowest TCO to the highest TCO. From this, the additional range suitability of each powertrain is calculated. For the cheapest option this will equal its range suitability. For the second cheapest option this will equal its range suitability above and beyond that of the cheapest option. For the third cheapest option this will equal its range suitability above and beyond that of the second cheapest option and so on until every powertrain option has been considered. The final number of zero-emission vehicles of each powertrain type to be chosen is then calculated as the total number of vehicles to make it through the filtering stages multiplied by the fraction of the additional range suitability over

[25] As of March 2020, 173 local authorities have declared climate emergency and set a target of net zero for 2040 or earlier, the majority being for 2030. Source: https://www.climateemergency.uk/blog/list-of-councils/

the full range suitability. The result of this calculation is that operators choose the cheapest zero-emission powertrain option that is suitable for their operational requirements.

9.1.7 Step 9. OEM Supply Constraints

The final step in the model is to constrain the rollout of zero-emission HDVs based on the expected supply by OEMs. This constraint acts as a cap preventing zero-emission sales exceeding a set percentage of sales in a given year. If the sales of zero-emission vehicles predicted by the model are already below the supply cap, then the supply cap has no effect on the results for that year. The OEM supply constraint is only applied to trucks and coaches as the supply of zero-emission buses is expanding very quickly and is not expected to delay rollout. The supply constraints are applied to the outcome of the model filtering in each year up to and including 2030. After 2030 the market is expected to have developed sufficiently that OEMs will be able to meet demand and so the OEM supply constraint is removed.

Two different supply constraint curves have been developed, one for Trajectories 1-4 where supply is expected to come predominantly from large established European OEMs and a second for Trajectory 5 where OEMs new to the European market are expected to bring major disruption. The supply constraint curve for Trajectories 1-4 is expected to see the slower introduction of zero-emission models because existing OEMs want to avoid stranding existing diesel truck/coach manufacturing assets. The supply constraint curve in Trajectory 5 is expected to see the faster introduction of zero-emission models because OEMs new to the European market will only develop zero-emission vehicle production capacity in Europe and will have no reason not to ramp up their zero-emission production capacity as quickly as they are able to meet demand growth.

The growth of a new technology goes through three phases.

1. Phase 1. Very slow linear growth occurs over the early years. In this phase the technology is only purchased by early adopters. The growth rate is low because of a lack of confidence in the new technology and in the case of vehicles very little refuelling infrastructure is available.
2. Phase 2. The linear growth phase is followed by the first half of the S-Curve growth phase which sees exponential growth. This is where the technology becomes accepted by the wider population as the cheapest/best options and sales very quickly increase.
3. Phase 3. The final phase is the second half of the S-Curve growth phase where the rate of increase in sales starts to drop off, although the total number of sales continues to increase. The final group of consumers to move over to the new technology do so more slowly because they are more conservative or because the new technology does not meet their needs as well as the old technology. In the end all users move over to the new technology as the supporting infrastructure for the old technology is removed.

For Trajectories 1-4, the duration of Phase 1 and the growth rate are assessed based on the trend observed in the UK for BEV cars, over the last 10 years. Phase 2 and 3 have then been designed to follow on from Phase 1 while meeting 100% zero-emission HDV sales in 2040 (Daimler recently announced that all its truck and bus sales in Europe will be CO_2 neutral from tank to wheels by 2039[26] and it is expected that other existing OEMs will follow a similar trajectory). For Trajectory 5. the duration and growth rate of Phase 1 have been assessed based on the trend observed for Tesla's global production of the model S (this

[26] Daimler, 2019, CO_2 neutral fleet of new vehicles, https://www.daimler.com/investors/reports-news/financial-news/20191025-co2-neutral-fleet-of-new-vehicles.html

trend was selected as it demonstrates the speed at which a new vehicle can be rolled out by an existing OEM with a complete focus on zero-emission vehicles). Phase 2 and 3 for Trajectory 5 are the same shape as for Trajectories 1-4 but occur earlier as Phase 1 for Trajectory 5 is much shorter.

