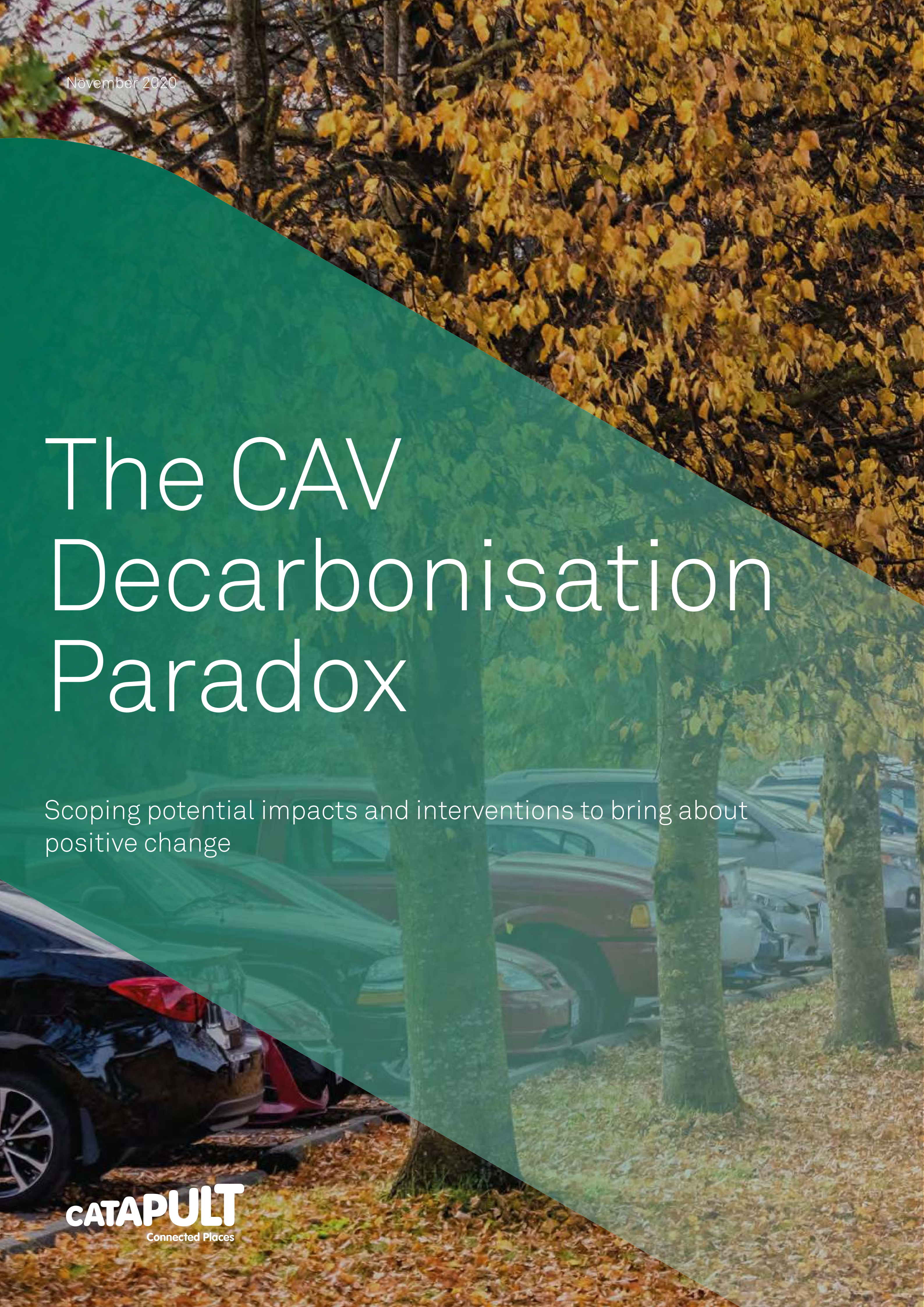


November 2020

The CAV Decarbonisation Paradox

Scoping potential impacts and interventions to bring about positive change

CATAPULT
Connected Places

Executive Summary

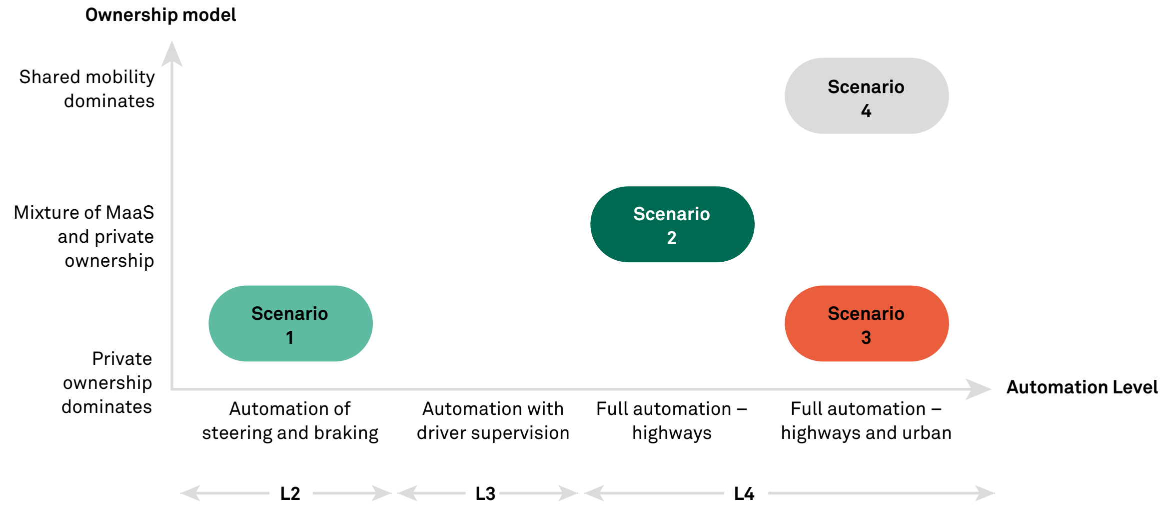
CAV technology has the potential to make significant contributions to the decarbonisation of transport. However, there is a risk of negative environmental consequences if deployment and policy interventions are not carefully considered.

The deployment of CAVs is likely to make significant changes to the carbon emissions associated with both the passenger and freight vehicle fleets. To meet the UK's 2050 Net Zero target, the decarbonisation of road transport is imperative. At this time, it is unclear whether the overall impact of CAV deployment on the UK's total carbon emissions will be positive or negative. There are many assumptions which have to be made when forecasting the total carbon impact of CAV deployment, but acknowledges that there may be opportunities to accelerate this. Based on a review of existing literature, this report makes the reasonable assumption that Level 4 passenger vehicles will be battery electric by default.

This report explores some of the main mechanisms through which CAVs may impact the sustainability of road transport and how they may positively or negatively affect carbon emissions. It assumes that the transition to zero emission vehicles and the decarbonisation of the UK's energy mix are largely unaffected by CAV deployment. The CAV mechanisms established from existing literature have been categorised into **five fundamental factors:** number of vehicles manufactured, emissions per vehicle manufactured, total vehicle miles travelled, well/windmill-wheel emissions per vehicle mile travelled, and embedded emissions in infrastructure. An increase in any of these fundamental factors will increase the carbon emissions directly associated with CAV technology; however some mechanisms can be linked to multiple fundamental factors, sometimes with contradicting impacts. As such, the sensitivity of each mechanism and fundamental factor needs to be explored in more detail.

Four potential scenarios for CAV deployment in 2035 have been developed. These will act as baselines from which the impact of certain policy interventions will be determined. The key drivers within the scenarios are level of vehicle automation and proportion of journeys taken by shared services versus private vehicles, which were chosen due to their high uncertainty and substantial impact on overall carbon emissions. Figure A displays the scenarios according to their relative automation levels and ownership models.

Figure A: Summary of four baseline scenarios; **Scenario 1:** The Platooning Plateau, **Scenario 2:** Highway to the Middle Ground, **Scenario 3:** My CAV is my Castle, **Scenario 4:** Autonomy as a Service. The L2, L3 and L4 on the lower x-axis refer to SAE autonomy levels (SAE International, 2018).



Scenario 1: The Platooning Plateau explores the carbon impacts of introducing limited automation features to a fleet dominated by private ownership.

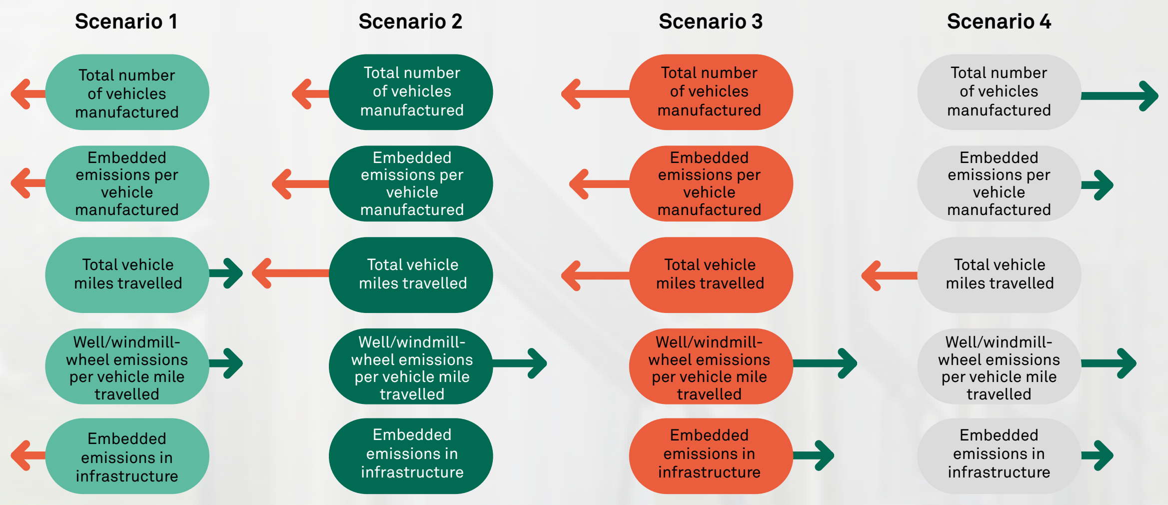
Scenario 2: Highway to the Middle Ground explores the carbon impacts resulting from full automation on highways and a mixture of operating models for passenger transport.

Scenario 3: My CAV is my Castle explores the carbon impacts of full automation operating along highways and in urban areas while private ownership continues to dominate.

Scenario 4: Autonomy as a Service explores the carbon impacts of full automation operating along highways and in urban centres which facilitates a paradigm shift to shared mobility services.

For each scenario, an assessment of the key mechanisms affecting carbon emissions was conducted. Figure B displays the forecasted carbon emissions impacts across each baseline scenario according to the five fundamental factors. There are distinct differences in the carbon impacts of each scenario depending on the relative strength of each driver. This demonstrates the need for interventions to prevent overall increases in carbon emissions and maximise potential benefits of CAV deployment.

Figure B: Comparison of carbon emission forecasts for each baseline scenario



KEY

Increase emissions

←

Decrease emissions

→

By analysing the main CAV mechanisms and the forecasted outcomes of each baseline scenario, a list of interventions was proposed to maximise the benefits of CAV deployment and mitigate the risks. The interventions are categorised according to their main desired outcome: encourage shared vehicle use, discourage empty miles, introduce direct road use charging, encourage interoperability with public transport, optimise use of land and infrastructure or disincentivise longer CAV journeys.

This report lays out the immediate knowledge-gathering steps needed for this planning, and suggests that, given the right interventions, CAV deployment can significantly reduce carbon emissions from the transport sector.

Contents

1

1 Introduction

Connected and automated vehicles (CAVs) are set to have a major impact on society. Safety is prominent - but not yet sustainability. There's an urgent need to understand how the benefits of CAVs can be realised while maintaining or reducing carbon emissions.

The UK has set out to become a world leader in sustainability, pledging to end its contribution to climate change by 2050. Transportation is the biggest contributor to UK domestic greenhouse gas emissions, accounting for 28% of the total emissions in 2018. Within the transportation sector road transport is the largest emitter. The Department for Transport's publication of the Decarbonising Transport report in 2020 set out the major challenges which need to be overcome within the transport sector to meet the Net Zero target. These challenges cover accelerating modal shift to public and active transport, decarbonisation of road vehicles, decarbonising how we get our goods, place-based solutions, UK as a hub for green transport technology and innovation, and reducing carbon in a global economy *(Department for Transport, 2020)*. It is our belief that CAV technology is fundamental to addressing some of these challenges yet also has the potential to exacerbate existing issues and create new ones.

To date, much investment has gone into reducing the emissions on a vehicle level, aided by more fuel-efficient engines and electrification. The success of these interventions can be demonstrated by the car and taxi industry's 22% increase in vehicle miles travelled between 1990-2018, yet a 5% decrease in overall greenhouse gas (GHG) emissions from the fleet across the same period. Similarly, Heavy Goods Vehicles (HGVs) travelled 10% more miles in 2018 compared with 1990 and yet the GHG emissions rose only 1% proving their increased fuel efficiency. While a step in the right direction, these improvements at the vehicle level alone are unlikely to be sufficient to reach Net Zero targets unless other revolutions such as automation and a transition to shared journeys are also set in motion.

In this report, the Connected Places Catapult presents the results of a literature review on the carbon impacts of CAVs. It sets out to understand the CAV decarbonisation mechanisms, explore four likely scenarios which may arise by 2035 from unrestricted CAV deployment and provide some intervention ideas to ensure that CAVs contribute positively towards the UK's Net Zero ambitions.

