# Appraisal of Electric Vehicle Retrofit for Transport Decarbonisation within Agriculture: Whole System Approach

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**Abstract**

This research appraises electric vehicle retrofit as a pathway to support the decarbonisation of transport. This appraisal is conducted through a microscopic, mesoscopic, and macroscopic analysis of a central case study concerning the retrofit of internal combustion engine Land Rover Defender vehicles to electric. The vehicles studied are operating within the agricultural sector which is considered difficult to decarbonise.

The use of three perspectives to investigate retrofit within the context of the central case study aims to establish a more holistic 'whole system' appraisal. This broader methodological approach was inspired by literature on socio-technical transitions and specifically the Multi-Level Perspective. The microscopic, mesoscopic, and macroscopic analyses of this research are presented across three technical chapters termed the bottom-up, middle-out, and top-down perspective.

The bottom-up perspective appraises electric vehicle retrofit at the level of the individual vehicle and considers how an individual retrofitted vehicle is produced and could perform technologically and economically. The middle-out perspective investigates electric vehicle retrofit by considering how multiple retrofitted vehicles should be integrated into a wider context. For example, within the case study, the local agricultural environment, vehicle users, charging infrastructure, and energy system are considered. The top-down perspective evaluates electric vehicle retrofit at a broader policy measure for transport decarbonisation.

Findings from the three perspectives of appraisal indicate that overall, electric vehicle retrofit could be a useful tool to aid the decarbonisation of certain categories of vehicles within the agricultural sector and other analogous sectors. Retrofitting vehicles to electric is useful to expedite the decarbonisation of vehicle models where an effective low emissions alternative is unavailable. Furthermore, retrofitting vehicles can form a more cost-effective method of decarbonisation where retrofit specification is personalised to a specific use case.

The retrofitted Land Rover Defenders considered in this research exhibited similar energy consumption to a new electric vehicle in this particular case studies context and could significantly reduce the direct emissions of the original donor internal combustion engine Land Rover Defender. Considering the end user and operations of retrofitted vehicles on a case-by-case basis is paramount to increase the benefits of retrofitting. Finally, under more widespread adoption of electric vehicle retrofit across a population of vehicles, the flow of embodied emissions vehicles into landfill can be slowed (i.e., circularity is increased) through the remanufacture, reuse, recycling, and repurposing of vehicles. Although the potential for widespread adoption of retrofit would depend heavily on a number of underlying factors and dynamic causal relationships, for example, supportive policy conditions and the publics attraction to the pathway.

**Summary of Contributions**

1. Completed a techno-economic evaluation of an electric vehicle retrofit in the context of the agricultural transport sector and documented it for the first time in the academic literature, to the knowledge of the author.

2. Completed the first appraisal of electric vehicle retrofit in agriculture as a transport decarbonisation measure through the application of microscopic, mesoscopic, and macroscopic perspectives of investigation.

3. Provided additional critique to the utility of agent-based, causal loop and stock and flow modelling techniques in the transport decarbonisation context.

4. Appraised electric vehicle retrofit as a broader transport decarbonisation pathway, including both its potential to mitigate exhaust emissions and alter the progression of vehicle stockpile embodied emissions to landfill.

**Publications**

D. D. Snell, C. Featherston and L. Cipcigan, "Electric Vehicle Retrofit for Transport Decarbonisation within Agriculture – Case Study of a Land Rover Defender," presented at the 55th Annual UTSG Conference, Cardiff, UK, Jul. 10-12, 2023.

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## List of Abbreviations

| | |
|---|---|
| ABM | Agent Based Model (Modelling) |
| AEE | Average Embodied Emissions |
| BEV | Battery Electric Vehicle |
| CAN | Controller Area Network |
| CLD | Causal Loop Diagram |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalent |
| CVRAS | Clean Vehicle Retrofit Accreditation Scheme |
| DEF | Diesel Exhaust Fluid |
| DVLA | Driver and Vehicle Licensing Agency |
| EU | European Union |
| EV | Electric Vehicle |
| FASTSim | Future Automotive Systems Technology Simulator |
| FES | Future Energy Scenarios (National Grid) |
| GHG | Greenhouse Gas |
| GIS | Geographic Information System |
| HGV | Heavy Goods Vehicle |
| HOC | Hub Operation Category |
| ICE(V) | Internal Combustion Engine (Vehicle) |
| ISO | International Organisation for Standardisation |
| JLR | Jaguar Land Rover |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LRD | Land Rover Defender |
| MLP | Multi-Level Perspective |
| NEV | New Electric Vehicle |
| NRMM | Non-Road Mobile Machinery |
| OEM | Original Equipment Manufacturer |
| PAS | Publicly Available Standards |
| PV | Photovoltaic |
| REV | Retrofitted Electric Vehicle |
| RUC | Road User Charging |
| SCR | Selective Catalytic Reduction |
| SD | System Dynamics |
| SFM | Stock and Flow Model |
| SOC | State of Charge |
| SORN | Statutory Off-Road Notice |
| TC | Transport Chain |
| TCE | Transport Chain Element |
| TOC | Transport Operation Category |
| UK | United Kingdom |
| VED | Vehicle Excise Duty |
| WFDC | Worthy Farm Drive Cycle |

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# Chapter 1 Introduction

## 1.1 Transport Decarbonisation and Retrofit

Transport systems are key components of thriving civilisations. They facilitate the mobility of people, goods and information; and in general, permit access to life's opportunities [1]. However, pollutants from transport systems in the form of greenhouse gases (GHGs), noxious compounds and particulate matter now pose an ever growing threat to the environment and to human health [2], [3]. Consequently, the transport sector is now at the top of many national decarbonisation agendas.

The task to decarbonise is exceptionally challenging, due to the complex nature of large systems. Making a change to one part of a system can easily result in an unintended consequence in another, for example, electric vehicles (EVs) may be introduced to help alleviate air pollution and climate change but sourcing of their raw materials (particularly for battery manufacture) may introduce new, problematic, supply chains [4], [5]. So, to improve upon any system, careful consideration of the interdependencies between its constituent elements is required. Accordingly, literature concerning transport decarbonisation often references a desire for stakeholders to adopt more systemic, integrated transport appraisal approaches and to probe unique solutions within their decarbonisation agendas [6], [7], [8], [9], [10], [11], [12], [13], [14]. This is seen as essential to efficiently decouple the provision of mobility from its emissions and to effectively appraise and integrate new transport decarbonisation solutions [15], [16].

One nascent transport decarbonisation solution is the production of low emission vehicles through retrofitting. Broadly, to retrofit means to "provide a machine with a part, or a place with equipment, that it did not originally have when it was built". This could be as simple as adding a case to a phone or as complex as adding central heating to a house [17]. In the context of transport, retrofit as a term spans many practices, from engine modifications to locomotives in the rail sector, hull adjustments to vessels in the maritime industry to installing avionic improvements within aircraft [18], [19], [20].

Within the academic literature, retrofit of vehicles, especially for decarbonisation is an under-researched topic. There is also not a consistent academic terminology for vehicle retrofit across the literature. For example, commercial vehicle retrofit is sometimes termed 'upcycling' whereas retrofitted classic cars are often named 'restomod's' [21], [22]; 'ecofitting' is used in reference to vehicle retrofit within the circular economy [23] and the term 'conversion' is also widespread [24]. The disciplines of business and economics have investigated vehicle retrofit under the themes of product longevity, or as a practice in the post-production economy [25]. Ultimately, all of these variations in language still relate to retrofit.

As alluded to previously, retrofit processes occur across a number of different types of vehicles, however, the justification of each retrofit is different, especially when considering if a vehicle is a capital or consumer good. Vehicles classed as capital goods are those which have a use case associated with the production of other consumer goods and services e.g., delivery vans, heavy goods vehicles, construction machinery and agricultural vehicles. Vehicles classed as consumer goods end up in the hands of end-users to satisfy current wants and needs e.g., typical private cars [26]. There are examples of retrofit for both category of vehicle however, generally, capital goods are more likely to be beneficiaries of ongoing retrofit processes rather than consumer goods as they are planned to operate over long life cycles to generate as much productive effort and revenue as possible as long as it makes economic sense to do so [27], [28]. Hence, retrofits are completed to capital goods for reasons including but not limited to improving efficiency, usability, complying with new regulations and/or increasing asset lifespan, but the retrofit process in many cases should pay for itself.

Although retrofit is less common for vehicles classed as consumer goods (e.g., private cars) a significant market has developed for retrofit of historic cars to EVs as a route for enthusiasts to achieve technological renovation of their vehicles [29]. This type of retrofit, in short, means to remove the existing powertrain of a vehicle, typically an internal combustion engine (ICE), and to replace it with an electric powertrain to produce a retrofitted EV whilst preserving much of the donor vehicle. Historic vehicle electrification through retrofit can reduce vehicle emissions, improve efficiency, performance, and acts to preserve the vehicle [30]. Retrofit of historic vehicles also allows for bespoke vehicle specification post-production whilst still gaining the benefits of a zero-emission electric powertrain. This form of retrofit is also not always conditional of practical economics with practitioners often charging customers large fees (see Table 17) [31] and this has arguably incentivised many new market entrants to this industry (see Table 7). For simplicity hereafter, the use of the term retrofit will only refer to EV retrofit unless otherwise stated.

### 1.2 Research Focus and Central Case Study

The focus of this research is on the appraisal of retrofit for transport decarbonisation through the analysis of the retrofit process applied to Land Rover Defender (LRD) vehicles within a central case study. Due to the context of the case study, the main sector of focus for this research is agriculture. Written evidence from DEFRA to a UK Parliamentary Committee in September 2019 suggests that agriculture accounts for 10% of the UK's total GHG emissions, 62% of which is produced by livestock, 28% via nutrient management and 10% from agricultural fuel use (from machinery and transport) [32]. Although a relatively low contribution of agricultural emissions are attributed to transport related sources, due to the popularity and wide application of LRD vehicles across many sectors, this vehicle (which often acts as a capital-good with a long life cycle) forms a useful representative ‘test-case’ with which to consider the opportunities to generalise this research of retrofit for decarbonisation into other sectors [33], [34], [35].

Since 1948, over two million LRD vehicles have been produced [34]. The vehicle has been described as a ‘workhorse’ and is often utilised/modified to perform a wide variety of functional roles across many sectors beyond agriculture including but not limited to electrical networks/utilities, construction, mining, breakdown recovery, military, safari, and emergency services [35]. Furthermore, the LRD has been reported to have been used for specific roles such as a mobile workshop, police vehicle, ambulance, fire engine, flatbed transporter, expedition/safari vehicle, and carriage for national park rangers. Note that despite these explicit functions, generally, the vehicle is used for all manner of general off-roading and can also function as a useful family vehicle [35].