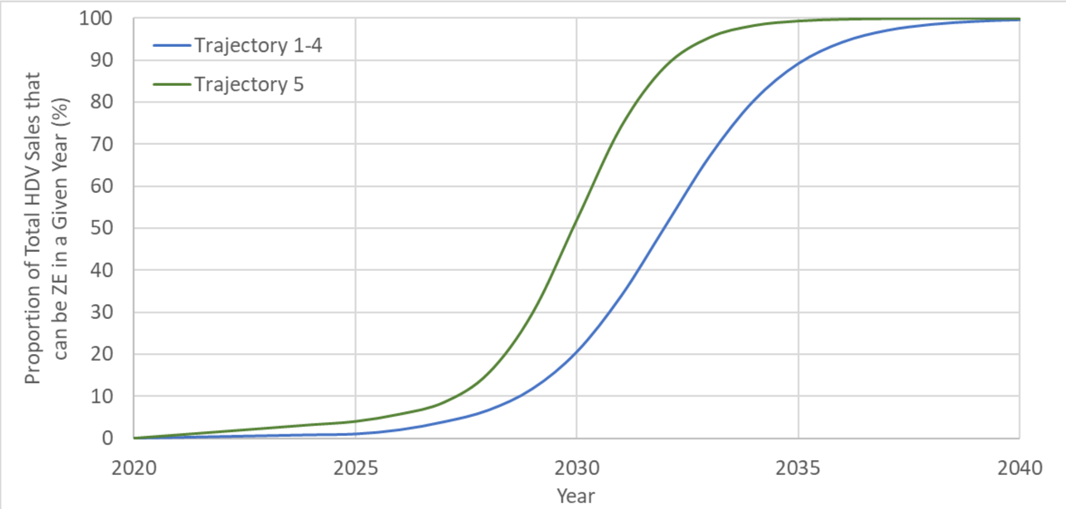


Figure 64: OEM Supply Constraint Curves for Trucks and Coaches

9.2 Fuel Costs

9.2.1 Fuel Costs in Trajectories 1&4

Fuel	Unit	2020	2025	2030	2035	2040	2045	2050	2055	2060
Diesel	£/L	1.09	1.14	1.20	1.22	1.24	1.27	1.29	1.32	1.35
Electricity Depot	£/kWh	0.15	0.15	0.15	0.13	0.13	0.12	0.12	0.12	0.11
Electricity ERS	£/kWh	0.21	0.21	0.20	0.17	0.17	0.17	0.18	0.19	0.19
Electricity Mega-charger	£/kWh	0.18	0.18	0.17	0.15	0.14	0.13	0.12	0.12	0.12
Hydrogen 350Bar Depot	£/kg	5.90	5.80	4.00	3.37	3.10	2.93	2.80	2.80	2.80
Hydrogen 700Bar Depot	£/kg	7.19	7.08	5.28	4.24	3.87	3.68	3.55	3.57	3.58
Hydrogen 350Bar HRS	£/kg	7.08	6.96	4.80	4.04	3.72	3.52	3.36	3.36	3.36
Hydrogen 700Bar HRS	£/kg	8.62	8.49	6.34	5.09	4.64	4.41	4.26	4.29	4.30

9.2.2 Fuel Costs in Trajectory 3

Fuel	Unit	2020	2025	2030	2035	2040	2045	2050	2055	2060
Diesel	£/L	1.09	1.14	1.20	1.22	1.24	1.27	1.29	1.32	1.35
Electricity Depot	£/kWh	0.15	0.15	0.15	0.13	0.13	0.12	0.11	0.11	0.11
Electricity ERS	£/kWh	0.21	0.21	0.20	0.17	0.17	0.17	0.17	0.18	0.19
Electricity Mega-charger	£/kWh	0.18	0.18	0.17	0.15	0.14	0.13	0.12	0.12	0.11
Hydrogen 350Bar Depot	£/kg	5.90	5.80	4.62	3.94	3.62	3.46	3.33	3.33	3.33
Hydrogen 700Bar Depot	£/kg	7.19	7.08	5.90	4.82	4.39	4.20	4.07	4.10	4.10
Hydrogen 350Bar HRS	£/kg	7.08	6.96	5.54	4.73	4.35	4.15	3.99	3.99	3.99
Hydrogen 700Bar HRS	£/kg	8.62	8.49	7.08	5.78	5.27	5.04	4.88	4.91	4.92

9.2.3 Fuel Costs in Trajectories 2&5

Fuel	Unit	2020	2025	2030	2035	2040	2045	2050	2055	2060
Diesel	£/L	1.09	1.14	1.20	1.22	1.24	1.27	1.29	1.32	1.35
Electricity Depot	£/kWh	0.15	0.15	0.15	0.13	0.12	0.11	0.10	0.09	0.09
Electricity ERS	£/kWh	0.21	0.21	0.20	0.17	0.16	0.16	0.15	0.16	0.16
Electricity Mega-charger	£/kWh	0.18	0.18	0.17	0.15	0.13	0.12	0.10	0.10	0.09
Hydrogen 350Bar Depot	£/kg	5.90	5.80	3.95	3.20	2.82	2.65	2.52	2.52	2.52
Hydrogen 700Bar Depot	£/kg	7.19	7.08	5.23	4.08	3.59	3.40	3.27	3.29	3.30
Hydrogen 350Bar HRS	£/kg	7.08	6.96	4.73	3.84	3.38	3.19	3.03	3.03	3.03
Hydrogen 700Bar HRS	£/kg	8.62	8.49	6.27	4.89	4.31	4.08	3.92	3.95	3.96