Recent research has highlighted that it is imperative to consider all the sustainability impacts of CAVs when planning for the otherwise utopian future CAVs promise. A set of candidate interventions is presented, along with an outline of work needed to evaluate the effectiveness of such interventions in each baseline scenario. An indication of the widespread recognition of these needs is summarised by *(Mora, Wu, & Panori, 2020):*

> Sustainability research is urgently required to produce an evidence-based understanding of what new sociotechnical arrangements are needed to ensure that the systemic technological change introduced by AV-based transport systems can fulfil societal functions while meeting the urgent need for more sustainable transport solutions.

1.1 Acronyms and abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
BEV	Battery Electric Vehicle
CAV	Connected Automated Vehicle
DfT	Department for Transport
EV	Electric Vehicle
GHG	Greenhouse Gas
HARPS	Highly Automated Road Passenger Service
HGV	Heavy Goods Vehicle
ICE	Internal Combustion Engine
LiDAR	Light Detection and Ranging
MaaS	Mobility as a Service
SAE	Society of Automotive Engineering
UK	United Kingdom
V2I	Vehicle-to-infrastructure
VMT	Vehicle Miles travelled
VOTT	Value of Travel Time
ZEV	Zero Emission Vehicle

1.2 Motivation for this work

CAVs have the potential to transform the transport landscape, from making journeys more efficient and less stressful, to moving goods around the road network without a driver, to reducing the level of ownership of private cars. Many, if not all, of these will have environmental impacts, and a more in-depth understanding of these impacts will be valuable for policy-makers. This understanding will enable them to:

- Plan changes to national infrastructure that take account of the impact of CAVs; and
- Use the right tools to channel CAV development and deployment to those paths with the best sustainability outcomes.

Many of the changes expected from widespread CAV deployment are beneficial, for example easier transport access for the elderly and disabled, and recovering productive time that would have been lost to driving otherwise. Additionally, the CAV sector already employs many knowledge workers in AI and software development roles, with the potential to grow significantly and act as an advert for the high-tech capabilities of the UK. However, the sustainability outcomes cannot be ignored when considering investment and policy for CAVs.

Given appropriate interventions, it seems likely that CAVs can help the UK in achieving its Net Zero target. Research has been split on whether CAVs will result in increased or decreased overall emissions: positive factors include eco-driving, smoothing of traffic flow, and fewer accidents, contrasted with negative factors related to the convenience and cost of travelling by car. It is hard to predict which of these factors will eventually dominate, but this uncertainty creates an opportunity, in that a relatively small intervention could drive the system in the right direction. Therefore, there were two aims for this project: firstly to review the literature on CAV environmental impacts, and secondly scope potential projects to investigate the effectiveness of a range of policy interventions. The literature review of decarbonising effects of CAVs is set apart from most others as it only considers the scenario that Level 4 CAVs have zero emission powertrains.

1.3 Scope and assumptions

The scope of this project includes the impacts of CAVs on sustainability of movement of people and goods, focusing on passenger transport, HGV freight logistics and last mile travel in urban settings. Only the impacts that autonomy can have on the decarbonisation agenda are considered, with a set level of connectivity assumed to be adopted across vehicle fleets regardless of SAE automation level. The same logic has been applied to ZEV adoption, with a fixed adoption curve of BEV and hydrogen vehicles assumed for all baseline scenarios. In this report, increased sustainability is synonymous with decarbonisation, while it is clear that measures to reduce carbon emissions will also improve air quality, and vice versa, air quality is not directly considered in the scope.

Similarly, it is assumed that other factors relevant to carbon impact, such as societal trends in population size, travel patterns impacted from Covid-19 and (de)urbanisation, will apply equally to all the baseline scenarios presented.

The report considers CAV-impacted emissions that the UK has responsibility for, which is taken to mean emissions generated by travel by road vehicle within the UK, emissions generated by the manufacture, maintenance, and disposal of CAVs for use in the UK (regardless of where this occurs), and emissions from parking and charging infrastructure where this is impacted by CAVs. Issues of emissions embodied in international trade (EEIT) are ignored, as attribution of these is an area of active research *(Zhang, Bai, Ning, Ding, & Zhang, 2020).*

Any (de)carbonising effects that are expected to happen independent of CAV uptake are considered out-of-scope, including:

- Reducing weight of vehicles through lower density materials
- More efficient manufacturing processes
- Reduction in emissions of electricity generation

ZEVs have a carbon cost associated with every mile travelled due to the electricity or hydrogen generation and distribution process. The UK consumption-based electricity emissions are forecasted to be significantly reduced in 2035, which will have major impacts on the carbon cost per mile travelled. This in turn will reduce the importance of the number of vehicle miles travelled for decarbonisation and will shift the focus onto the other fundamental factors. Table 1 shows the expected change in grid carbon emissions per kWh.

Table 1: Carbon emissions per unit energy from the UK grid for 2020 and (predicted) 2035[1]

kgCO$_2$e/kWh	**2020**	**2035**
Domestic	0.295	0.083
Commercial	0.290	0.082
Industrial	0.284	0.080

Finally, this report makes the assumption that all SAE Level 4 CAVs will be BEVs.

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[1] SOURCE: Department for Business, Energy & Industrial Strategy, Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal, kast updated March 2020, accessed from [https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal]

1.4 Background

This work builds on a previous report the Transport Systems Catapult[2] created for the Department for Transport in 2016, titled "Effect of Connected and Automated Vehicles on Energy Usage and Emissions". The 2016 work (which was not published) consisted of a literature review, a series of stakeholder interviews, and the creation of a System Dynamics model to understand the mechanisms and their effects better. Figure 1 shows the top-level of interactions in this model. The report further described four scenarios, and used the model to supply numerical predictions of metrics such as total emissions or total VMT within each scenario.

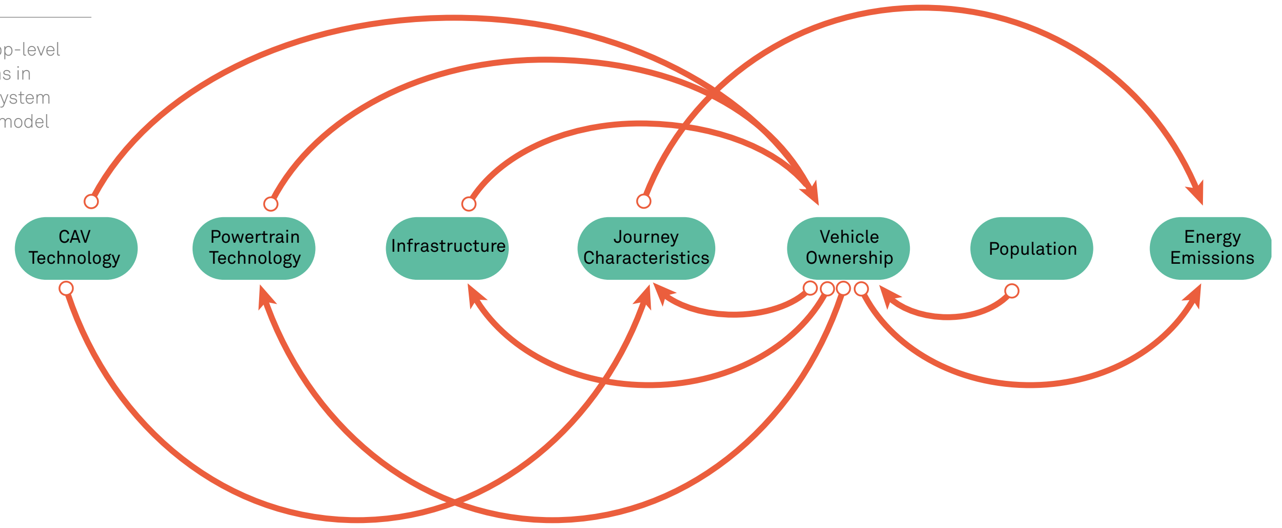

Figure 1: Top-level interactions in the 2016 System Dynamics model

Since this work was completed there have been a large number of new publications, so a refreshed literature review was considered desirable. Additionally, the focus of this report is on how to steer the carbon impacts of CAVs, in addition to simply understanding what these impacts might be.

From 2017 onwards, the Connected Places Catapult has carried out extensive work on analysing and assessing the behaviour of CAVs from a safety perspective, including on the VeriCAV[3], MUSICC[4] *(Saigol, Myers, Peters, & Edwards, 2020)* and CertiCAV projects. This safety work provided inspiration and key background knowledge to address the sustainability issues of CAV roll-out.

Finally, the Catapult also runs a research programme called TranZET, standing for Transition to Zero Emission Transport, on behalf of the Department for Transport. TranZET has initially concentrated on technologies that can help transition long-haul heavy goods vehicles to zero-emission operations, starting with a study titled Hydrogen for Smart Mobility (H2SM). More recent work has compared Hydrogen Fuel Cell enabled HGVs with Electric Road System (ERS) enabled HGVs (Pantograph / Catenary system) and Battery Electric HGVs. The model produced indicated that, given best current estimates of future vehicle, fuel and infrastructure costs, the total cost of ownership is very similar between the three options. However, each option has conditions under which it outperforms the others, so a combination of options may end up being optimal.

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[2] In April 2019, the Transport Systems Catapult and Future Cities Catapult merged to become the Connected Places Catapult

[3] https://vericav-project.co.uk/

[4] https://cp.catapult.org.uk/case-studies/musicc/

2

2 Methodology

2.1 Scenario-based evaluation of interventions

This report addresses the objective of allowing the introduction of CAVs to UK roads, but steering this deployment so that it has the most advantageous carbon impact possible (hopefully a reduction in emissions compared to 'conventional' vehicles). A framework is needed in which to evaluate the carbon effects of any possible policy intervention, in order to select the most beneficial intervention(s).

To do this, it is first necessary to understand the likely changes in the transport system without any interventions. However, some of the factors creating change are **hard to predict** yet have a **significant effect on emissions** likely to be caused by CAVs. Therefore a set of baseline scenarios to cover the space of possibilities for these uncertain factors have been postulated (see *Section 4 Baseline scenarios* for the details of these scenarios).

Next, to determine which intervention is best, the effect of each intervention in each scenario has to be estimated. Then the 'expected' effect of each intervention can be calculated by weighting its effect in each scenario by the likelihood of that scenario transpiring, and select the intervention with the best expected impact. For example, if an intervention results in a large emissions reduction for one scenario but a small emissions increase in the others, it may well not be as good as an intervention that results in a small emissions decrease in every scenario. The mathematical basis for this is Expected Utility Theory (see for example *(Briggs, 2019)*), and a more detailed summary of the method is given in *Appendix A: Expected Utility Calculation*.

The method relies on several assumptions:

- The baseline scenarios cover all of the possible alternative futures (to a reasonable approximation).
- Accurate estimates for the probability of each scenario occurring can be made.
- A sensible method for evaluating positive emissions effects against other societal impacts can be applied. For example, if CAVs made it possible to fulfil societies travel needs with half the number of vehicles, this would have significant environmental benefits but would also considerably reduce the size of the automotive manufacturing industry.

Section 5 Future projects discusses some of the priorities for future work in this area.

2.2 Scenario selection

Four baseline scenarios have been developed which act as possible representations of what 2035 could look like if no major policy interventions are made (other than the permission of automation) and travel behaviour is left to the choice of the consumer.

Each baseline scenario considers the highest SAE level of automation *(SAE International, 2018)* which is available from both a technological and legislative perspective and the level of uptake of shared mobility versus the private ownership model. Assumptions on when the automation level is introduced and levels of uptake by 2035 will be made for each scenario, as and when modelling is required.

CAV automation level and the uptake of shared mobility are not strictly independent variables since it is widely accepted that CAVs are an enabler of shared mobility services. However, the actual uptake of shared services versus private ownership is highly uncertain given the number of other factors involved.

Table 2 and Table 3 display the different features and considerations which may impact carbon impacts of the different automation levels and ownership models respectively *(Vosooghi & et al, 2019)*.

The Society of Automotive Engineering (SAE) have defined six levels of automation which are widely used to categorise vehicles. They range from Level 0 where any features are limited to providing warnings and momentary assistance to Level 5 where the feature can drive the vehicle under all conditions *(Warrendael, 2018)*. In our scenarios we are considering CAVs which are between Level 2 (which are widely available on the market today) to a maximum of Level 4, since we assume that technological advancements will not have reached Level 5 by 2035. It is uncertain the extent of the environments that Level 4 vehicles will be permitted to drive in unassisted so Level 4 has been split into Level 4a which permits autonomous driving under highway conditions only and Level 4b which permits autonomous driving under highway conditions and in urban centres.