The LRDs within the central case study are used as general off-road utility vehicles for assisting with day-to-day agricultural operations. The location of the case study is Worthy Farm (host to Glastonbury Festival) located in Pilton, Shepton Mallet, Somerset, England. Decarbonisation of the agricultural operations here has already begun (through the installation of renewable energy generating assets [36]), and the farm operators now wish to change focus to vehicle decarbonisation. Part of the motivation for transport decarbonisation through retrofit and its research at this this particular farm holding is the open sustainability commitments (values) of Worthy Farm, the potential fuel savings the farm holding could gain from retrofit and using its existing renewables and the fact that it has the desire to act as an innovator [37]. To assess the decarbonisation potential of retrofit at Worthy Farms vehicles, three of its LRDs were retrofitted by Electrogenic, the main industrial partner of this project funded as part of Innovate UK grant 80658.

Electrogenic currently delivers a wide variety of retrofitted vehicles for clients and is continuously developing more accessible retrofit kits [38]. The development of retrofit kits allows for the bulk purchase of components (driving economies of scale), retrofit standardisation, reduction in retrofit time, inclusion of warranties, and provision of installation services. One key objective for Electrogenic during this project was to develop a retrofit kit for the LRD which can be commercialised. As part of this development, they installed data acquisition equipment on the retrofits at Worthy Farm and granted access to acquired data for completion of this research.

It is worth noting that although it was potentially possible to have utilised another case study context for this type of retrofit research, the alignment of motivations and values between Worthy Farm, retrofitter (Electrogenic) and Cardiff University as an academic partner was a mutually beneficial opportunity that facilitated the completion of this particular work.

## 1.3 Research Objectives

This section describes the specific objectives of this research in relation to several gaps in knowledge of retrofit practice. The overall aim of the objectives is to help answer the following central research question:

**Can electric vehicle retrofit aid the decarbonisation of transport?**

To work towards answering this question in the context of the central case study, a number of factors need to be investigated including the following:

- Whether the retrofit of a LRD is comparable technologically, economically, and/or socially to full replacement with a second zero emission vehicle.
- The extent to which a LRD retrofit is a compromise (perceived or actual) over a full zero-emission vehicle replacement for decarbonisation.
- How this decarbonisation pathway will perform more broadly considering the policy context and scale of each tipping point in adopting retrofit for each vehicle type e.g., high value, capital goods or niche vehicles are more attractive to retrofit, whereas mass market cars are less attractive.

Considering the complexity of the factors outlined above in working towards an answer to the central research question, the following research objectives have been devised to direct the appraisal of retrofit:

1. Evaluate quantitatively the energy consumption of a retrofit, its donor ICEV and a new EV to determine how it compares technically to its donor vehicle or a new EV operating under a similar use case.
2. Estimate quantitatively the cost of the retrofit of one donor ICEV to determine if it is attractive economically (e.g., capital/operational cost) when compared to its donor vehicle or a new EV with a similar purpose.
3. Consider qualitatively and quantitatively the operational changes that may be required to better integrate retrofitted EVs into transport operations.
4. Consider how potential UK policy may benefit and/or hinder retrofit adoption more broadly as a transport decarbonisation pathway.
5. Estimate quantitatively the flow of embodied emissions between vehicles during retrofit and how this compares to new vehicle replacement.

To capture the intricacies of these research objectives, the methodology of this research utilises three perspectives of enquiry inspired by the Multi-Level Perspective (MLP) framework for analysing socio-technical transitions [39]. The three perspectives are presented across three technical chapters termed the “bottom-up perspective”, “middle-out perspective”, and “top-down perspective”. The chapters correspond to microscopic, mesoscopic, and macroscopic analyses of retrofit respectively through use of the central case study. The central aim of this methodological approach is for it to structure a holistic appraisal which is detailed further in Chapter 3. Furthermore, considering retrofit at different levels of abstraction could also indicate the scalability of any benefits of retrofit and/or challenges of scalability where results across the microscopic, mesoscopic and/or macroscopic investigations are less coherent.

It is noted that the focus on electrification through retrofit in this research has resulted in electricity being the predominant energy vector studied in this analysis. Although other energy vectors have decarbonisation potential, the sole focus on electricity is not seen as problematic as it is a mature, multi-modal transport energy vector with proven potential for scale deployment, and the potential for zero emission generation/significant emission reductions (any near term prospect of climate stabilisation can only be achieved with technologies proven to work at scale) [40], [41], [42]. Additionally, electrification is already being adopted significantly as a transport fuel within agriculture and food (i.e., AgriFood) [43], road (freight [44] and passenger [45]), rail and micro mobility [46], [47]. As a result, many vehicles are being developed and improved that support this transport fuel [48].

### 1.4 Thesis Structure

This thesis is organised into seven chapters. Chapter 1 introduced transport decarbonisation, retrofit and the objectives of this research. Chapter 2 provides a review of transport system emissions, their quantification, monitoring, and reporting; further detail on agricultural transport to give context to the central case study, a review of differing vehicle retrofit methods and the retrofit market. Chapter 3 details the research methodology and commentary on each of the technical chapters' methodological approaches. Chapter 4 evaluates the retrofit from the perspective of an individual LRD beginning with an analytical exploration of retrofit at the component level. This analysis is followed by an investigation of an original LRD, new EV, and retrofit LRD energy consumption and emissions through simulation and use of primary data. This leads onto an economic evaluation focused on the same vehicles. The chapter concludes with the presentation of a concept retrofit tool that could aid with the commercialisation of retrofit.

Chapter 5 investigates the integration of LRD retrofits into existing operations at Worthy Farm. It focuses on exploring the relationship between the retrofits, their charging infrastructure, the farm energy system, and its operations through use of an agent-based model (ABM). The model explores the use of the retrofitted LRDs under different scenarios including an examination of the effects of varying their installed battery capacity. Chapter 6 considers the impact of retrofit as a broader transport decarbonisation policy measure. Specifically, the potential for a retrofit policy to influence the flow of embodied emissions within a stockpile of vehicles to landfill. This is accomplished through use of a combination of life cycle assessment (LCA) and system dynamics (SD) methods. Chapter 7 contains a final discussion, concluding remarks and potential future work.

# Chapter 2 Literature Review

## 2.1 Introduction

This chapter aims to provide a review of the literature necessary to further contextualise this research. First a general introduction to transport emissions is provided. This is followed by an overview of the current methods of transport emission quantification, monitoring, and reporting comprehended through an analysis of international standards. This also covers processes for demarcating a transport system boundary. Next, agricultural transport is outlined in further detail to provide context to the central case study. This chapter concludes with an overview of retrofit methods across different transport modes, and an outline of the wider retrofit market.

## 2.2 Transport Emissions

To fully comprehend the potential of retrofit for transport decarbonisation, it is necessary to consider the emissions from transport in general, and to provide justification as to why they need to be abated. Transport systems emit GHGs which include carbon dioxide ($CO_2$) into the atmosphere. Global concentrations of $CO_2$ and other GHGs are measured in parts per million (ppm). $CO_2$ has an overwhelming causal relationship with global temperatures [49]. Analysis of planetary data sources has demonstrated that atmospheric $CO_2$ levels have fluctuated in a recurrent pattern between 180 parts per million (ppm) and 300 ppm for the last two million years [50], [51]. Global atmospheric $CO_2$ concentrations have now surpassed 419 ppm (February 2022) with carbon dioxide equivalent ($CO_2e$) concentrations now estimated to have surpassed 500ppm [52], [53]. These quantitative markers mutually establish that the contribution of anthropogenic emissions has led to this high ppm of $CO_2$, not previously observed in modern times. It is now almost universally accepted that humanity has an ethical responsibility to rapidly alleviate anthropogenic emissions to benefit future inhabitants of this planet through curbing any associated temperature rise, improving air quality and mitigating other knock on impacts of environmental degradation [54].

Transport systems globally, directly emitted 8 $GtCO_2$ in 2022, with this figure falling only to 7.2 $GtCO_2$ during 2020, a year of unprecedented reduction in global transport usage as a result of COVID-19 [55], [56]. The emission trend for transport has veered almost entirely upwards since 1975 despite technological innovation and improved transport system efficiencies [57]. Within the UK, transport system emission reductions through system improvements have been opposed by increased transport system usage and a sustained modal shift to the automobile [58]. Regulatory progress in the UK to support emission abatement has been perceptible. The Climate Change Act of 2008 [32] formed an emblematic step to creating legally binding Carbon Budgets to push the UK into a low emission age; however, these budgets are ultimately non-prescriptive [59], [60], [61].

More recently, the UK has released its transport decarbonisation plan which sets out a more detailed, but still high-level approach for transport emission reduction; more specific proposals include a phase out date for new petrol and diesel cars along with a consultation on a phase out of combustion engine heavy goods vehicles (HGVs) [8], [62], [63], [64]. Despite regulatory announcements, the UK transport system still comprises a quarter of national emissions. Transport is now firmly the largest emission source within the UK. Figure 1 shows the change in sectoral UK emissions since 1990 and Figure 2 displays the change in transport emissions in $CO_2e$, by mode, from 1990 to 2019, distinguishing clearly between domestic and international emissions.

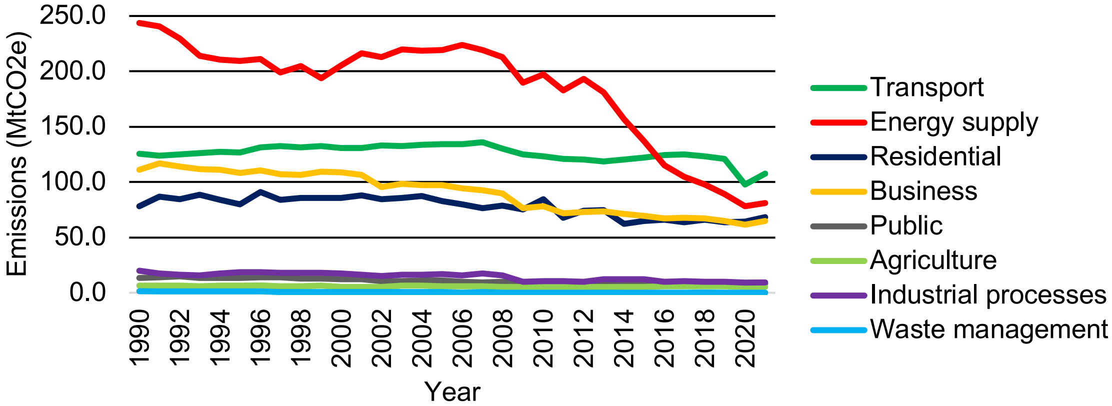


Figure 1: UK territorial GHG emissions by source (1990-2021) adapted from [27].