Table 2: Overview of automation Level factors affecting carbon emissions

Level 2 (Level 2)	Level 3 (Level 3)	Level 4 (Level 4a)	Level 4 (Level 4b)
Platooning Increased safety features	Traffic jam automated driving Highway autopilot (with human supervision)	Driverless valet parking Automated highway driving Repurposed travel time Valet EV charging	Empty journeys Automated urban driving No driving licence necessary Reduced labour costs Reduced requirement for signs, traffic signals and lighting

Table 3: Overview of ownership model factors affecting carbon emissions

Factor	Private ownership	MaaS (fleet operated)
Charging responsibility	Lies with end user to locate and wait for recharging	Responsibility of the fleet operator, power can be distributed more efficiently across the fleet
Cost	High initial investment in sunken costs of car ownership	Shared ownership, shares some maintenance and operational costs but introduces labour cost implications
Size of vehicle	As versatile as possible	Right sizing based on the on-demand capacity per journey
Parking land use	High parking space per vehicle ratio	Lower land use required since no parking required near to origin/destination
Fleet renewal	Slow uptake of new technologies	More intense use cycles, increase rate of vehicle of turnover
Centralised fleet management	Possible but many difficulties	Easier to implement centralised planning leading to efficiencies

3

3 CAV decarbonisation mechanisms

The decarbonisation impact of introducing CAVs to the road transport ecosystem is highly uncertain due to the vast number of factors involved and the complexity of the dependencies between mechanisms.

To simplify the problem, the mechanisms have been broken down into five fundamental factors. These are designed to comprehensively cover any (de)carbonising impacts that CAV introduction could impose. In our scenarios we will assess how the autonomy level of CAVs and the ownership model are likely to affect the baseline of emissions produced in the UK in the year 2035 so that the relative impacts of interventions can be forecasted.

Figure 2 displays the main CAV (de)carbonising mechanisms categorised into **five fundamental factors:**

1. Total number of vehicles manufactured
2. Embedded emissions per vehicle manufactured
3. Total vehicle miles travelled
4. Well/Windmill-wheel emissions per vehicle mile travelled
5. Embedded emissions in infrastructure

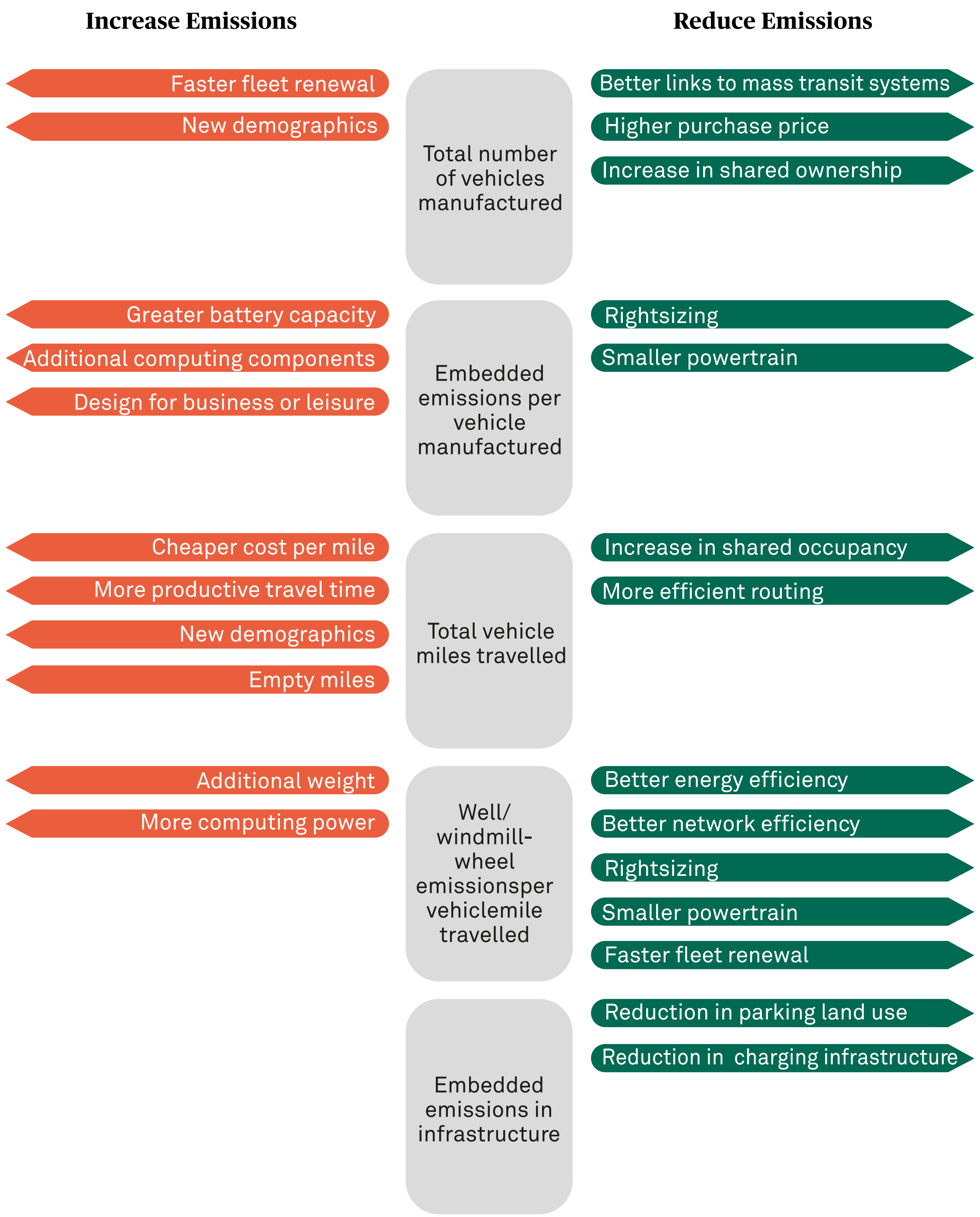


Figure 2: Overview of CAV mechanisms influencing carbon emissions

The five fundamental factors do not encompass the carbon impact of modal shift. For example if total vehicle miles travelled is increased due to a shift in modal choice from active travel to CAV usage, then this will increase overall carbon emissions, while if automated HGVs can displace air travel for some journeys, this would reduce overall emissions from transportation.

Vehicle decarbonisation has historically focussed on reducing the emissions per vehicle mile travelled (VMT) through improving fuel efficiency, and that is where much of the research into the environmental impacts of CAVs has been conducted. As the government brings in a ban of new fossil fuel vehicle sales which will accelerate the transition from internal combustion engines (ICE) to zero emission vehicles (ZEVs), this decarbonising benefit of CAVs compared with conventional vehicles becomes far less significant. Instead, we need to take into account the wider ecosystem of vehicle design and manufacture, vehicle miles travelled and network efficiencies when forecasting the total carbon impact of CAVs.

In the sections below, each of the five fundamental factors in Figure 2 is explored in more detail, explaining why they are carbon contributors and which CAV decarbonising mechanisms will impact their significance to overall carbon impact. A systematic literature review was undertaken to build a comprehensive list of the decarbonisation mechanisms and key statistics on the decarbonisation potential of mechanisms are quoted where appropriate.

3.1

Total number of vehicles manufactured

The UK's demand for new vehicles requires manufacture, assembly and distribution, all of which contribute to carbon emissions, as do the processes of disposal and waste management of older vehicles. CAVs have the potential to increase demand for new vehicles through faster fleet renewal if rapid technological upgrades drive more consumers to renew their vehicle more often to benefit from the autonomous features. Shared fleets with high utilisation rates are replaced more quickly than privately owned vehicles as they complete more miles in the same timeframe and therefore deteriorate quicker. CAVs may also lead to an increase in travel demand if they are able to offer more convenient and lower travel cost compared to other modes, increasing propensity to travel by road. Driving up peak travel demand will result in a larger vehicle fleet required to meet travel demand, depending on the achievable level of shared journeys. On the other hand, the higher cost of CAVs over conventional vehicles may be a barrier to adoption and the facilitation of more shared ownership and shared occupancy of vehicles would be a driver to reduce the demand for vehicles. CAVs could further complement mass transit services, offering fast and convenient first and last mile travel to public transport hubs and therefore shifting journeys from cars to other modes.

The mechanisms which have the potential to **increase carbon emissions** and therefore have a negative impact are:

Fast fleet renewal is often cited as a key requirement to improve the fuel efficiency of the fleet, as the rate of technological progression outpaces natural vehicle turnover. For example, the expected lifetime of passenger cars in Europe is 18 years and the average gCO_2/km travelled reduced by 27.9% between 2000 and 2019 *(European Environment Agency, 2020)*. However, in the context of vehicle manufacture there is a trade-off for total lifecycle carbon emissions; the optimisation of which depends on the number of years in use and the number of miles travelled throughout the lifetime *(Transport and Environment, 2018)*. CAVs are likely to increase the rate of fleet renewal as the rapid technology advancements offer a reduction in operation costs for fleets which are likely to offset the initial investment. Similarly, the improved driving experience which CAVs can bring to private vehicle ownership may see a faster rate of vehicle renewal, especially if the SAE automation levels are released chronologically e.g. if the benefits of replacing a Level 3 vehicle with a Level 4 outweighs the cost of replacement before the natural end of its use cycle.

New demographics could become a target market for CAVs and as such drive up vehicle sales. Level 4 automation would allow people who are currently prevented from driving due to medical conditions (particularly the elderly) to enjoy car ownership. Small businesses who may not be able to offer delivery services due to high labour costs could also be candidates for purchasing Level 4 light goods vehicles for conducting deliveries.

The mechanisms which have the potential to **decrease carbon emissions** and therefore have a positive impact are:

Higher purchase price of vehicles leads to a reduction in the demographics which can afford them, this reduces new vehicle sales which slows the rate of fleet renewal. In 2019, there were 2.31 million newly registered passenger vehicles in the United Kingdom *(Statista Research Department , 2020)*. This number has been decreasing since 2016, however the value of vehicles purchased has been on the rise and reached a high of 112.2 consumer price index (CPI) in 2019 compared with 90.6, 10 years prior *(Statista Research Department , 2020)*. The additional software and hardware components required for automation such as LiDAR sensors, cameras and embedded controls will increase the base costs of such vehicles. The 2017 Market Forecast for Connected and Autonomous vehicles estimated that the costs of autonomy packages in 2035 would be approximately £1350 for Level 3 and £2750 for Level 4/5 package *(Transport Systems Catapult, 2017)* . There are many uncertainties within this number as it depends on the timeline of introduction of automation and as an emerging technology the costs are expected to reduce with increased uptake.

Shared ownership of vehicles can be facilitated in a number of ways; through a car club-like service giving access to members, by multiple members of a community having a joint investment in a shared vehicle or a through fleet operated vehicle system referred to as mobility as a service (MaaS) or highly automated road passenger services (HARPS). With the introduction of Level 4 autonomous vehicles, it may merge the business cases of car clubs and MaaS offerings given the absence of a driver in both cases and the ability of vehicles to locate and travel to riders. The private ownership model consists of individual vehicles dedicated to a specific user or household and is inefficient at a network level, with utilisation rates approximately 4% - private vehicles spend 80% of time parked at home and the remaining 16% parked at a destination *(Bates & Leibling, 2012)*. Shared ownership has the potential to greatly reduce the number of vehicles manufactured, especially if complemented with a spread of peak vehicle demand which can be achieved through increased **shared occupancy**. Level 4 CAVs are an enabler of shared usage given their ability to independently return to base, and plan routes to pick up and drop off multiple passengers at different locations, while this can be done using driven MaaS systems, CAVs can do it at lower operating costs. Bischoff and Maciejewski (2016) modelled the city of Berlin, replacing all private vehicle trips with shared CAVs and found that the number of vehicles required to process the current private vehicle demand was 91% lower *(Bischoff & Maciejewski, 2016)*. However, the desirability of the change from private to shared mobility is low according to the CAV public acceptability dialogue engagement report 2019 *(McCool, 2019)*. While it there is a consumer understanding that overall network benefits could be realised through shared journeys, loss of freedom (flexibility in when to travel) was the largest deterrent for shared ownership and safety concerns were a barrier to shared occupancy. The findings suggest that cost savings below 25-50% of baseline costs would not override the barriers.

Better links to mass transit systems can be facilitated by CAVs. This requires the CAV operating models to complement rather than compete with mass transit systems such as trains and buses by providing first and last mile travel to transportation hubs rather than fulfilling the entire journey in a single CAV mode. Enabling a more mixed modal spread of journeys will help to reduce car dependency and therefore reduce demand of new cars. With the expected price reductions in HARPS journeys compared with existing taxi services, feasible alternatives would need to be price competitive to limit CAV usage. The equivalent in freight terms would be better links to and from freight consolidation centres, where HGV payloads could be split into smaller, automated vehicles which would be more likely to accommodate electric powertrains.

3.2 Embedded emissions per vehicle manufactured

The embedded carbon costs attributed to the manufacture of a vehicle is the sum of its components plus assembly and distribution. The carbon cost of vehicle manufacture can vary greatly depending on size, weight, powertrain, materials and level of comfort features. The carbon cost of the vehicle manufacturing process depends on process efficiency, manufacturing techniques, extraction of raw materials and the carbon released in the electricity generation used to power the process. BEVs are significantly more carbon intensive to manufacture than ICE vehicles; as we expect CAV and conventional vehicles to transition to BEVs, we are considering the impacts that automated features may have on embedded carbon compared with the average, privately owned battery electric vehicle. CAVs have the potential to impact the emissions per vehicle manufactured compared with a non-automated BEV by influencing battery capacity requirements, vehicle sizing, vehicle purpose and by introducing new computing and sensing components for automated driving.

The mechanisms which have the potential to **increase carbon emissions** and therefore have a negative impact are:

Greater battery capacity may be demanded by CAVs since they draw more energy from batteries than conventional electric vehicles due to the increased computing power required for automated driving. In, addition greater battery range could be desirable for electric CAVs to enable longer unbroken journeys and higher utilisation rates of shared fleets by reducing time spent recharging. Lithium-ion batteries used today in BEVs have significant embedded carbon associated with their production as the process requires extracting and refining rare earth metals, and is energy intensive because of the high heat and sterile conditions involved. Furthermore, the majority of lithium-ion batteries found in electric vehicles in Europe in 2016 were produced in Japan and South Korea, where between 25%-40% of electricity generation is from coal *(ICCT, 2018)*. Studies looking to quantify the mass of carbon dioxide released per kilowatt hour of battery capacity (kg CO_2e/kWh) produced vary considerably with method, the ICCT quotes a range of 56 to 494 kilograms of carbon dioxide per kilowatt-hour of battery capacity while the Circular Energy Storage research and consulting group offer a range of 39 kg CO_2e/kWh to 196 kg CO_2e/kWh *(Melin, 2019)*. The higher the battery capacity (assuming no improvement in energy density and battery technology) the greater the initial emissions per vehicle manufactured. As such, it is important to consider the carbon lifecycle of a vehicle and explore whether electric CAVs will have use cases with sufficient VMT miles at a lower emissions per vehicle mile to justify their carbon intensive manufacture. The energy intensive process of battery disposal, reuse or recycling must be considered in a vehicle lifecycle analysis.

Additional computing components are required for CAVs compared with conventional vehicles, which increases the embedded carbon emissions in vehicles. The sensor and computing components require the mining and or processing of rare earth metals, aluminium, copper, steel, electronics, and plastics which are carbon intensive activities.

Design for business or leisure may result in additional comfort features and/or larger cabins to provide space for productive and leisure activities inside vehicles. Each additional feature will result in embedded emissions of manufacture, assembly and distribution.

The mechanisms which have the potential to **decrease carbon emissions** and therefore have a positive impact are:

Rightsizing refers to the process of matching vehicle capacity with occupancy demand. If CAVs lead to a mobility as a service shared occupancy system, rightsizing may become commonplace. If so, given the high percentage of single and dual occupancy journeys taken in the UK, it is likely that to 'rightsize' a vehicle would be to reduce the size to an occupancy of two for most journeys and thus lead to smaller, less carbon intensive vehicles being manufactured. HARPS could consist of a fleet of CAVs in differing sizes which will be deployed to match the demand for the journey.

Smaller powertrains are likely to come with a shared model of CAVs, since features such as fast acceleration and high top speeds will be rendered moot when the vehicle is not driven and instead programmed to drive to an optimised set of acceleration and speed patterns. HARPS would be designed to have the minimum powertrain requirements rather than excess performance characteristics which has the potential to dramatically reduced the weight of vehicles and energy embedded in manufacture. The combination of rightsizing and smaller powertrains could dramatically reduce embedded emissions per vehicle manufactured.

3.3 Total vehicle miles travelled

An increase in vehicle miles travelled (VMT) results mainly from an increased demand for travel. This section focusses on the CAV mechanisms which may impact demand for road travel but does not consider the carbon impacts of whether this is new or displaced demand (modal shift). Every vehicle mile travelled has a carbon cost associated with it (even those travelled by zero emission vehicles), so reducing the total VMT is an important aspect to consider for decarbonisation. The number of VMT can also affect congestion, number of collisions and the rate of degradation of infrastructure such as road surface which all have a carbon cost. CAVs have the potential to increase the number of journeys taken by car and the length of each journey taken as well as introduce the concept of empty miles to the road system.

Given all these considerations, the overall impact of CAVs on total vehicle miles travelled is quite uncertain. There is an expectation that CAVs will make car journeys more productive and convenient leading to a rise in demand. In addition, cheap, on-demand last mile deliveries could be enabled by CAVs increasing demand for last mile deliveries and faster, cheaper long-haul HGV travel could increase demand for freight logistics by road. CAVs are also expected to be an enabler for increased shared occupancy journeys which could dramatically reduce the ratio of vehicle to passenger miles.

The mechanisms which have the potential to **increase carbon emissions** and therefore have a negative impact are:

Cost per mile of CAV travel is expected to be highly reduced from today's conventional vehicle travel in addition to the assumed electrification of vehicles which are cheaper to run than fossil fuels. CAVs are expected to increase fuel efficiency which will reduce running costs. A UBS report suggested that the cost of a journey via shared, electric Highly Automated Road Passenger Services (HARPS) could be up to 80% cheaper than an on-demand ride hailing trip today which would make its cost comparable with mass public transport systems and cheaper than private vehicle ownership *(UBS Limited, 2017)*. In fact, studies suggest that owning a private car could be up to twice as expensive as using shared HARPS regularly *(UBS Limited, 2017)*. This is largely attributed to the absence of a driver and therefore labour costs which currently makes up 60% of an on-demand ride hailing fare. This reduced cost per mile will increase accessibility of small vehicle service-based road travel, opening it up to a wider demographic and increasing the frequency in which people can afford to travel - both of which will increase demand. Logistics companies are currently reliant on human drivers for the distribution of goods by road; labour costs make up a third of road freight costs and therefore considerable savings are possible in this market (Vivid Economics, 2019). Reduced cost per mile, in addition to other CAV benefits such as increased safety, improved fuel efficiency and better journey reliability could lead to an increase in the number of VMT by HGVs.

More productive travel time is a large selling point of highly automated CAVs over human operated vehicles. Value of travel time (VOTT) refers to a consumer's willingness to pay to reduce total travel time *(Athira, Muneera, Krishnamurthy, & Anjaneyulu, 2017)*, and it varies significantly between industries, local context and on an individual level. CAVs enable occupants to repurpose their driving time to conduct other tasks such as sleeping, working, or emailing, and this is expected to reduce the VOTT associated with car travel. A reduction in sensitivity to travel time means that people are willing to make longer journeys by car even if there is a faster alternative and will not be as be as discouraged from car travel by congestion since they perceive they can remain productive throughout the journey. If the average length of commutes increases, this will increase the VMT and lead to urban sprawl. In freight logistics, repurposing driving time with sleeping will have an impact on cost per mile and speed of deliveries.

New demographics of car users are expected to make use of CAVs such as the elderly population who may be unable to drive due to medical conditions and the young who have not got a driver's licence. By opening up car travel to these populations, the overall VMT is expected to grow significantly. Harper et al. considered the impact of the elderly and those with medical conditions becoming new users and predicted an increase of up to 12% in VMT based on serving their demand *(Harper, Hendrickson, Mangones, & Samarasa, 2019)*. In contrast there has been little research conducted into the demand that unaccompanied minors may have on VMT *(Stephens & et al , 2016)*. Given that the elderly and the young are likely to be more cost-sensitive, a decrease in cost per mile is likely to exacerbate the extra demand.

Empty miles is a term which refers to unproductive journeys carried out with no occupants (or goods) in a vehicle, enabled by full (Level 4+) automation levels. Empty miles could be used to fulfil return-to-home trips, to run errands or to locate and use a recharging or refuelling station. CAVs could also be programmed to 'circle the block' by their owners while they complete an errand to avoid parking charges. HARPS fleets are expected to perform empty miles when redistributing CAVs to find the next passenger. Stephens et al. estimated that with full automation the introduction of empty miles could increase VMT in cities by up to 11% assuming no ridesharing and by up to 5% with ridesharing considered *(Stephens & et al , 2016).*

The mechanisms which have the potential to **decrease carbon emissions** and therefore have a positive impact are:

Shared occupancy journeys can consolidate multiple trips with similar origin and destinations which would be taken by separate vehicles into a single vehicle trip. This reduces the vehicle miles travelled by a factor of the number of consolidated vehicles, minus any minor detours required to complete all passenger journeys. CAVs are likely to increase the number of shared occupancy journeys by facilitating a cheaper and more convenient service. Santi et. al modelled the potential that ridesharing trips could have on the reduction of total travel time in New York City and found that theoretically up to 40% reduction could be achieved through ridesharing (assuming that two trips are replaced with one), if future demand for journeys is known to the system. In the real-time model a 32% saving in travel time is achieved under the same conditions *(Santi & et al, 2014).*

More efficient routing for end to end journeys can be facilitated with CAVs by reducing the miles spent hunting for a parking space and those where drivers have got lost. A report from the National Renewable Energy Laboratory estimated that CAVs could result in a 5-11% reduction of VMT in city driving from reduced searching for parking *(Stephens & et al , 2016).*

3.4 Well/Windmill-wheel emissions per vehicle mile travelled

The mass of carbon emitted per vehicle mile travelled depends on the carbon content of the fuel and the energy intensity of travel. CAVs on an individual vehicle level are generally assumed to be less energy intensive than their conventional vehicle counterparts due to more efficient driving profiles. While carbon content of fuel is traditionally used to measure ICE vehicle emissions, there are carbon emissions associated with electric vehicle travel too and these are measured in kilograms of carbon dioxide released per kilowatt hour of electricity consumed. Similarly, hydrogen-powered vehicles have a CO_2e/km travelled from hydrogen generation and distribution. Both automated and connected vehicle fleets are expected to transition to ZEVs due to UK government vehicle sale restrictions, with significant penetration by 2035. As the UK electricity grid decarbonises, the major decarbonising impact of CAVs to reduce emissions per VMT lies in their potential to reduce energy intensity of travel at network level. There are also some attributes of CAVs which are expected to increase emissions per vehicle mile travelled by increasing energy intensity of travel from additional weight and computing power.

The mechanisms which have the potential to **increase carbon emissions** and therefore have a negative impact are:

Additional weight is expected from the computing components, sensors and additional wiring. Reports have suggested that every 10% reduction in vehicle weight can be responsible for a direct fuel economy improvement of 6-8% *(Taiebat, Brown, Safford, Qu, & Xu, 2018).* Gawron et al. consider the weight of CAV subsystems to be approximately 17kg, 22.5kg or 55kg based on whether they are small, medium or large *(Gawron, Keoleian, De Kleine, Wallington, & Kim, 2018).* Added weight would also be a consequence of increased comfort features such as reclining seats and entertainment systems and a demand for greater battery capacity as discussed in *3.2 Embedded emissions per vehicle manufactured.* While there is speculation that weight could be reduced due to the redundancy of passive safety measures given the infrequency of collisions, this would require high penetration of CAVs beyond what is likely by 2035. There is a more realistic argument for the removal of safety systems in goods-carrying vehicles if no passengers are onboard, but the safety systems would still need to protect the safety of other road users in any potential collisions.

The computing power required from the automated and connectivity features will lead to increased energy intensity of travel (reduced range per kWh of battery capacity) since power which could be used for propulsion is consumed to enable autonomy features. In other words, vehicles must use more fuel or charge to travel the same distance, thus increasing the emissions attributed to each vehicle mile travelled.

The mechanisms which have the potential to **decrease carbon emissions** and therefore have a positive impact are:

Better energy efficiency is one of the key expected outcomes of CAV deployment due to automated driving characteristics referred to as 'eco-driving' which are a set of driving behaviours that reduce fuel consumption compared with a human operator. This includes reducing unnecessary acceleration and braking cycles, operating at the most efficient speeds for the vehicle and enabling platooning. For ICE vehicles, better energy efficiency leads directly to less fossil fuel consumed and fewer tailpipe emissions released per mile travelled. For electric vehicles improving energy efficiency will result in increased battery range from the same capacity which will also reduce the electricity consumed per vehicle mile travelled thus reducing carbon emissions (assuming the UK grid is not 100% decarbonised). Platooning reduces the energy intensity of travel by reducing the drag forces on vehicles which are travelling in close convoy along highways and can be facilitated by Level 2 vehicles and above. Full automation CAVs (Level 4+) have the potential to further increase platooning efficiency by enabling smaller headways (0.3 seconds) as the reaction times of CAVs are much quicker than human drivers *(Janssen, Zwijnenberg, Blankers, & de Kruijff, 2015).* The European Automobile Manufacturers forecast that emissions of trailing vehicles in a platooning convoy could be reduced by 16% *(SMMT, 2020).* While this will only be effective during highway driving, in Great Britain in 2019, 19.5% of motorised VMT were driven on motorways and 26.8% on the Strategic Road Network, presenting a significant opportunity for emission reduction. Platooning has great potential for reducing emissions in heavy goods vehicles as they conduct many highway miles and have the most significant aerodynamic drag losses.

Better network efficiency can be achieved through the improved driving characteristics of CAVs including eco-routing, softer acceleration and deceleration and communication between vehicles (V2V) leading to reduced congestion and unnecessary stopping. The extent of network efficiency improvements depends on several factors including penetration of CAVs in the network. A study found that introducing just one CAV into the vehicle network leads to a dampening on stop and start traffic waves which can result in up to a 40% reduction in total traffic fuel consumption *(Taiebat, Brown, Safford, Qu, & Xu, 2018)*. It is reported that 94% of road traffic accidents in the UK occur due to human error regarding observation, decision making and response, therefore by reducing the frequency of collisions, CAVs can greatly diminish the effects of accident related congestion *(Paddeu, Calvert, Clark, & Parkhurst, 2019)*. Wadud et al. estimated that given the rising percentage of fuel wasted in the US being attributed to congestion, the complete elimination of congestion from the network would reduce energy intensity of passenger and heavy goods vehicle travel by 2% today and 4% by 2040 *(Wadud, MacKenzie, & Leiby, 2016)*.