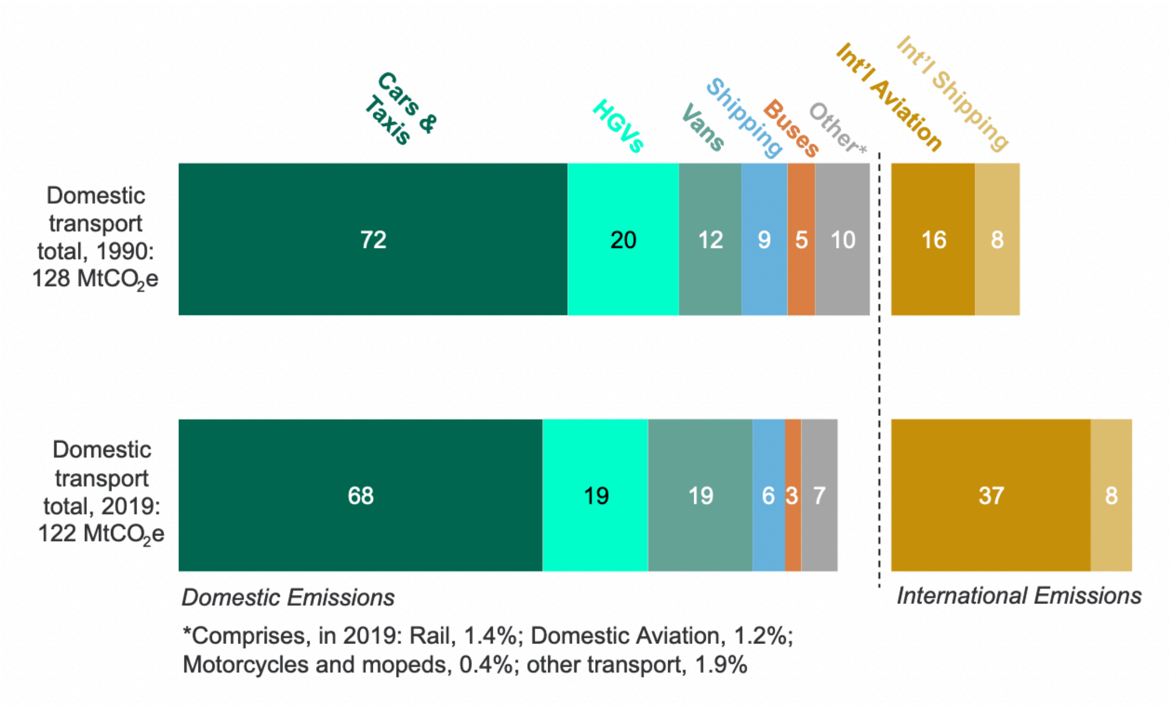


Figure 2: Change in UK transport emissions from 1990 to 2019 [57].

As shown, the automobile makes up the majority of domestic transport emissions (56%), and road-based transport comprises almost all domestic emissions (90%). Two notable sectors experiencing emissions growth between 1990 and 2019 in percentile terms are found to be vans (7%) and international aviation (21%). For aviation, this is likely due to continued growth in passenger air travel along with increased demand for international freight. Growth in van emissions could potentially be caused by recent under regulation in the sector when compared to HGVs and favourable tax incentives that have also led to an increased number of van purchases [65]. Last mile delivery and online shopping are also potential sources of van emissions growth with this style of delivery becoming increasingly popular since COVID-19 [66].

Although growth of emissions in the van/aviation sectors is problematic, the stagnation of emissions reductions in the car/taxi sectors is perhaps more concerning. In 1995 the average new passenger car in the UK produced 191g of $CO_2$ per km and significantly more air pollutants; the target for passenger cars from 2020 was 95g of $CO_2$ per km as a fleet average. This is a targeted per vehicle reduction of more than 50%, yet total emissions reductions for cars and taxis over 30 years is only 5.6%. According to [57] and [58], technological gains in efficiency have been dependably countered by the purchase of higher mass vehicles (particularly from the sport utility vehicle market segment) and the growth in higher transport mileages per passenger. Ultimately, these increases in land transport use and energy intensity per vehicle has sustained the sectors emission intensity. These emissions continue to cause negative consequences such as climate change, urban air pollution, and environmental degradation [67].

As mentioned, effects on global temperature only form a part of the motivation to decarbonise transport. Transport also forms a significant source of air pollution in the form of gaseous substances and particulate matters, often localised to urban population centres. Pollutants are directly emitted from exhaust gases, but particulate matter is also produced during vehicle braking actions and tyre abrasion [68]. Particulate matter is typically classified into larger 10 µm and smaller 2.5 µm particulates. The most prominent gaseous pollutants include nitrogen oxides, sulphur oxides, carbon monoxide, and non-methane volatile organic compounds [57].

The Department for Environment Food and Rural Affairs notes ten main sources of air pollution (particulate matter, oxides of nitrogen, ozone, sulphur dioxide, polycyclic aromatic hydrocarbons, benzene, 1,3-butadine, carbon monoxide, lead, ammonia) of which transport contributes to six (particulate matter, oxides of nitrogen, polycyclic aromatic hydrocarbons, benzene, carbon monoxide, ammonia) and is a major contributor to five of those six sources (particulate matter, oxides of nitrogen, polycyclic aromatic hydrocarbons, benzene, carbon monoxide) [69]. The effects of air pollutants on human health are widespread and significant. At elevated levels, nitrogen oxides, sulphur oxides, and ozone can irritate airways and elevate symptoms for sufferers of respiratory diseases. Particulate matter can cause lung inflammation and carbon monoxide reduces oxygen supply to the heart. Curbing these pollutants from transport is likely to result in a significant reduction in human mortality, especially for inhabitants of densely populated urban communities [70]. The World Health Organisation and European Environment Agency now describe air pollution as the world's largest single environmental health hazard [71], [72].

Since 1990 there have been significant reductions in the most prominent gaseous pollutants in transport, namely carbon monoxide, benzene, butadiene, lead, and sulphur oxides. This is highlighted in Figure 3. One reason reductions in these emission classes has been achieved more easily is that more significant regulatory interventions including but not limited to the removal of lead from petrol, the introduction of the catalytic converter, advances in particulate filtration and smart engine control systems have been introduced [73].

The elimination of particulate matter and nitrogen oxides has been more problematic. This is potentially due to the recent rise in popularity of the diesel powertrain, though this trend is now being countered as EVs and hybrids replace diesel vehicles. As the penetration of EVs continues to increase, the reduction in non-exhaust particulate matter will likely continue due to a reduction in brake pad usage as a by-product of electric powertrain regenerative action [74]. The reduction in particulate matter is however likely to be smaller than the reduction in nitrogen oxides from the adoption of electric powertrains [75].

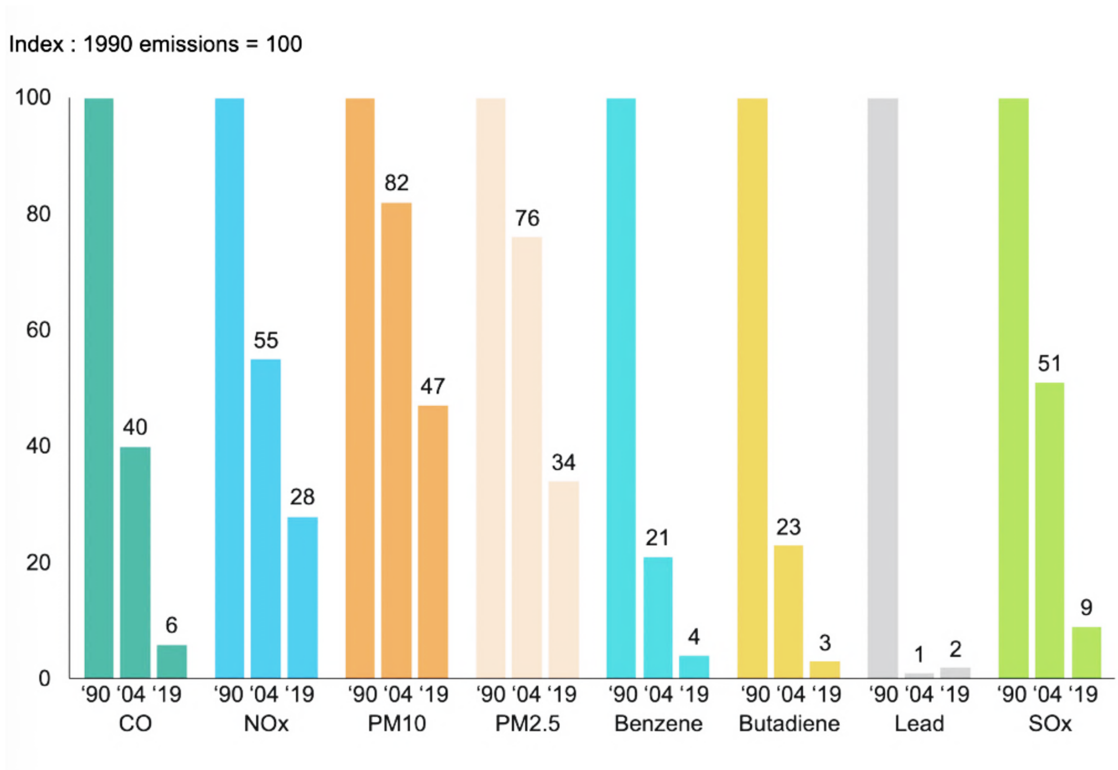


Figure 3: Transport pollutant emissions 1990-2019 [57].

### 2.3 Quantifying, Monitoring, and Reporting Transport Emissions

From the previous section it is clear that abating transport emissions is vital to tackle a number of ever worsening environmental harms and impacts on public health. This decarbonisation of transport will likely require many methodological approaches. The aim of this research is to complete an appraisal of one approach, the under researched methodology of vehicle retrofit. To assess the impact of retrofit on transport system decarbonisation, the methods of quantifying, monitoring, and reporting transport emissions need to be understood. There are many designs of transport system and thus defining the system boundary in which emissions are investigated is difficult. The system boundary also remains dynamic as any one system evolves over time. Stakeholders should consider emissions throughout any transport system's life cycle from its manufacture, installation, maintenance, and subsequent decommissioning. Ideally, quantifications should also endeavour to include embodied carbon in calculations, and to reduce approximations where possible. Furthermore, all stakeholders, need to 'count' in the same way, so there has to be an adoption of standards for quantification monitoring and reporting worldwide. Some international standards are covered in the next section. As a simplistic representation, Figure 4 reproduced from the Fifth Assessment Report from the Intergovernmental Panel on Climate Change. It represents the factors contributing to total transport system emissions. This is sometimes also referred to as the activity-structure-intensity-fuel type model. An example of an emissions quantification involving these factors is provided within Section 2.3.3.

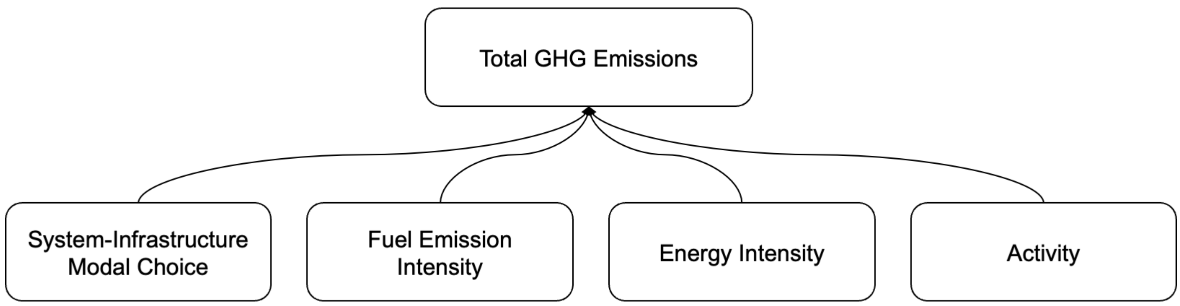


Figure 4: Total transport system emissions, reproduced from [76].