Rightsizing refers to the process of matching vehicle capacity with occupancy demand. While most cars have capacity for between 4 and 6 occupants, the average occupancy of car and van trips in the UK in 2019 was 1.6, a figure which has remained the same since 2000. This figure drops to 1.1 for commuting trips and rises to a maximum of 2.0 for education trips - presumably due to the presence of an accompanying/driving adult (Department for Transport, 2020). This wasted capacity leads to inefficiencies from excess vehicle weight for the journeys they fulfil and thus results in unnecessary fuel usage. Reports have suggested that every 10% reduction in vehicle weight can be responsible for a direct fuel economy improvement of 6-8% *(Taiebat, Brown, Safford, Qu, & Xu, 2018)*. The potential for rightsizing is largely reliant on shared fleets of autonomous vehicles or HARPS since fleet operators can dispatch an appropriately sized vehicle based on the passenger requirements. The private ownership model is unlikely to support rightsizing, since consumers want the most versatile vehicle to justify the cost of investment and this means catering for higher occupancy even if that only represents a small percentage of journeys taken.

Smaller powertrains are likely to come with a shared model of CAVs as discussed in *3.2 Embedded emissions per vehicle manufactured*. According to a report by Transport Environment, the weight of new cars rose by 124kg between 2000 and 2017 which equates to an additional 10 grams of carbon dioxide emitted per kilometre travelled *(Transport and Environment, 2018)*. Some of this additional weight can be attributed to an average increase in power of 28% resulting from consumer demand for faster acceleration and higher top speeds. HARPS would be designed to have the minimum powertrain requirements rather than excess performance characteristics which has the potential to dramatically reduced the weight of vehicles which reduces energy intensity of travel. The combination of rightsizing and smaller powertrains could dramatically reduce the energy intensity of travel.

3.5 Embedded emissions in infrastructure

CAVs have a different set of infrastructure requirements to conventional vehicles. While some elements such as road surfaces remain consistent, and CAVs will have to be able to perform safely on the current road network, there are opportunities for reducing the embedded emissions in parking land use and electric charging networks. Additional infrastructure requirements such as 5G towers are expected for safe and successful CAV deployment but they have other use cases outside of transportation and therefore are deemed as inevitable regardless of CAV automation level and uptake.

The mechanisms which have the potential to **decrease carbon emissions** and therefore have a positive impact are:

Parking land use could be substantially reduced with the introduction of CAVs. Autonomous valet parking allows for vehicles to park in a much more space efficient way compared with human drivers, which could allow for up to 20% more vehicles to be parked within the same land space *(Transport Systems Catapult, 2017)*. Audi estimated that if CAVs are permitted to block each other in and release vehicles as required up to 2.5 times more CAVs could fit into the same land space compared with conventional vehicles. Introducing fleet-operated shared CAVs reduces the parking demand even further, since vehicles will have much higher utilisation rates. How the land use is repurposed plays an important part in the decarbonising effect, but making the land available gives urban planners the opportunity to create more green, sustainable spaces. Zhang et al. simulated an environment where shared, autonomous vehicles could reduce the parking demand by 90% for willing users of shared CAVs compared with private vehicle ownership *(Zhang W. & et al, 2015)*. Reaching this figure is dependent on many interlinking factors which are discussed further in the paper including fleet size, average waiting time for a CAV service, average number of empty miles between trips, and willingness to share.

Charging infrastructure for electric vehicles is being installed to cater for a private ownership model of conventional vehicles. This model consists of myriad of networks including home charging, workplace charging and public charging. Since the UK's fleet of privately owned passenger vehicles are parked at home for 80% of the day *(Bates & Leibling, 2012)*, slow overnight charging at home is a popular choice of EV owners. The DfT reported in 2019 that approximately 80% of charging events are conducted at home in the UK *(Department for Transport, 2019)*. Similarly to reduced parking land requirements, CAVs can operate with a more efficient charging network, given their ability to travel to charge points rather than charge points being required at popular destinations. CAVs can also free up a charger once they reach a satisfactory state of charge, unlike unoccupied conventional vehicles which will remain blocking the charger from use until a driver returns to move on. This presents an opportunity for strategic hubs, opposed to a flooding of the market approach, where chargers are expected at any parking location. Shared CAVs will likely require rapid charging infrastructure to optimise utilisation time and fleet size, as faster charging speeds allow for higher vehicle turnover and therefore the fewer chargers required. Vosooghi et al. reported that the best efficiencies (maximising passenger kilometres travelled) for shared CAVs can be achieved through battery swapping stations strategically located to minimise the distance between potential demands and charging stations *(Vosooghi & et al, 2019)*.

4

4 Baseline scenarios

Figure 3 displays where the four baseline scenarios sit on the driving axes of available automation level and ownership model.

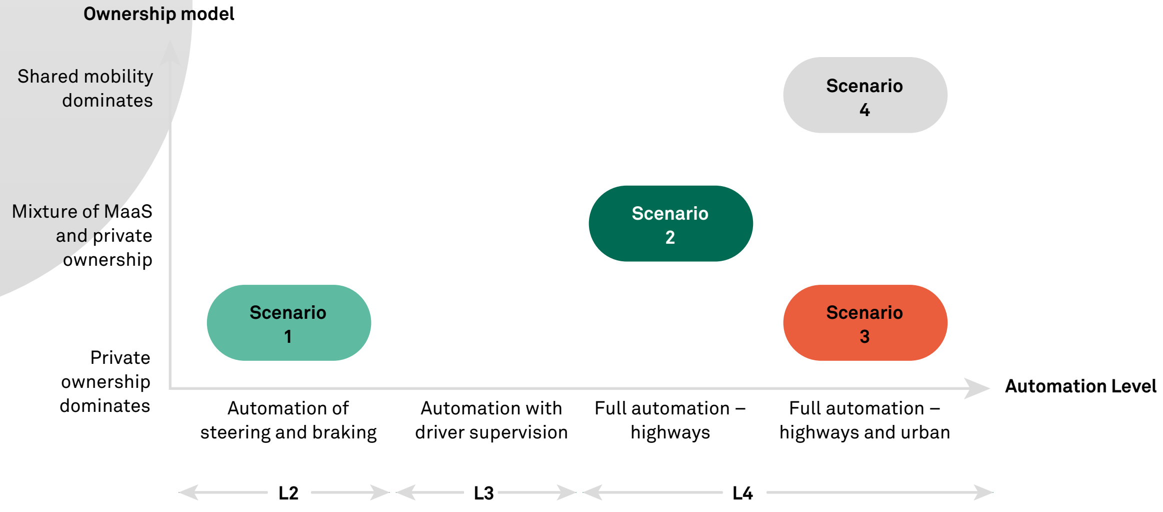


Figure 3: Summary of four baseline scenarios; Scenario 1: The Platooning Plateau, Scenario 2: Highway to the Middle Ground, Scenario 3: My CAV Is my Castle, Scenario 4: Autonomy as a Service. The L2, L3 and L4 on the lower x-axis refer to SAE autonomy levels (SAE International, 2018).

The sections below describe each of the basline scenarios in terms of the highest level of automation available on the market and the balance between private ownership and service-operated journeys. A brief **narrative** of the state of play in 2035 in each scenario is provided to give a sense of the road transport ecosystem. The **key CAV decarbonisation mechanisms** are listed to show the main drivers of the carbon impacts in each scenario. Finally a diagram is provided which presents a high level view of the **overall forecasted impacts** on each of the five fundamental factors within each baseline scenario, giving an indication of whether they increase or decrease carbon emissions and the relative impact of each.

4.1 Scenario 1: The Platooning Plateau

4.1.1 Narrative

Automation Level: Automation of vehicles is limited to Level 2 capabilities.

Ownership model: Private ownership dominates with mobility as a service journeys representing a negligible proportion of total vehicle miles travelled.

- Level 2 CAV technology has been standard for new car sales for many years and there is a very high penetration of Level 2 throughout the passenger fleet which brings small improvements in safety, network and fuel efficiency.
- The private ownership model dominates and technological advances are slow to penetrate the passenger car fleet due to slow fleet renewal.
- Measures to reduce car usage especially in urban areas (congestion charges, pedestrianising city centres and better cycling and walking infrastructure) have led to fewer vehicle miles travelled as people opt for active travel modes or public transport to avoid road user charging, high parking costs, or detours.
- The difference in cost between private ownership and MaaS-based solutions remains constant with private ownership working out cheaper for high mileage vehicles.
- Level 2 technology is adopted by HGV freight logistics who benefit from platooning features and improved safety systems. However, the continued need for drivers in all vehicles results in little change in the economic case for HGVs versus other forms of long distant freight transport such as rail or air so use cases remain stable.
- Given the slow progress of automated technology, vehicle-based last mile delivery solutions remain dependent on human drivers which keeps cost relatively high. This causes operators to invest more in delivery robots and micro mobility solutions such as e-scooters and bikes.

4.1.2 Key mechanisms

The key CAV decarbonisation mechanisms which are expected to have the most impact in Scenario 1 are:

1. Total number of vehicles manufactured
   • **Increased peak travel demand:** The private ownership model is maintained and as population increases, the demand for road capacity at peak travel times increases.

   * **Slow fleet renewal:** Since the rate of technological advancement in automated features is slow, there is no increase in the rate of fleet renewal.
2. Embedded emissions per vehicle manufactured
   * No major CAV decarbonisation changes but following the trends of consumer demand for increased comfort, increased battery capacity and higher performance such as faster acceleration, vehicles are likely to have more embedded emissions.
3. Total vehicle miles travelled per year
   • Total vehicle miles are expected to reduce slightly as car usage declines, due to restricted access to certain urban areas and feasible alternative modes becoming available.
4. Well/Windmill-wheel emissions per vehicle mile travelled
   • **Better energy efficiency:** Platooning enables reductions in emissions per VMT which is especially significant in HGV travel.
5. Embedded emissions from implementation of infrastructure
   • **Increased demand for parking land use:** The private ownership model is maintained and as population increases the demand for parking land increases.

4.1.3 Overall forecasted impacts

Figure 4 shows that each of the fundamental factors are expected to be impacted to a similar degree but with conflicting effects on carbon emissions. Increases in emissions are expected from more vehicles manufactured, more emissions per vehicle manufactured and a greater need for infrastructure. Conversely there is a forecasted reduction in carbon emissions from a reduction in total vehicle miles travelled, and a reduction in the emissions per vehicle mile travelled.

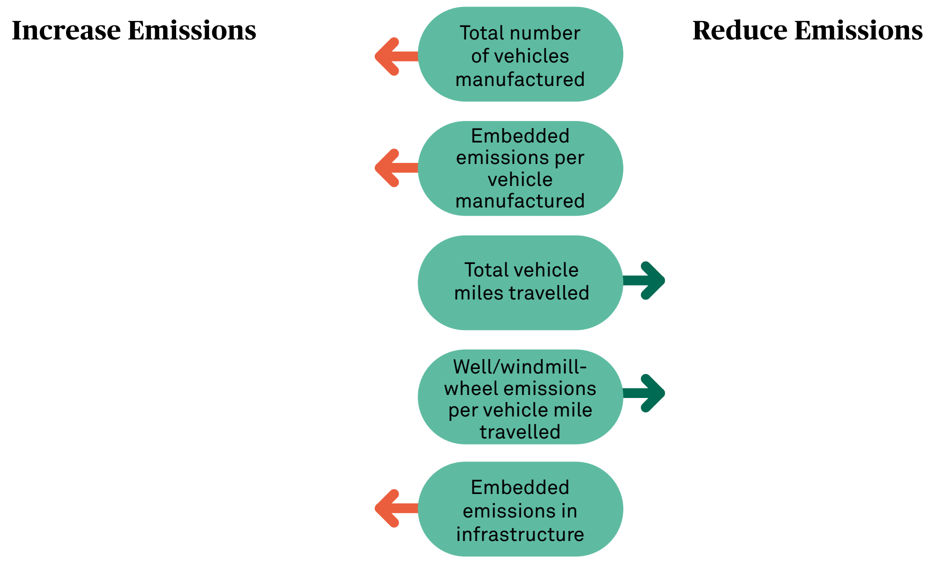


Figure 4: Scenario 1 overview of forecasted impacts

4.2 Scenario 2: Highway to the Middle Ground

4.2.1 Narrative

Automation Level: Level 4 vehicles are available on the market but they are only able to operate in Level 4 mode (without any human intervention) when travelling on highways. Level 2 and Level 3 vehicles are also available to purchase.

Ownership model: There is a general increase in usage of MaaS, especially in urban areas, but private ownership remains desirable instead of or in addition to service-based travel.

- Unassisted automation is limited to highway driving therefore the urban MaaS system remains reliant on drivers and as such larger vehicles with higher occupancies are more cost effective. This limits the effect of increased congestion from a greater number of vehicles on the road but also narrows the MaaS demographic to those willing to share and thus curbs uptake.
- There is little benefit for MaaS operators to adopt more expensive Level 4a technology over Level 3 since a driver must be present to complete end-to-end journeys and the cost/benefit analysis does not favour higher automation. This limits the network efficiency benefits associated with a higher penetration of Level 4a vehicles.
- Level 3 and Level 4a technologies are attractive to private car owners since it improves journey experience and productivity, enabling longer commutes and contributing to urban sprawl. Level 4a is reserved for more affluent drivers as the technology is only available in premium brands/models.
- Level 4a vehicles have high penetration in HGVs leading to great safety improvements in addition to fuel efficiency savings for operators. The logistics industry also benefits from reduced travel time and costs by either subbing drivers in and out at highway logistic centres located at highway junctions or simply by the fact that drivers can rest while travelling, shifting the limiting factor of continuous driving from driver requirements to vehicle range and refuelling times. In some instances, this extends the use cases of road freight.