#### 2.3.1 International Standards

There are a number of commonly used procedures to account, monitor, report, and conduct mitigative planning for GHG emissions, and these methods are continually evolving. Widely used are the international standards generated by the International Organisation for Standardisation (ISO). These cover the carbon footprints of organisations (ISO 14064), products (ISO 14067) and transport chains (ISO 14083) to name a few. The GHG Protocol is another widely used procedure documenting how emissions can be mitigated at the corporate, organisational and project level [77]. A comprehensive list of standards relating to emissions and transport are contained in Appendix A. The standards included range widely in scope, year of creation, and crossover in remit. Early standards have tended not to have been particularly prescriptive. Newer standards have more detail, but methods of quantification still rely on estimations. Furthermore, embodied emissions are underrepresented [78]. These standards are however useful as they:

- Simplify the widespread adoption of emissions accounting, monitoring, reporting, and planning procedures which are fundamental in mitigating climate change.
- Provide definitions for common terminology and a foundation for interoperability between stakeholders' emissions data.
- Allow for emissions to be documented from multiple perspectives e.g., emissions from the transport chain perspective, emissions from the perspective of an organisation using transport, and emissions of a product where transport is used within its supply chain.
- Provides a common set of documentation that can be continually improved and that attempts to show the state of the art.

However, standards always need to strike a balance between specificity and flexibility. Specificity can produce barriers to adoption or development. Flexibility can result in an ineffective foundation upon which to build interoperable standards. ISO in particular provides 'families' of standards which have relations to one another. The ISO 14060 family relate to each other as shown in Figure 5. Providing a family of standards is important as it allows for separate development of for example, quantification methods, reporting methods, validation methods, competency requirements etc.

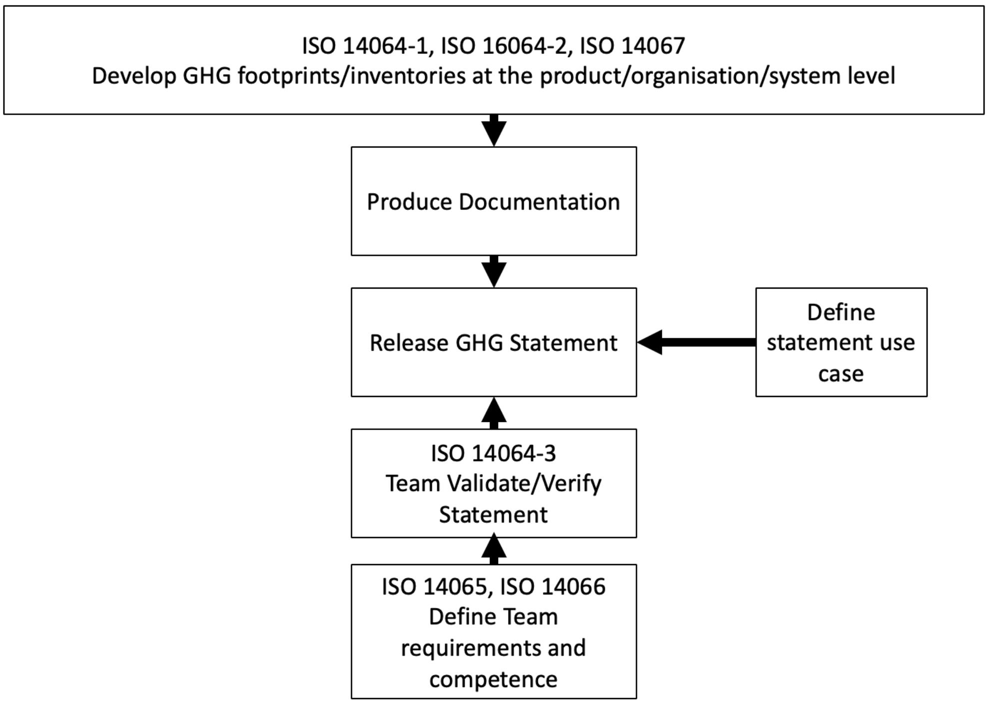


Figure 5: Relationships among the ISO 14060 family, redrawn and simplified from [18].

### 2.3.2 System Boundaries

For any given transport system, the definition of its system boundary is an essential component within which to assess its emissions. Boundaries need to be defined concretely but with an ability to change over time as the system develops [79]. Care must be taken to define nested boundaries which may fall under separate stakeholder remits e.g., national level transport system emissions which contain an aggregation of smaller transport sub-system emissions. The desired level of detail of a system boundary will vary depending on the goals of emission quantification. The more granular a system boundary is, the more confidence can be attributed to the results of any quantifications.

One standard which has codified the use of system boundaries and nested sub-system boundaries is the LCA methodology in ISO 14040. LCA is directly applicable to the study of transport emissions and has been used in several previous studies [80], [81]. Figure 6 contains an example of how a system boundary of a product is defined for an LCA.

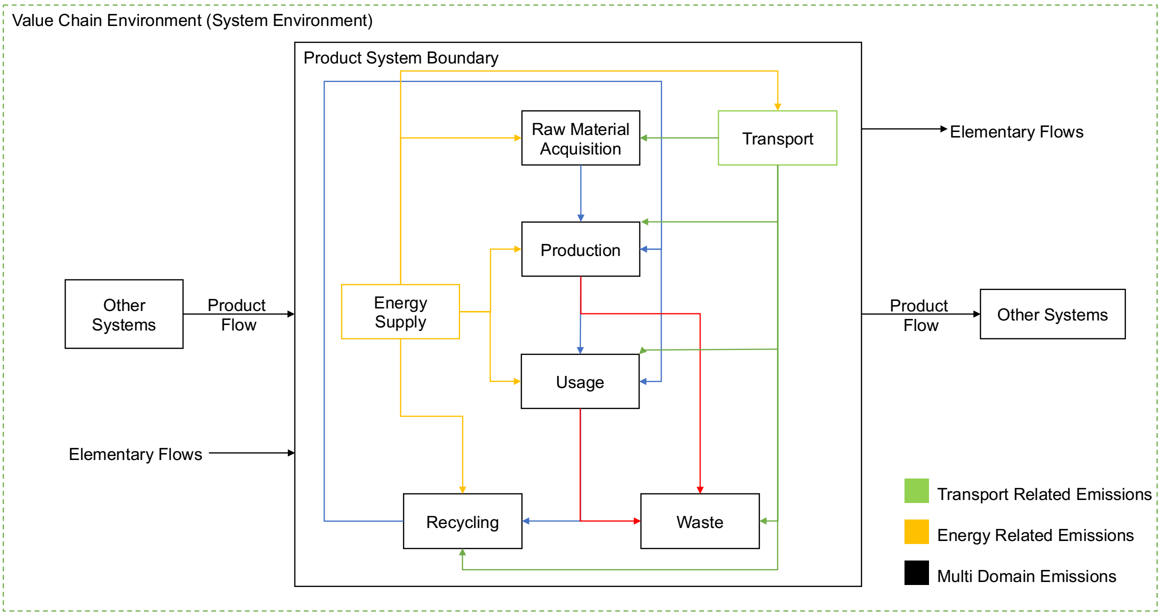


Figure 6: Assessing product emissions via the LCA method [82], [83].

From the diagram, it can be seen that for any whole system boundary, it can be comprised of a collection of nested sub-systems with their own independent boundaries. The boundaries of these sub-systems are connected via flows (in this case **product flows**) which define resources entering or leaving from or going to/entering other sub-systems. The activities of each sub-system are supported by **elementary flows** which are defined as material or energy entering or leaving a system boundary that are directly drawn/expelled to/from the environment without transformation.

Within a sub-system there are **intermediate flows** (coloured arrows) enabling the transfer of material, energy, or product between **unit processes** (boxes within the/a product sub-system boundary) which are the smallest elements considered in an LCA for which input, and output data is quantified. Any product flows between unit processes are termed **intermediate products** [82].

Transport system boundaries also often cross over organisational structures which utilise transport systems as part of their processes e.g., freight operations as part of a product/service value chain. Transport emissions can often be quantified from the perspective of:

- Organisations (ISO 14064) as a function of their transport usage.
- Products (ISO 14067) whose value chains utilise transport.
- Transport system operators (ISO 14083).

Figure 7 helps to demonstrate this cross over, its green lines form an indication of how transport system boundaries interact, and the blue lines show where the LCA standards could overlap. In many cases, multiple quantifications/reports on emissions could be associated with the same transport system.