4.2.2 Key mechanisms

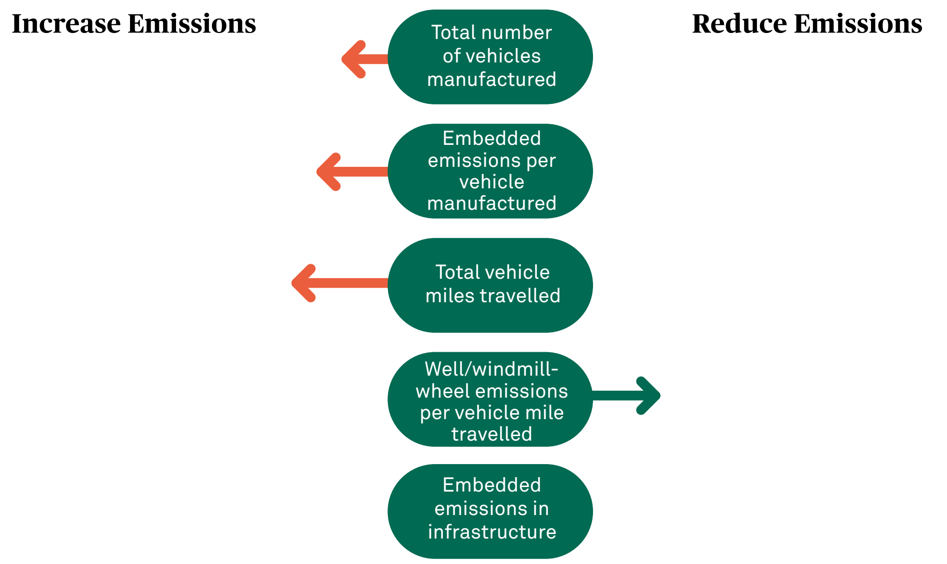
The key CAV decarbonisation mechanisms which are expected to have the most impact in Scenario 2 are:

1. Total number of vehicles manufactured
   - **Faster fleet renewal:** A chronological advancement through the SAE levels leads to faster fleet renewal as does a general increase in MaaS vehicles.
2. Embedded emissions per vehicle manufactured
   - **Greater battery capacity:** Increased power requirements from more energy intensive automated systems plus the longer commutes encouraged by more productive journeys leads to a demand for more battery capacity to extend vehicle range.
3. Total vehicle miles travelled per year
   - **Longer journeys:** Level 3 and Level 4 vehicles provide better journey experience for highway driving leading to more comfortable longer journeys.
   - **Reduced cost per mile:** The reduction in operating costs for freight operators leads to an increase in VMT from HGVs.
4. Well/Windmill-wheel emissions per vehicle mile travelled
   - **Better energy efficiency:** Platooning and better driving characteristics reduce energy intensity of travel.
   - **Better network efficiency:** Reduced collisions and smoother acceleration profiles from higher automation levels leads to reduced congestion.
5. Embedded emissions from implementation of infrastructure
   - No major decarbonisation impacts from CAV deployment

4.2.3 Overall forecasted impacts

Figure 5 shows that there is small increase in the demand for vehicles to be manufactured and a greater increase in the emissions per vehicle manufactured, both of which will increase carbon emissions. The biggest negative carbon impact is from a significant increase in total vehicle miles travelled. The only offsetting factor is a reduction in emissions per vehicle mile travelled. There is no forecasted change in the embedded emissions in required infrastructure in Scenario 2.

Figure 5: Scenario 2 overview of forecasted impacts



4.3 Scenario 3: My CAV is my Castle

4.3.1 Narrative

Automation Level: Level 4 vehicles are operating in both urban and highway environments. Level 2 and Level 3 vehicles are also available to purchase.

Ownership model: Private ownership dominates with some shared ownership between households but mobility as a service journeys represents a negligible proportion of vehicle miles travelled.

- Level 4 technology is highly affordable and leads to a high uptake in the private ownership market. The removed need for a driver means that one vehicle is able to serve multiple members of a family/community by making empty return trips, which increases vehicle miles travelled but reduces the number of vehicles manufactured. Full automation in highway and urban settings also opens up the possibility of car ownership for new demographics.
- Vehicles are able to locate and occupy a parking space independently or choose to 'circle the block' until required again by the dedicated user. This alleviates stress and/or parking fees for the owner but contributes to more vehicle miles travelled and increased demand on the road network.
- Level 4b technology makes journeys more productive and convenient by car, enabling longer commutes leading to urban sprawl. The ability to sleep during the journey also leads to a displacement of sleeper trains and air travel in favour of autonomous road vehicles. Vehicles are designed for the comfort of the user leading to larger bodies in most cases.
- Last mile movement of goods is dominated by autonomous vehicle deliveries displacing active travel and micro mobility solutions due to the low cost of driverless journeys and increased speed of delivery. The displacement of journeys comes from both direct modal shift for deliveries and the replacement of people taking short trips to pick up goods with robot deliveries due higher convenience.
- Long distance HGV travel makes use of Level 4b technology which reduces delivery costs and times and makes HGVs a viable alternative to air travel in some cases. This creates new use cases for heavy freight transportation on roads and increased demand from consumers who also benefit from goods being delivered more quickly for less money. Since HGVs can travel autonomously in urban areas there is less incentive for freight operators to switch to smaller vehicles in urban centres which contributes to higher levels of congestion.

4.3.2 Key mechanisms

The key CAV decarbonisation mechanisms which are expected to have the most impact in Scenario 3 are:

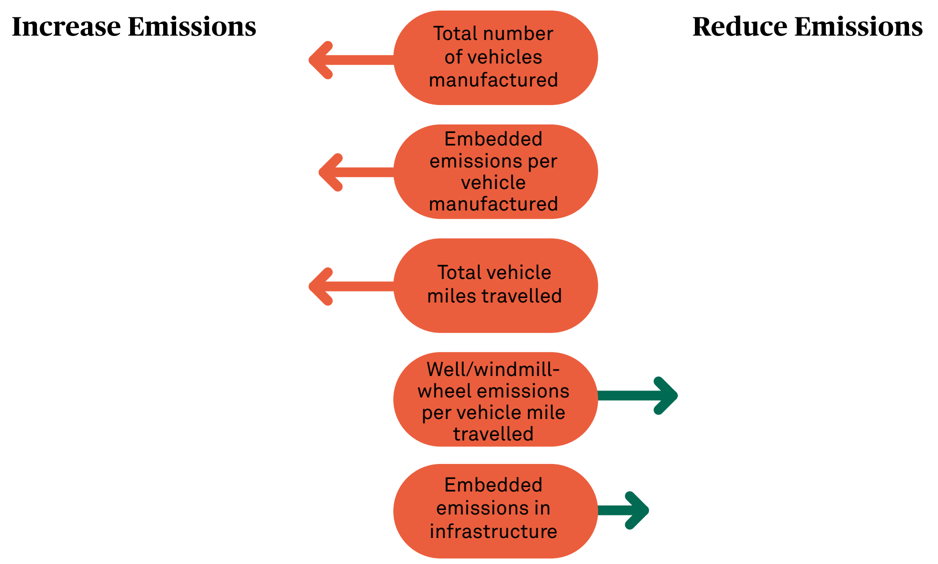
1. Total number of vehicles manufactured
   - **Low cost of vehicles:** CAVs have become very affordable leading to a high uptake in the private ownership market.
   - **Shared ownership:** full automation enables more shared ownership options and leads to a reduction in the number of vehicles per household.

2. Embedded emissions per vehicle manufactured
   - **Design for business or leisure:** Privately owned CAVs are personalised for maximum comfort and productivity during journeys.
   - **Greater battery capacity:** demand for longer commutes and increased power drawn for automated features increases the average size of batteries.
3. Total vehicle miles travelled per year
   - **Longer journeys:** Level 3 and Level 4 vehicles provide better journey experience for highway driving leading to more comfortable longer journeys.
   - **New demographics:** Full automation allows currently underserved populations of society to enjoy travel by car.
4. Well/Windmill-wheel emissions per vehicle mile travelled
   - **Better energy efficiency:** Significant improvements in energy efficiency from reduced energy intensity of travel in higher automated vehicles.
   - **Additional weight:** Increased weight from larger batteries and increased comfort features from design for business or leisure.
5. Embedded emissions from implementation of infrastructure
   - **Reduced demand for charging infrastructure:** The private ownership model is maintained but CAVs can locate and travel to charging points independently and rearrange themselves autonomously reducing the charging point to parking space ratio required.

4.3.3 Overall forecasted impacts

Figure 6 shows an expected high increase in carbon emissions resulting from more embedded emissions per vehicle manufactured and from more vehicle miles travelled. Conversely, emissions per vehicle mile travelled are expected to be reduced, which has a high impact on reducing carbon emissions. A reduction in demand for charging and parking infrastructure will reduce the embedded emissions in infrastructure to a small degree. Overall there will be negligible change to the number of vehicles manufactured since more goods vehicles and a faster fleet turnover negate the reduction in passenger vehicles per household.

Figure 6: Scenario 3 overview of forecasted impacts



4.4 Scenario 4: Autonomy as a Service

4.4.1 Narrative

Automation Level: Level 4 vehicles are operating in both urban and highway environments.

Ownership model: MaaS uptake is accelerated by fleets of Level 4b vehicles leading to HARPS replacing the need for many to own a private vehicle

- Level 4 technology is significantly more expensive to purchase than conventional vehicles and compared with Level 3 and Level 2.
- Level 4 HARPS are convenient, affordable and highly available and are viewed by the many as their primary and default travel mode in place of public transportation, active travel or private car ownership.
- The downturn in private car ownership reduces the number of vehicles in circulation and means parking land use can be repurposed for other uses such as more housing in city centres which reduces commuting distances for new residents.
- Fleet operators can react quickly to user demand and rightsizing of vehicles is common to cater for single and dual occupancy journeys, as many users are unwilling to share vehicles with strangers.
- Last mile movement of goods is dominated by autonomous vehicle deliveries displacing active travel and micro mobility solutions due to the low cost of driverless journeys and increased speed of delivery.
- Long distance HGV travel makes use of Level 4b technology which reduces delivery costs and times and makes HGVs a viable alternative to air travel in some cases. This creates new use cases for heavy freight transportation on roads and increased demand from consumers who also benefit from goods being delivered more quickly for less money.

4.4.2 Key mechanisms

The key CAV decarbonisation mechanisms which are expected to have the most impact in Scenario 4 are:

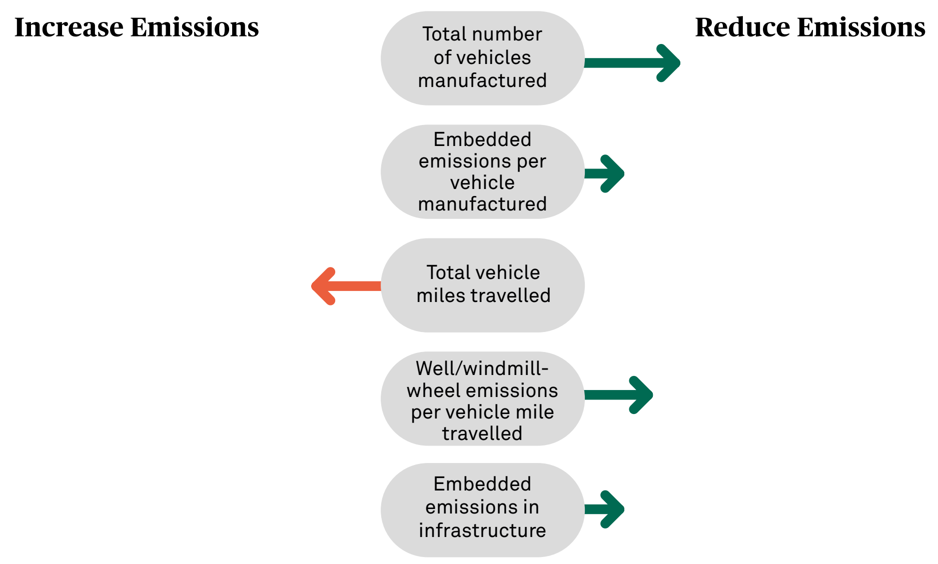
1. Total number of vehicles manufactured
   - **Higher purchase price:** CAVs have a higher purchase price than non-CAVs which reduces the accessibility to consumers but the lifecycle cost savings make Level 4 CAVs a good investment for fleet operators.
   - **Shared journeys:** Shared HARPS is culturally accepted in younger populations.
2. Embedded emissions per vehicle manufactured
   - **Rightsizing:** Fleets managed by operators allow for vehicle size to be reduced to meet average demand.

3. Total vehicle miles travelled per year
   - **Cost per mile:** relative cost per mile of HARPS compared with public transport increases total vehicle miles travelled. The low cost attracts last mile deliveries to be performed by CAVs as opposed to active travel.
   - **More productive travel time:** Level 4 vehicles encourage longer commutes.
   - **New demographics:** Greater accessibility of car travel from underserved populations due to Level 4 automation.
4. Well/Windmill-wheel emissions per vehicle mile travelled
   - **Better network efficiency:** Congestion improvements are realised in urban and highway settings.
   - **Smaller powertrains**: the shift from private ownership removes the need for excess performance.
5. Embedded emissions from implementation of infrastructure
   - **Reduction in parking land use:** Managed fleets make more efficient use of space and have reduced downtime.
   - **Reduction in charging infrastructure:** Managed fleets make more efficient use of charging infrastructure and eliminates charging/range anxiety leading to reduced demand for excess charging points.