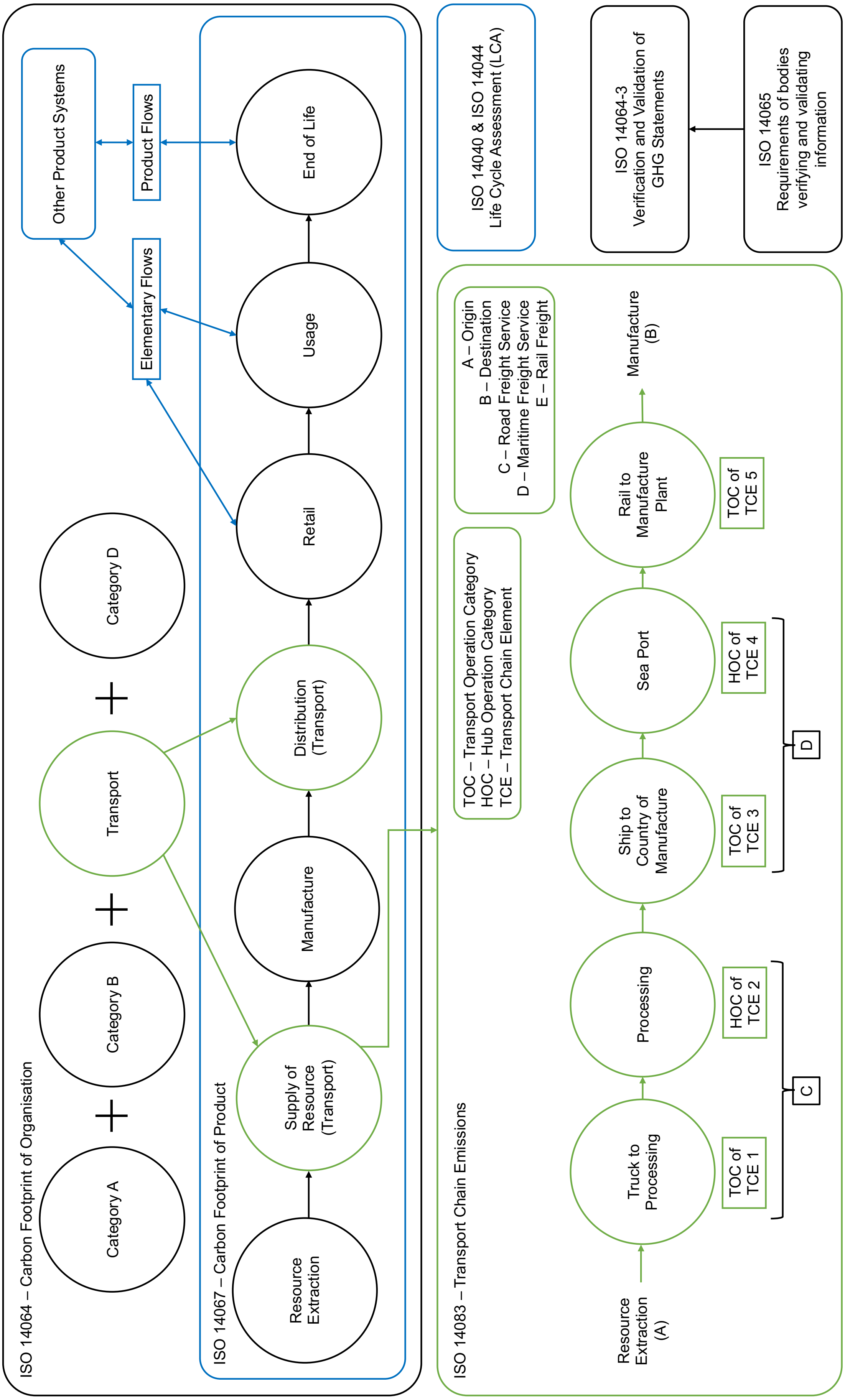


Figure 7: Standards overlap, reproduced and simplified from [84].

### 2.3.3 Quantification

In simple terms, transport system emissions are often referred to in terms of a mass of $CO_2e$. For any system they are calculated as a product of the system's material/energy flows and the flow's associated emission factors. Material flow is typically measured in kg per functional unit, and energy flow in litres for liquid fuel, $m^3$ for gases, and kWh for electricity. The associated emission factor is provided in terms of a per unit per mass of $CO_2e$ e.g., $kgCO_2e$/litre. Emissions factors can be found from various sources e.g., the Intergovernmental Panel on Climate Change in [85] or in [86] for the UK in 2021. Other data sources also exist with similar statistics [87]. Flow quantities are calculated from system activity data. Details of emission factor data sources are discussed later in this section [88], [89]. However, as discussed previously, systems can take many forms and thus utilise many types of assets. So, the aim of quantification is to convert all possibilities of individual emission types and quantities to common comparable values.

Once a transport system is designed and commissioned, direct (operational) emissions are produced through the operation of its elements as a function of their activity levels. These activity levels are combined with associated emission factors. Activity driven emissions typically result from transport fuel consumption and associated indirect effects. The emission intensity of a fuel (well to tank) includes emissions from its extraction and cultivation. For fossil-based transport fuels this can include refining, transforming, transporting, and distributing the fuel. For electricity, this typically consists of power generation, transmission, and associated losses. An example of an indirect effect is radiative forcing in aviation, these also must be quantified as the fuel is combusted [90].

Beyond activity, the consumption rate of a transport fuel is another consideration. The rate of consumption is related to the energy intensity of a transport asset e.g., the miles per gallon fuel consumption of a vehicle. All these values combine to form a well to wheel emission value. It is useful to have this per unit mass/passenger value as certain transport systems can exhibit large overall energy usage e.g., an electric train, but have very low per unit energy consumption i.e., per passenger.

When considering data sources, primary data is typically the most sought after. If primary data is not available, secondary data should be used i.e., through contacting a manufacturer. If secondary data is not available, data should be produced using modelling approaches, if modelling is impractical, some default data sources exist for emission intensity values for certain transport assets [91]. Emission quantifications often utilise many estimations/approximations. Estimations could be informed by average travel patterns so individual behaviour in a particular transport system can deviate significantly from a published average. Assumptions also negate day to day variability e.g., vehicle ages, traffic volumes (congestion) and weather (temperature).

According to ISO 14083, emissions (gaseous or particulate) within a transport system that should be quantified are: all vehicle operations; transport hub operations (for example storage/hosting passengers/re-packing freight); energy carriers utilised and consumed; both loaded and empty trips (return journeys are important i.e., for taxis or logistics); start-up/idling energy consumption of vehicles; cleaning/flushing of equipment; waste production/treatment/recycling; data equipment indirect emissions (as they facilitate system operation); the construction, service, maintenance, upgrading and decommissioning of transport assets. Processes to exclude during quantification include co-located business/organisational operations within a transport system boundary, and often, administrative related transport should also be excluded i.e., employee commutes (frequently this is from the perspective of a transport operator). This is due to the variety and uncorrelated nature of these emission sources. Note that in general it may be impractical to include all processes for quantification, but efforts should be made to be as specific as possible.

To systemise quantification, ISO 14083 utilises a method to analyse Transport Chains (TCs). These are made up of constituent transport chain elements (TCEs). These elements are made up of transport operation categories (TOCs) or hub operation categories (HOCs). To compute the emissions of a TOC or HOC, their total activity is multiplied by an appropriate emission factor. TOC/HOC emissions are them summated to compute their parent TCE emissions. TCE emissions are then summated to determine the total emissions of the TC. Activity data is typically provided as a product of mass/passengers transported and distance i.e., tonne kilometre.

When defining TCEs, TOCs and HOCs certain transport assets are less obvious but could be considered e.g., pipelines, short term assistance vehicles (tugboats), and vertical transport (elevators). The desired level of data granularity when computing a TCs emissions must also be actively considered e.g., if fleet operations are found to exhibit large levels of homogeneity in terms of their emissions, then a more simplified TOC could be acceptable.

To further explain quantifications in line with ISO 14083, consider the following hypothetical TC which consists of an airport terminal operating a flight whose passengers arrive via a single rail line. The rail line facilitates the operation of a diesel electric shuttle train from a nearby city centre. Figure 8 contains a depiction of the TC for this example where A and B represent the TC origin and destination respectively.

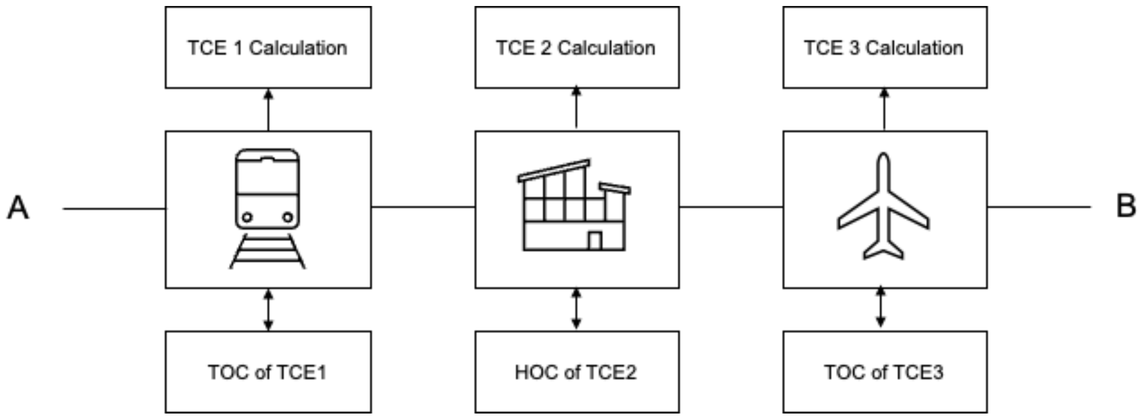


Figure 8: Simplified TC airport example.

The TC for this example contains two TOCs: the movement of passengers via rail and the movement of passengers via aircraft. The TC for this example contains one HOC: activities within the airport boundary.

Quantification of emissions in this example is from the perspective of the transport operator and is over a period of 12 months. Table 1 and Table 2 contain datasets for relevant TOCs and HOCs. Calculations are for indicative purposes only and quantification in this example could have been conducted differently e.g., inclusion of transport class, baggage mass, alternative airport activity, or trains of another category e.g. bi-modal [92].

Table 1: TOC example data.

| **Type** | **Capacity (passengers)** | **Load Factor (%)** | **Trip Distance (km)** | **Annual Trips** | **Emission Factor (kgCO$_2$e/passenger.km)** |
|---|---|---|---|---|---|
| Rail | 250 | 30 | 10 | 5840 | 0.03549 |
| Aircraft | 180 | 75 | 600 | 1460 | 0.24587 |

Table 2: HOC example data.

| **Type** | **Annual Electricity Consumption (kWh/m2)** | **Airport Terminal Area (m2)** | **Emission Factor (kgCO$_2$e/kWh)** |
|---|---|---|---|
| Airport | 1.83 | 207000 | 0.21233 |

**Calculating emissions of TCE 1 and TCE 3**

Equation 1 describes how emissions $G$ from transport asset $X$ conducting activity (i.e., a single trip) $Y$ is a product of its emission factor $ef_{X,Y}$ and the sum of its individual passenger or freight activities. Individual activities are computed by multiplying the number of passengers $pax_X$ or mass $M_X$ transported on asset $X$ by the distance $D_X$ .

$$G_{X,Y} = ef_{X,Y} \cdot \left[\sum pax_X \cdot D_X \ \text{ or } \ \sum M_X \cdot D_X\right] \tag{1}$$

$pax_X$ is calculated by multiplying transport asset capacity by its load factor. $M_X$ is not used in this example. $D_X$ is calculated by multiplying the single trip distance associated with a transport asset by the number of trips it makes.

Therefore:

$pax_{TCE1}$ = 250 · 0.3 = 75 passengers $D_{TCE1}$ = 10 · 5840 = 58400km

$pax_{TCE3}$ = 180 · 0.75 = 135 passengers $D_{TCE3}$ = 600 · 1460 = 876000km

$G_{TCE1} = pax_{TCE1} \cdot D_{TCE1} \cdot ef_{TCE1}$ = 75 · 58400 · 0.03549 = 153t$CO_2$e

$G_{TCE3} = pax_{TCE3} \cdot D_{TCE3} \cdot ef_{TCE3}$ = 135 · 876000 · 0.24587 = 29kt$CO_2$e

**Calculating emissions of TCE 2**

Equation 2 represents hub emissions as a function of hub activity.

$$G_{hub} = \sum_i (Q_X \cdot ef_X) \quad (2)$$

Where $G_{hub}$ is total emissions from hub activities, $Q_X$ is the quantity of each GHG activity type X e.g., electricity could be $Q_{elec}$ and $ef_A$ is the emission factor of activity type X.

$Q_{elec}$ = terminal area · electricity consumption per $m^2$ = 378810 kWh

$G_{hub} = Q_{elec} \cdot ef_{elec}$ = 378810 · 0.21233 = 80 t$CO_2$e

**Calculating total emissions**

$G_{TC} = \sum_i (G_{TCE_i})$ = TCE1 + TCE2 + TCE3 = 152 + 80 + 29000 = 29233 t$CO_2$e

### 2.3.4 Monitoring and Reporting

The main monitoring and reporting requirements for emissions in the UK are set out in the Environmental Reporting Guidelines of [93] which centres its guidance on streamlined energy and carbon reporting. This document builds upon a number of previously existing programmes covering energy/carbon reporting and taxation. Streamlined energy and carbon reporting specifically was introduced in April 2019 and was developed on the back of The Company's Act 2006, Companies (Directors' Report) and Limited Liability Partnerships (Energy and Carbon Report) Regulations 2018. Streamlined energy and carbon reporting requirements mandate that all large businesses to report carbon emissions in their annual reports/accounts (this was originally only a requirement of FTSE Main Market Companies).

Reports by businesses must be relevant, quantitative, accurate, complete, consistent, comparable, and transparent. In terms of transport emissions, reports must “include the annual quantity of energy consumed from activities for which the company is responsible, involving the consumption of fuel for the purposes of transport (as well, as above, from the purchase of electricity for its own use, including for the purpose of transport)” [93]. Note that this consumption of fuel must be purchased directly by the organisation, not indirectly. The transport journey must start, end, or start and end in the UK.

Streamlined energy and carbon reporting builds on the energy savings opportunity scheme, part of the European Union (EU) Energy Efficiency Directive 2012/27/EU. It requires large organisations to undertake mandatory monitoring and reporting of their energy use and energy efficiency opportunities once every four years. However, the energy savings opportunity scheme, under the UK’s new ambition for Net Zero needed replacing as it could not “be relied upon to generate the scale of carbon savings year on year” to mitigate climate change [94].

Streamlined energy and carbon reporting replaces the UK’s mandatory GHG reporting requirements. If a business qualifies, they must report UK energy use and associated GHG emissions relating to gas, electricity, and transport, as well as an intensity ratio, and information relating to energy efficiency action, within their annual reports (unless less than 40MWh of energy is consumed which makes disclosure less detailed). Penalties are not finalised for non-compliances but are likely to be substantial [94].

To successfully monitor and target lower emissions, tools such as Science Based Targets, Supply Chain Footprinting and ISO 14001 are often utilised. The Quality Assurance Standard also provides advice on approved carbon offsetting. For businesses bidding for government contracts (more than £5 million per annum), they must follow the Net Zero Carbon Procurement Policy and the procurement policy note 06/21 as of September 2021. This requires annual reporting of Scope 1, Scope 2, and some Scope 3 emissions, a Net Zero 2050 commitment and the construction of a carbon reduction plan. This can involve standards such as PAS 2060 and the plan must be disclosed publicly [95].

For context, Scope 1 emissions are GHG emissions that an organisation makes directly e.g., from running their vehicles, Scope 2 emissions are indirect organisational emissions e.g., from energy purchased for heating and cooling buildings, Scope 3 emissions are all emissions associated, not with the organisation itself, but that the organisation is indirectly responsible for, throughout its value chain e.g., buying products from its suppliers, and from the utilisation of products purchased by its customers [96].

### 2.4 Agricultural Transport

Written evidence from DEFRA to a UK Parliamentary Committee in September 2019 implies that agriculture accounts for 10% of the UK's total GHG emissions, 10% of which is attributable to agricultural fuel use i.e., agricultural transport and machinery accounts for approximately 1% of UK GHG emissions [32]. This is similar to the EU 27 where agricultural machinery and vehicles have been estimated to account for approximately 1% of emissions [97].

Although this contribution to national GHG emissions is relatively small, the challenge this sector faces in terms of transport emission abatement is high [98]. According to the Royal Agricultural Society of England "it is highly likely that … farm vehicles powered by internal combustion technology will remain in use on farms up to 2040 and beyond" [99]. This gap in knowledge and practice on how to abate agricultural transport emissions is important and overcoming the challenge could help analogous sectors e.g. construction. Current reasons for low emission abatement include but are not limited to a dependence on commercially available mitigation technologies; a current lack of cost effective, low carbon, vehicular solutions; no presence of incentives or critical challenges to implement solutions and high up-front investments for decarbonisation by farmers [98].

Farm business performance in the UK has changed very little since 2009/10 and net profits on average are small, this limits scope to decarbonise [100]. In terms of transport asset improvements, the 2018 Farm Business Survey indicates that in the 2017/18 financial year the average expenditure per farm on machinery (for those farms undertaking transactions) was £18100 and £10100 was spent on new or used cars, motorcycles, all-terrain vehicles, vans, or trucks, respectively [101]. This suggests that in terms of purchasing new, off the shelf, zero emissions vehicles (if they are available), a significant proportion of farms will not possess the capital in any one year to purchase, for example, a new EV at an average price of circa. £43000 (in 2022) [102].

Generally, the purpose of an agricultural transport system is to provide mobility for a variety of agricultural duties such as soil cultivation, planting, fertilizers/pesticide dispensing, irrigation, produce sorting, harvesting, post-harvest processing, hay making, loading, milking, animal feeding etc. In many cases vehicles, machinery and assets are multipurpose, used for varying time periods, and vary in size/cost in proportion to the size of the agricultural operation [103]. Large agricultural operations can justify the expense of purchasing larger, more specialist, less adaptable vehicles such as large, dedicated combine harvesters. The variation in operations in the sector leads to the use of many vehicle types and an increased difficulty in providing decarbonisation solutions [104]. This diversity of vehicles and use cases has positive implications for generalising findings of this research to other vehicles.

The Driver and Vehicle Licensing Agency (DVLA) determines UK licence categories [105] and has provided categories typically used for specialist vehicles in agriculture which can be found in [106]. Statistics on these licencing categories can provide some indication as to the number and types of vehicles operating in the agricultural industry, however this does not extend to more generic farming equipment such as general purpose four-wheel-drive vehicles as these are captured under car driving licence categories.

Overall, the challenges faced by this sector in terms of emissions abatement indicate that research into alternative decarbonisation pathways such as retrofit is required e.g. to potentially reduce vehicle decarbonisation cost to overcome economic challenges. Moreover, the focus on LRD retrofit in this study is advantageous due to the varied use cases of the vehicle model historically (as previously outlined in Section 1.2) and its popularity. This makes the study of the vehicle representative enough that research outputs could be replicated in other sectors. Overall, the study of the retrofit of this vehicle in the agricultural context forms a good exploratory project upon which to consider broader applications of retrofit as a practice.

### 2.4.1 Agricultural NRMM and Vehicles Declared SORN

Two important vehicle designations which are often used within the agricultural sector are non-road mobile machinery (NRMM) and vehicles with a statutory off-road notice (SORN). Vehicles classified as NRMM or SORN are not driven on public roads, do not require insurance, an MOT, are exempt from vehicle excise duty (VED) and can often utilise red diesel as a fuel. Also, NRMM assets in particular are often quite long lasting and as such, at the time of asset manufacture, not subject to emissions standards. As noted in [107] "*there are considerable numbers of older, 'legacy' equipment which have high emissions because* [they were] *subject to less stringent or no emission standards".* This is difficult to rectify through asset replacement as NRMM is a capital good with potentially long-life cycles. Figure 9 contains qualitative estimates for NRMM life cycles and shows that around 25% of NRMM is estimated not to be replaced for at least 10 years [108].

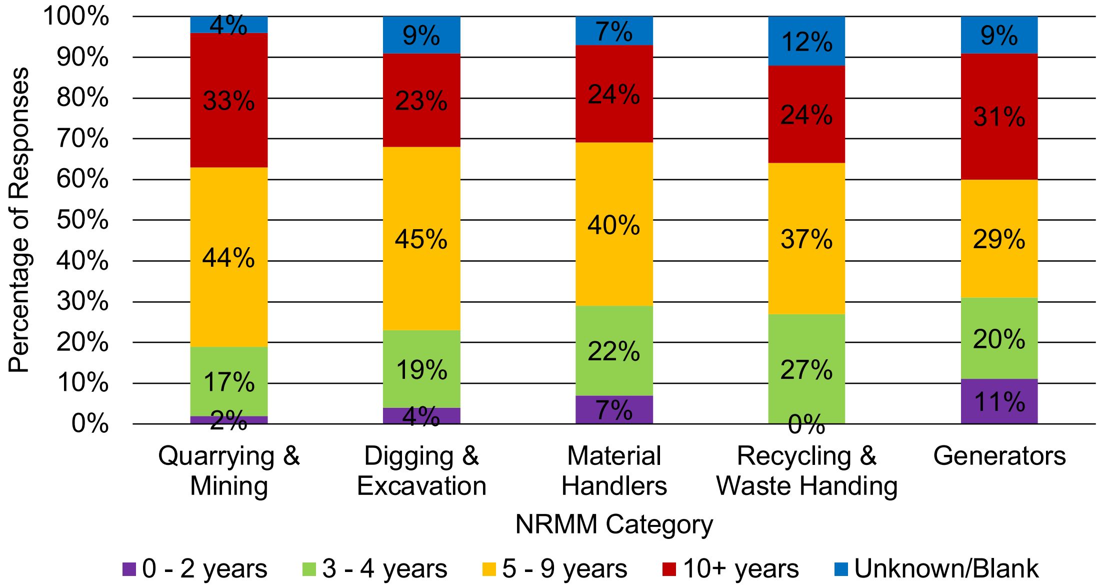


Figure 9: NRMM expected life cycles (qualitative study) reproduced from [108].

Similarly, a 2004 report commissioned by the Department for Transport contains data on NRMM populations (though these figures are now likely inaccurate). Data on tractors and combines is presented in Table 3.

Table 3: NRMM data in agriculture, reproduced from [109].

| NRMM Type | Average Power (kW) | Population (units) | Annual Usage (hours/year) | Life cycle (years) |
|---|---|---|---|---|
| Tractors | 78 | 239344 | 812 | 11 |
| Combines | 75 | 12636 | 332 | 7 |

Work in [110] has stated that "*new policy to regulate GHG emissions from NRMM is urgently needed*". New regulation must also not allow in service NRMM to subvert requirements [111]. Table 4 provides a non-exhaustive summary of NRMM asset examples across a multitude of sectors.