4.4.3 Overall forecasted impacts

Figure 7 shows there is expected to be a medium increase in carbon emissions from a greater number of vehicle miles travelled. On the other hand, reductions in carbon emissions are expected to occur to a small degree from fewer embedded emissions per vehicle manufactured and reduced demand for infrastructure, to a medium degree from reduced well/windmill-wheel emissions per vehicle mile travelled and to a large extent from a significant reduction in the total number of vehicles manufactured to meet demand.

Figure 7: Scenario 4 overview of forecasted impacts



4.4.4 Summary of baseline scenarios

Figure 8 highlights the stark differences between overall carbon impacts which are forecast to arise depending on the CAV deployment scenario. This demonstrates the importance of planning interventions to mitigate the possibilities of increased carbon emissions and steer the scenarios towards more beneficial environmental outcomes.

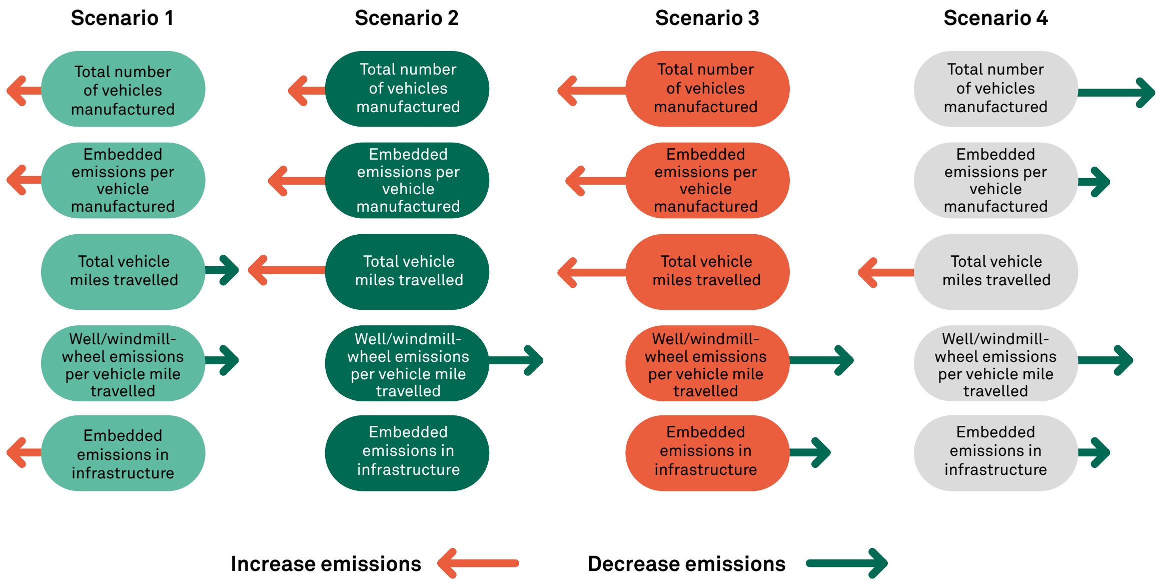


Figure 8: Comparison of baseline scenario carbon emission forecasts

COMMONALITIES: In every baseline scenario, the well/windmill-wheel emissions per vehicle mile travelled are reduced, as this a key characteristic of CAVs. The extent of the reduction in emissions per VMT does increase with more advanced automation level.

SCENARIO 1: The Platooning Plateau explores a scenario in which no significant disruptions have been made to disturb today's dominant private ownership model and new automated features are limited beyond platooning. The carbon impacts are the least severe across all the fundamental factors with no major increases or decreases in carbon emissions. CAV deployment of the type seen in Scenario 1 is unlikely to make any considerable progress towards the decarbonising agenda but will amount in no major increase in emissions either.

SCENARIO 2: Highway to the Middle Ground explores the effects of increasing both the level of automated features and the proportion of shared journeys, but only slightly. This scenario encourages faster renewal of privately owned vehicles which are spacious and have large battery capacities to accommodate travelling long distances and does nothing to reduce the infrastructure requirements. Scenario 2 is forecast to generate an increase in carbon emissions by introducing new issues while doing little to address existing ones, highlighting the value of mitigating interventions.

SCENARIO 3: My CAV is my Castle explores the impact of having affordable, highly automated CAVs along highways and in urban areas which are popular within the private ownership market. This scenario explores the impacts of CAVs becoming an extension of the home enabling travel time to be repurposed for productive work, leisure or sleeping. The high carbon cost of increased demand for vehicles which are more energy intensive to produce and travel longer distances is unable to be counteracted by the reduced emissions per VMT, reduced infrastructure requirements. CAVs dominate last mile and long distance freight delivery increasing demand for vehicles which negates any reduction in emission from increased in shared vehicle usage. Scenario 3 is forecast to generate a significant increase in carbon emissions, again highlighting the value of mitigating interventions.

SCENARIO 4: Autonomy as a Service explores the effects of highly automated vehicles operating both on highways and in urban environments which facilitates an on-demand shared CAV service for passenger transport. While there is a risk of a significant increase in vehicle miles travelled due to the improved ease of travel, all other aspects of CAV deployment lead to the reduction of carbon emissions from road transport and as such this is the most promising scenario to achieve Net Zero targets.

5 Future projects

This section outlines the priorities for future work on decarbonisation impacts and beneficial interventions relating to CAVs. It considers the aims that future project(s) should meet and suggests some candidate interventions to explore further. The work required to execute these projects is summarised in *Appendix B: Process for further analysis of interventions.*

5.1 Desired outcomes and components of future work

This report has presented the major factors determining the decarbonisation impact of CAVs, and explored the mechanisms within each factor. It has also presented a set of baseline scenarios that can be used to analyse the impact of proposed policy interventions. Building on this, it is important to gain a deeper understanding of these mechanisms and interventions, including numerical estimates of their impact.

Future work should therefore:

Analyse lifecycle carbon impacts of different sizes and modes of transport. For example, the advent of electric, autonomous vehicles may tilt the cost/benefit balance away from heavy, diesel powered transport (HGVs and trains) and toward light road vehicles.

- Not requiring a driver or having to own a vehicle creates significant freedom in the sizing of vehicles that does not exist without Level 4+ CAVs.
- Most people own a five-seat passenger car as this gives them the freedom to use it for five people - not because they will carry five people for most journeys.
- Similarly, fixed overheads such as drivers and having to manage scheduling mean that larger vehicles make economic sense for buses and trains, but these overheads disappear with on-demand HARPS services.

Noting that, even though it is unlikely that emissions-per-passenger-mile remain constant as passenger capacity is decreased (assuming vehicles at full capacity), smaller vehicles can still have significant benefits.

Develop a more in-depth understanding of CAV decarbonisation factors, including the causal relationships within and between them (and covering the carbon impacts of the interaction between shared ownership and vehicle lifespan).

Systematically generate and select interventions to explore further. There are a great many potential policy interventions, and it is important to find a wide selection of these and then develop an understanding of which are the most promising. *Section 5.2 Interventions for further consideration and Appendix B.1:Generation and selection of interventions to model* provide more detail on this.

Flesh out the details of the baseline scenarios, including the probability of each, numerical estimates for all parameters within the scenarios, and ensuring the set of scenarios provides reasonable coverage of all likely outcomes.

Define principles and criteria for choosing decarbonisation interventions. This is critical because the carbon impacts any intervention will have to be assessed against the wider, non-carbon societal impacts. Non-carbon impacts might include providing easy transport access to disadvantaged sectors, freeing extra productive time from the workforce, or supporting the automotive industry in the UK.

Perform in-depth analysis of the most promising interventions to understand their impact on decarbonisation, taking into account uncertainty over the baseline scenarios. Further details on how this can be done are given in *Appendix A: Expected Utility Calculation and Appendix B.2:Steps to model the impact of interventions.*

Future work should also clearly articulate which of the challenges and opportunities apply to the different sectors involved - government, local authorities, academia, and industry.

5.2 Interventions for further consideration

This section presents several strawman ideas that could enable and enhance the CAV mechanisms which reduce carbon emissions, and/or mitigate the CAV mechanisms which will increase carbon emissions. The intention is to provide a sample set of ideas as input to a future project where a more complete set of possible interventions would be developed and considered (as discussed in *Appendix B.1 Generation and selection of interventions to model).*

These interventions could be implemented through various methods and by various stakeholders, for example:

- R&D funding competitions to focus research efforts in desirable directions.
- Road authorities.
- Local planning regulations.
- National regulatory framework for HARPS and/or CAVs.

5.2.1 Encourage shared vehicle use

- Encourage developers to create isolated compartments within vehicles, which would enable users to feel significantly more comfortable about a shared vehicle.
- Subsidise HARPS in sparsely populated rural areas.
- Coordinate industry to standardise on payload size and shape for light goods CAVs, to allow sharing of vehicles and make “delivery as a service” easier to implement.
- Encourage HARPS operators to join into a single network, minimising the wait times for a CAV (encouraging adoption) and reducing the number of empty miles operators need to reposition vehicles.
- Fund research projects developing algorithms for efficient, commercially-aware joint scheduling and routing of HARPS vehicles from disparate companies.

5.2.2 Discourage empty miles

- Discourage private ownership of Level 4b capable vehicles (while allowing private ownership for Level 4a, i.e. vehicles that can operate Level 4 on motorways)
- Discourage private ownership of all Level 4 CAVs
  - There may be a strong safety argument for this anyway, given the importance of keeping CAVs well maintained, and ensuring they are not operated outside their operational design domain.

5.2.3 Direct road use charging

- Direct road use charging would discourage empty miles. Empty miles could even be charged at a premium rate.
- Charging HARPS operators on the basis of emissions-per-passenger-mile would leave them freedom in how to lower this measure, for example they could use rightsized vehicles, or they could incentivise shared occupancy for trips.

5.2.4 Encourage interoperability with public transport

- Provide CAV-dedicated easy drop off points at railway stations.
- Provide integrated journey booking systems; “autonomous LDVs could increase the use of mass transit if they are offered via consumer programs that integrate various modes of transportation though unified trip management.” *(U.S. Department of Energy, 2018)*

5.2.5 Optimise use of land and infrastructure

- Encourage sharing of charging points between operators, and compatibility of charging points between manufacturers.
- Make sure land reclaimed from parking is used in a sustainable way.

5.2.6 Disincentivise longer AV journeys

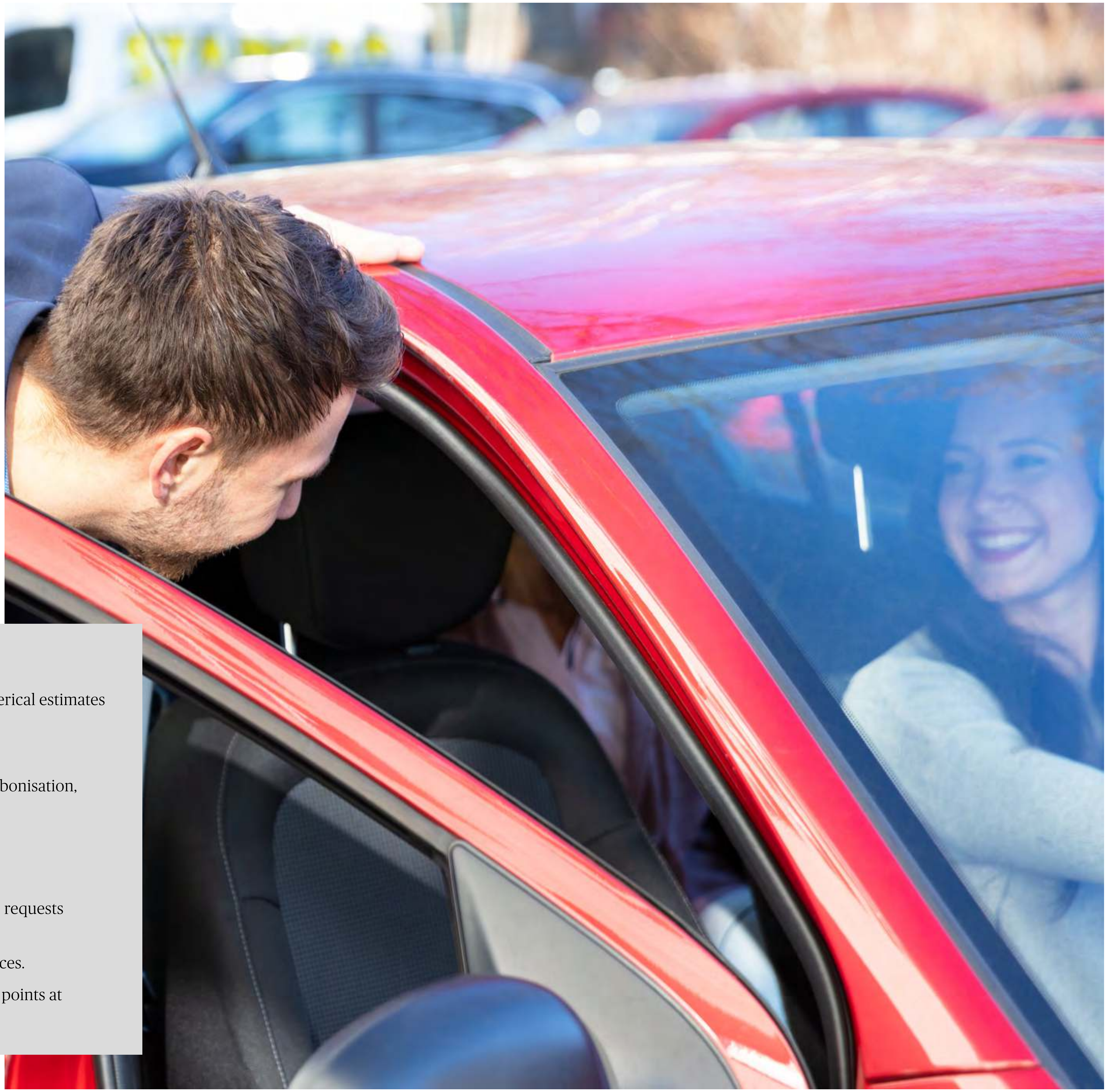
A workable way of discouraging a shift to long commutes was not identified. Long commutes of 1.5 hours or more may become more popular if working or relaxation activities during the journey become feasible, but this would be particularly problematic as it represents additional travel demand with few societal benefits.