Table 4: Typical examples of NRMM sectors utilising red diesel [109].

| Sector | Description/Examples |
| --- | --- |
| Aviation | Aircraft tugs, stairs, luggage conveyor belts. |
| Agriculture | Tractors, combines, shredders, all-terrain vehicles. |
| Construction | Rough terrain forklifts, access platforms, welding equipment, air/gas compressors, wheeled loaders, industrial tractors (not for agriculture), cranes, concrete pavers, surfacing equipment, concrete saws, crawler tractors, asphalt pavers, paving equipment, bore/drill rigs, skid-steer loaders, crushing/processing equipment, tracked loaders, graders, scrapers. |
| Forestry | Woodchippers, stump grinders. |
| Groundwork Contractors | Backhoe loaders, mini excavators, wheeled excavators, crawler excavators, rigid/articulated dump trucks, bulldozers. |
| Haulage | Auxiliary power plants, e.g., providing refrigeration, or driving a concrete mixing drum. |
| Generators | Providing portable onsite power for outdoor events, street market traders, funfairs, construction sites etc. |
| Logistics and Freight | Ports, rail terminals, other sites handling shipping containers; warehouses, distribution hubs. |
| Machinery Installers | Installers of manufacturing plant or electrical turbines. |
| Manufacturing | Works trucks moving materials around a site. |
| Maritime | Maritime vessel and inland waterway vessel operators. |
| Property | Grass mowing and using elevating work platforms. |
| Quarrying and Mining | On site transport operations. |
| Rail | Motive power for freight and passenger trains. |
| Waste | Transport to handle and recycle. |

Although NRMM decarbonisation and/or retrofit is not explicitly tackled in this research (as its focus on LRDs) it is worth noting their significant estimated contribution to UK GHG emissions of 2.7% [112], long life cycles and the fact that these assets also often utilise red diesel. Red (i.e., rebated) diesel is functionally the same as conventional diesel, but it is taxed at a lower rate and hence acts as a subsidy. According to the UK government, red diesel makes up 15% of total diesel use and is often used by NRMM in the sectors of agriculture, fishing, forestry, horticulture, and construction [107]. The use of the red diesel is tracked broadly (through tax refunds post usage), however it is not possible to determine at a granular level the types of assets using the fuel. This leads to uncertainty in quantifying emissions attributed to red diesel. During the UK's 2020 budget it was announced that the use of rebated fuels would be further restricted from April 2022. However, agriculture, horticulture, fish farming and forestry are some of the sectors still exempted which potentially highlights the economic constraints (and therefore subsidy required) by these sectors [113]. The Department for Transport has also sought to include NRMM within the remit of the Renewable Transport Fuel Obligation. Amendments sought have also included obligations to include 4.75% biofuel in NRMM fuel, increases in this percentile obligation, and more recently the inclusion of renewable hydrogen fuel for NRMM [114]. From September 2020 all NRMM located in Greater London will be required to meet emission standard Stage IIIB at a minimum. New NRMM already complies with these standards (e.g., Stage I, II, IIIA, IIIB, IV and V) however, this new legislation will push NRMM owners to improve their existing assets. Unfortunately, this emission standard change in London will likely only influence the construction industry. It is also primarily associated with air quality rather than decarbonisation [115]. NRMM regulations could be expanded into other sectors however, the cost of compliance could be significant. There is a limited evidence base surrounding NRMM in the UK, hence the UK government recently issued a call for evidence on the subject [116]. Moreover, several works to acquire NRMM data in sectors such as construction are taking place [117], [118], [119].

Vehicles declared SORN are also as difficult to investigate as NRMM. Vehicle declared SORN are the conventional vehicle equivalent of NRMM i.e., 'off the road' but not machinery. Vehicles that are declared SORN are likely to be a low priority to decarbonise, their emissions are difficult to quantify, the duration of each SORN is unknown, the function/operation of each SORN is unknown and the reason for each SORN is not specified. The data issues stated make it very difficult to determine which SORN represents an emitting vehicle and at what level the vehicle is emitting. Many vehicles could be broken down for parts, awaiting repair, in storage, awaiting scrappage, or in continual operation. Many agricultural vehicles carry a SORN designation, for example, a significant proportion of the LRDs operating at Worthy Farm were classified SORN. Furthermore, many vehicles designated SORN could pre-date modern emission regulations. Only a small number of vehicles need to still emit to have an impact [120]. The total number of vehicles declared SORN in the UK is depicted in Figure 10 between Q3 2014 and Q3 2023.

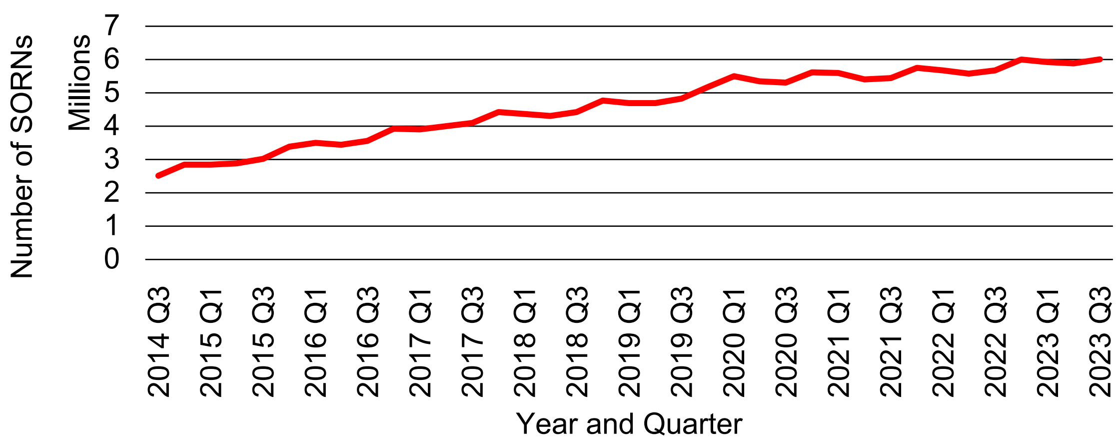


Figure 10: Estimated UK vehicles with SORN, created from DVLA data in [121].

To place an estimation on the significance of SORN emissions and to highlight the relevance of this vehicle classification to achieving transport emission abatement, LRD vehicles declared SORN are summated. Dataset VEH0121 was filtered across all available categories for “Make” = “LAND ROVER” and “Model” containing the strings “110”, “127”, “130”, “90” and “DEFENDER”. This identifies all documented vehicles declared SORN associated with LRDs. Figure 11 contains the change in total LRD SORNs as per this search criteria between 2014 – 2021.

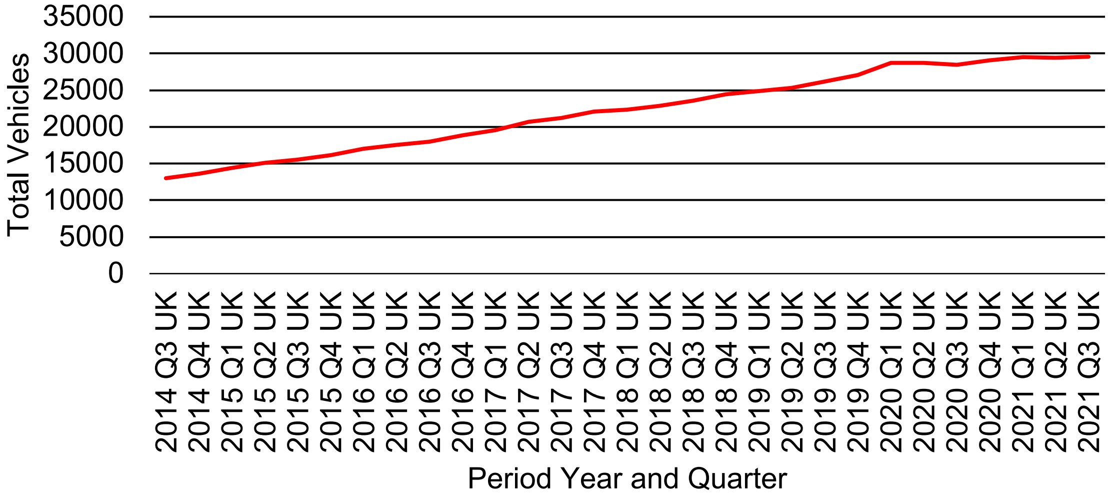


Figure 11: Change in UK LRDs declared SORN, Q3 2014 - Q3 2021 [121].

To estimate LRD SORN emissions, a scenario is presented whereby it is assumed that 50% of LRD SORN’s are still emitting, the emitting LRDs are assumed to utilise a 300Tdi powertrains with a $CO_2$ emission intensity of 258g per km of travel (note that due to uncertainty in emissions test data and older vehicles being declared SORN there is a strong likelihood that this figure is forms a conservative estimate). Also, the average distance travelled annually by each vehicle is 9282km (this is the mean annual usage of the three LRDs in the case study). These assumptions are crude, but this is necessary given the poor availability of data and this calculation only aims to highlight the potential significance of a small segment of SORN emissions on the transport sector.

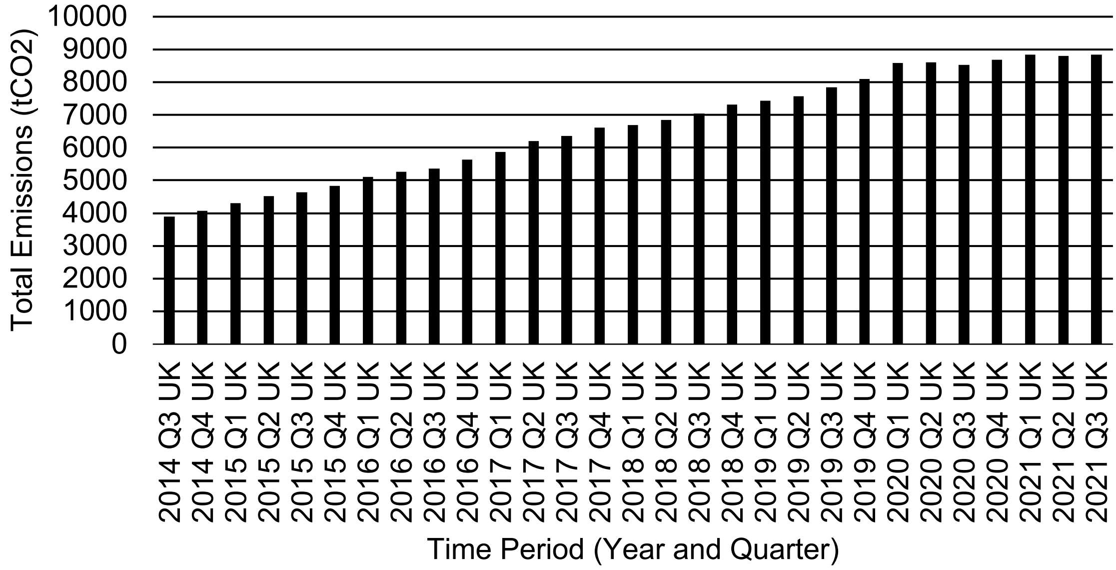


Figure 12: Estimated $CO_2$ emissions of SORN LRDs in the UK (Q3 2014 - Q3 2021).

Under the assumptions outlined, the estimated emissions between Q4 2020 and Q3 2021 from LRDs declared SORN is approximately 35000 $tCO_2$. This is equivalent to 12% of the GHG emissions from transport of the average local authority in the UK in 2021 (assuming that the transport emissions data utilised is accurate) [122].

Overall, quantifying the emissions from NRMM and vehicles declared SORN will be difficult, but it is essential in ensuring an accurate Net Zero. Methods of decarbonisation for these vehicle types need to be developed and retrofit could potentially form one of these methods. Especially considering the longer life cycles of many of these assets, the fact that they are often capital goods, frequently prevalent in hard to abate sectors such as agriculture and decarbonisation policy to date has struggled to make adequate progress.