Key next steps:

1. Develop deeper understanding of the mechanisms of CAV decarbonisation, including numerical estimates within each of the baseline scenarios.
2. Systematically generate and then short-list potential policy interventions.
3. Model the shortlisted interventions to gain an understanding of their effectiveness in decarbonisation, as well as their non-decarbonisation impacts.

Example interventions:

- Encourage shared vehicle use by subsidising HARPS in sparsely populated rural areas.
- Encourage shared vehicle use by incentivising regional HARPS operators to coordinate ride requests through a single booking system.
- Encourage sustainable use of land reclaimed from parking, for example as public green spaces.
- Encourage interoperability with public transport by providing CAV-dedicated easy drop off points at railway stations.



6

6 Conclusions

Achieving a significant reduction in carbon emissions is arguably the greatest challenge of this generation. The UK is committed to a target of Net Zero by 2050, which means transport will have to decarbonise significantly. This in turn means vehicle automation technologies must firstly aid the decarbonisation agenda, in order that their benefits of increased safety, increased access to mobility, and freeing of productive time can be realised.

Vehicle automation systems will result in many technology and travel pattern changes, some of which will likely increase net emissions, and some of which will likely decrease them. For policy makers it is critical to understand these effects in order to plan for them, and also so that the positive effects can be maximised and the negative effects minimised.

This report makes the following key contributions:

- A clear explanation of the **key factors and underlying mechanisms** that cause CAVs to increase or decrease emissions.
- Identification of level of autonomy and degree to which shared ownership is adopted as the **critical levers with the highest uncertainty.**
- Creation of four **baseline scenarios** that provide reasonable coverage of the space of possible outcomes for these two uncertain levers. These scenarios can be valuable in evaluating potential impacts of CAVs, for decarbonisation and for other wider effects.
- Presentation of a **structured method for evaluating interventions** based on their impacts within each baseline scenario.
- Definition of the **next steps needed to inform policy making** in this area, and therefore to enable CAVs to achieve their potential of significant decarbonisation of transport.

7

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Appendices

Appendix A
Expected utility calculation

Expected Utility Theory (see for example *(Briggs, 2019)*) provides a method for making rational decisions in the face of uncertainty. In our case, we are interested in the expected reduction in future emissions by making a policy intervention; however, we don't know exactly what would happen to emissions anyway if we didn't make this intervention. To take an example from a different domain, our intervention might be to pass a law that all boilers fitted or replaced from 2030 must be air-source-heat-pumps; if air-source-heat-pumps are very unpopular, this intervention will have a large effect, but if air-source-heat-pumps are being bought by 95% of consumers anyway by then, the intervention will only have a small effect.

Mathematically, we want to find the 'expected' reduction in emissions R due to an intervention i. Because we do not know the future evolution of the world without any interventions, we have to average our intervention over all of the baseline scenarios s. This gives the equation

$$R(i) = \sum_{s} P(s)R(i|s)$$

Where R(i|s) is the reduction in emissions from performing intervention i given that baseline scenario s is the one that occurs, and P(s) is the probability of scenario s occurring.

Once the potential interventions, the baseline scenarios, and estimates of the probabilities of each baseline scenario have been established, there is still a complex cost/benefit analysis to be performed to decide on the best interventions to perform. This is because more than one intervention may be achievable, each intervention will have some cost (for example in direct funding, or in administrative implementation time), and may have societal impacts other than a reduction in emissions due from CAVs. All of these factors will have to be considered in formulating CAV decarbonisation policies.

Appendix B
Process for further analysis of interventions

B.1 Generation and selection of interventions to model

There are potentially a wide range of steps that could be taken by national and local government and public authorities in order to boost the positive environmental impact expected from CAV deployment. However, modelling the impact of each intervention is a resource-intensive task (as outlined in *Section B.2 Steps to model the impact of interventions)*, and can only be undertaken for a subset of the range of policy options available.

We propose a three-step approach to generating and selecting the interventions worthy of detailed modelling:

1. Systematic assessment of the mechanisms from *Section 3 CAV decarbonisation mechanisms.*
2. Extraction of suggestions from relevant literature.
3. Rough numerical estimation of effects (without performing any novel modelling, forecasting, or attitude surveys).

Item 1 is relatively complex, and we suggest a group of experts develop ideas through a systematic review of the factors affecting CAV carbon outputs, and considering the possible actions that can be performed by each stakeholder. For example, for the “Emissions per vehicle mile travelled”, the group should consider actions that could be taken by each stakeholder to improve the average efficiency of CAVs on the road. The list of potential stakeholders might include: CAV developers and manufacturers; CAV operators; central and local government (including bodies that regulate and approve CAVs); road/traffic authorities; the insurance industry; infrastructure owners and operators; and the public.

B.2 Steps to model the impact of interventions

The modelling stage will rely on the outputs of the work described in *Section 5.1 Desired outcomes and components of future work:* a reasoned set of baseline scenarios, a shortlist of interventions to model, and a set of criteria for evaluating the results.

Given then variety of interventions possible, each one will likely require a unique model to be applied to predict its impact. This makes selection of a short-list of interventions critical.

The modelling steps are described in the following subsections.

B.2.1 Identify the most appropriate modelling technique

The key modelling techniques available are:

- Macro-economics model of impact based on estimates of consumer behaviour and demand (for example using systems dynamics modelling, or creating a custom model in Microsoft Excel). This would be most appropriate for high Level analyses that do not depend on vehicle behaviour and traffic, such as vehicle right-sizing analysis.

- Traffic microsimulation tool that takes a road network and simulates the path taken by individual vehicles. This would work best for modelling interventions that affect vehicle-Level behaviour or routes, such as eco-driving, consolidated fleet route planning, fleet optimisation and V2X communications.

- Strategic macrosimulation transport model which will allow to model a city, a region or a strategic network and will assign demand for travel coming from different households (defined by composition, income Level, regular journeys) to the network, providing in output traffic flows (speeds, travel times, fleet composition). They will model a region at a zone Level (usually a predefined transport zone or at middle layer super output Level), and will likely take into account the costs and time taken for single trips at different times of the day based on traffic Levels and mode choice. The demand for travel for public transport comes usually from a public transport model where Rail and Bus services are represented.

- Agent-based (either activity-based or trip-based) transport model (ABM). These sit between macro models and microsimulation, since global behaviour of a population arises from single agent behaviour. ABM might model households or single agent's travel behaviour, considering both socio-demographic information (age, gender, income) and also personal preferences which might influence their mode choice (i.e. attitudes towards technology, environment). The model uses highly disaggregated spatial and temporal data and represents the demand for travel for 24 hours and their transport choice across all possible modes of transport, including fixed scheduled public transport and on demand mobility services. Activity-based modelling is a specific agent-based model that can represent even complex travel patterns and considers costs for travelling with different modes and different values of time depending on the activity (work, shopping, leisure, education etc.) and can explore different Level of integration.

B.2.2 Find, synthesise, or create the input datasets

All models will require data as an input, for calibration and validation of the model. Acquiring this data is one of the more challenging aspects of travel forecasting. The types of data that may be needed include:

- Emissions and efficiency information about CAVs;
- Users' preference models on the basis of journey time, journey cost, activities that can be performed during the journey, and other factors;
- Electricity generation data;
- Market research and consumer categorisation data.

This data can come from many potential sources and will often need to be merged or manipulated to meet the needs of the model. Sources include:

- Existing datasets;
- Research literature;
- Primary data gathered by face to face interviews, on-line surveys or other social research;
- New data sources, such as location-based data (Mobile Network Data, GPS, sensors dataset);
- Stated Preference or Revealed Preference surveys, especially when derived from studies specifically targeting users' behaviour and willingness to pay for shared mobility, especially when service runs with CAVs;
- Pilot studies specifically using CAVs in a real-world environment.

B.2.3 Create the models

First step for creating the models will need to define what output and features the model should represent. This will lead to the selection of the best tools to use (for example, SUMO, PTV VISSIM, PTV VISUM, Cube, Aimsun, MatSIM, Next, Microsoft Excel, Python). Then an implementation phase will be needed to build, calibrate and validate the model.

B.2.4 Run the model and analyse the results

Scenario testing will allow to choose the best possible intervention to minimise carbon footprint of the potential service run by CAVs either in isolation or in integration with other transport modes, optimise the routing and the expected carbon benefits of that intervention. Once all the candidate interventions have been analysed, the final step is to apply the criteria for trading off the carbon benefits, cost, and societal impacts of each intervention, and produce a recommendation (see *Section 5.1 Desired outcomes and components of future work and Appendix B: Process for further analysis of interventions).*

This process could be made more tractable by focusing on the potential interventions and budget of particular stakeholders (for example, local authorities).

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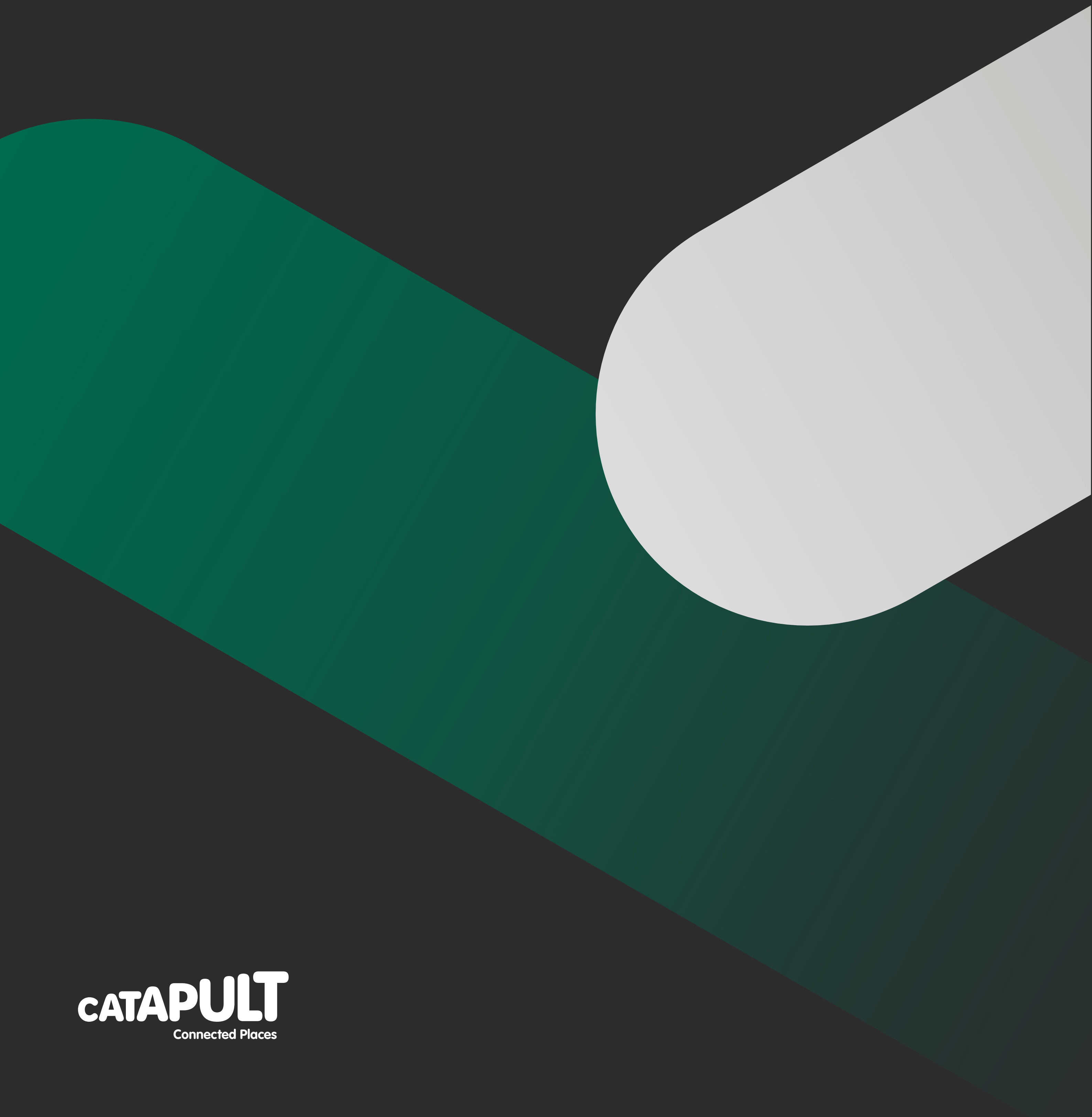

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