## 2.5 Review of Retrofit Methods

This section provides additional context to other retrofit techniques currently available across various transport modes in the road, rail, aviation, and maritime transport sectors. Therefore, in contrast to other sections of this document, the use of the term ‘retrofit’ will refer to multiple methodologies beyond vehicle electrification until section 2.5.4.3.

As previously mentioned, retrofit offers a methodology to improve a vehicular asset within its life cycle without the need to scrap the asset. This is a useful proposition for the achievement of transport decarbonisation as vehicular emissions can be improved in the short to medium term, and embodied emission wastage can potentially be reduced.

### 2.5.1 Aviation

The market for aviation retrofit largely centres itself around low invasivity projects aimed at increasing aircraft efficiency. Within the Civil Aviation Authority for the UK, the Federal

Aviation Authority in America, and the European Union Aviation Safety Agency for the EU, Supplemental Type Certificates are provided to ratify most retrofits of an aircraft. For example, the certificates can be used to update onboard equipment or to provide airframe modifications [123].

Typical examples of lower invasivity aviation retrofit include updating cockpit avionics; installing cabin modifications i.e., seat configurations or infotainment upgrades; and providing small structural retrofits such as installing wingtip winglets in the pursuit of increasing efficiency/fuel economy [124]. These types of aviation retrofits are useful as the sector has limited scope for emissions abatement in the short term. Moreover, aircraft have long service lives (in some cases exceeding 30 years) in highly regulated conditions so typically cannot undergo significant alteration [20]. The Independent Aircraft Modifier Alliance is an example of a business that encourages aircraft owners and operators to continually modernise their fleets through these retrofits.

Retrofits for deeper emission reductions in aviation are likely to be possible in the longer term, but in the short term regulations and aircraft designs will likely limit any retrofit solution to new drop-in fuels with power-to-liquid as a fuel production method due to scalability/practicality [125]. Some research has been conducted on retrofit of regional aircraft through engine replacement to electric in [126]. However, this particular study concludes that the electrified retrofit it considers is economically impractical. The cost savings from reduced fuel consumption and emissions in [126] do not offset the retrofit capital cost over 12 years. This is mostly due to the relatively low cost of aviation fuel. It is however useful to see the bottom-up approach in this study enabling research into specific solutions, tailored to an individual aircraft's requirements.

It is worth noting that retrofits in aviation also apply to vertical take-off and landing vehicles such as helicopters. Low invasivity retrofits to avionics are again popular but also more profound retrofits have been attempted, such as increasing rotor blade counts to improve performance. For example, Airbus recently performed a five-bladed H145 retrofit of a DRF Luftrettung helicopter [127].

### 2.5.2 Maritime

Retrofit is a very applicable practice in the maritime sector. Maritime vessels often have a life cycle of 25 years with many reaching ages of 30-35 years [19]. Over this long life cycle, vessels dry dock every 3-5 years [128], and after a vessel is newly launched, its systems can become outdated within 10-15 years so there are many stationary opportunities to conduct retrofit. Vessels often have large internal volumes and surface areas which reduces spatial constraints which might otherwise limit potential for modification. Surprisingly, despite their long life cycles and an abundance of space, many maritime stakeholders only consider vehicles under the age of 15 years candidates for retrofit [129], [130]. This retrofitting window is to ensure economic viability for the vessel owner. In general, any potential retrofit needs to pay for itself during vessel operation. Overall, it is generally quite difficult to determine the perfect age and/or type of vessel for retrofit. Work in [131] explains how variations in hours of operation and engine loads make quantifying the economic viability for a retrofit difficult. It explains that tools are now in development to aid in this estimation with one of these decision-support tools being a Life-cycle Cost Analysis (LCCA) framework.

Maritime sector retrofits aim to prolong service life, increase capability, reduce emissions/fuel consumption, improve safety, improve air quality and reduce operating costs of vessels [132]. Maritime retrofits typically include vessel fuel conversion, bulbous bow install, hull optimisation, rudder redesign, deck rearrangement, and propeller improvement. Furthermore, the installation of alternatively fuelled engines is common as vessel engines can need replacement before the end of their service life. Engine conversions are typically made to either liquified natural gas or methanol. Methanol engine retrofit is simpler than liquified natural gas retrofit, as it can utilise pre-existing fuel tanks. Shore electrification is another emerging retrofit technique with work in [133] indicating the benefit for port emission abatement. Retrofit for emissions abatement are becoming ever more incentivised as the International Maritime Organisation deploys more regulations.

In the longer-term maritime decarbonisation will rely on the use of energy dense liquid/compressed gaseous fuels as the energy requirements of vessels will likely disqualify electricity (assuming there isn't a leap in electrical energy storage technology) [125]. Retrofit to methanol-based or hydrogen/ammonia fuels are two of the most likely future emission mitigation methods. ShipFC is an example of a recent project considering the feasibility of ammonia as a zero-carbon marine fuel through retrofit of a vessel with a 2MW ammonia fuel cell [134].

### 2.5.3 Rail

The rail sector has employed retrofit of its fixed infrastructure, rolling stock and locomotives for many years. The most prominent form of retrofit in rail is of its fixed infrastructure in the form of line electrification. This change is one of the most scalable and mature solutions for rail decarbonisation and must continue to help the transport mode reach Net Zero. Unfortunately, replacing all diesel use in the rail sector is, in the short term, unfeasible as only around 38% of UK track is electrified. So more recently, rolling stock and in particular, locomotives, have begun to receive retrofitted technology in order to reduce their emissions and improve localised air quality. The approaches utilised for rolling stock retrofits are carried over from the HGV sector. Two popular techniques are employed, the first is exhaust gas recirculation and the second is selective catalytic reduction (SCR).

SCR involves the installation of an exhaust technology which targets nitrogen oxides. It utilises ammonia to breakdown nitrogen oxide emissions produced by diesel engines into nitrogen and water. Ammonia is delivered via a urea solution termed Diesel Exhaust Fluid (DEF), which is sprayed directly into the exhaust stream. This DEF is hydrolysed into ammonia gas in the exhaust then a catalytic reaction between nitrogen oxides and ammonia results in the production of nitrogen and water. DEF is also known by the name AdBlue. SCR systems are typically fitted after a Diesel Particulate Filter. Figure 13 contains a diagram representing the operating principle of an SCR system.

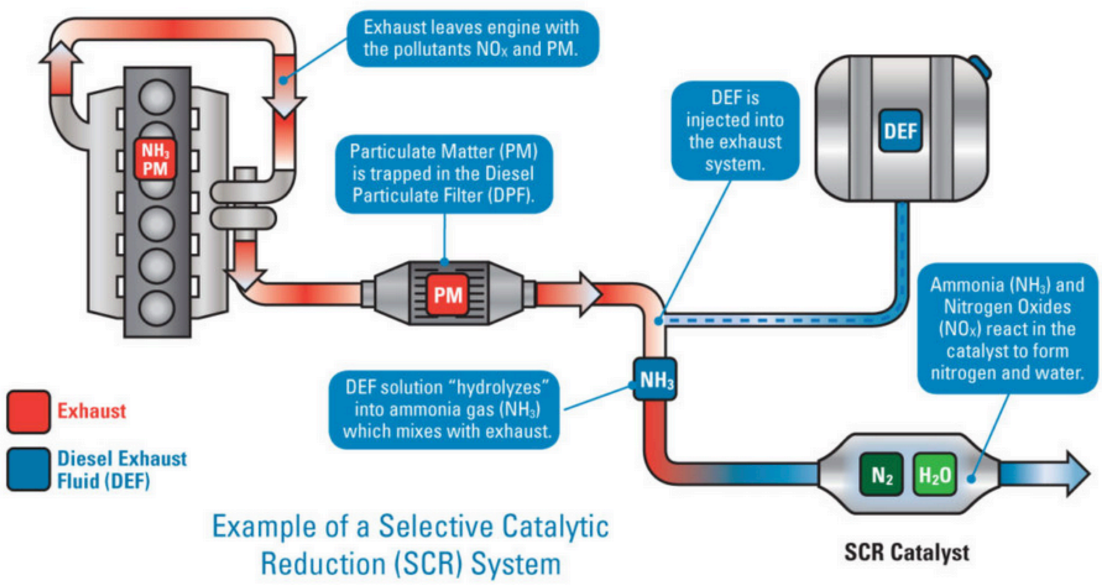


Figure 13: Example of a SCR system [135].

SCR is by no means a zero-emission solution. It was pioneered predominantly to improve air quality and is popular due to the unavailability of suitable zero emission vehicles. SCR was first pioneered at scale to meet European HGV emission standards, specifically Euro 4, 5 and 6 [28]. However, SCR can also increase fuel efficiency in some cases. It is highly suitable for buses, coaches, trucks and refuse collection vehicles due to their long-life cycles, but electrified alternatives are now becoming available. Currently, more than one million trucks and buses have been equipped with SCR technology in Europe (around 8000 in England) [27]. Within the UK, SCR is provided through the UK's Clean Vehicle Retrofit Accreditation Scheme (CVRAS) as part of government/local authority retrofit programmes [28]. SCR is also being considered for vans and taxis.

SCR in rail typically replaced exhaust gas recirculation which aimed to satisfy earlier diesel engine emission regulations. Exhaust gas recirculation, as the name suggests recirculates exhaust gases back into the engine. This is achieved by first cooling exhaust gases through a heat exchanger and then blending them with new fresh air. This blended gas is then fed back into the engine's intake for re-combustion. The mixed gas contains less oxygen, and more carbon dioxide and it acts to lower the combustion temperature. This reduced combustion temperature results in reduced nitrogen oxide emissions, but it often increases fuel consumption. Exhaust gas recirculation also requires a diesel particulate filter (DPF) which needs to actively regenerate to avoid blockage and higher fuel consumption. The technologies of exhaust gas recirculation and SCR are sometimes combined to further mitigate certain exhaust gases [18]. SCR is often the preferred choice for the rail sector as it is solely an exhaust treatment so an engine can be optimised for efficiency and not changed architecturally which can offset the DEF for SCR.

### 2.5.4 Road

The retrofit market for road transport is one of the broadest due to the large variety of vehicle types and models. To classify the methods available, Table 5 contains retrofit methodologies for the road sector categorised by low, moderate and high levels of invasivity [136]. For high levels of fleet decarbonisation in the road transport sector, low and medium invasivity methods will only remain practical in the short term. As such, only the high invasivity methods of retrofit are discussed in this section in detail apart from SCR as this has already been covered in the previous rail section.

Table 5: Examples of road sector retrofit as a function of procedure invasivity [136].

| **Low Invasivity** |
|---|
| Vehicle remapping e.g., improving engine control unit settings.<br>Over the air software updates e.g., remapping delivered remotely.<br>Fuel improvement e.g., higher bioethanol content (flex-fuel engines used in Brazil can run on 100% ethanol and have shown potential to reduce total GHG emissions [137].)<br>Fuel change e.g., using hydrotreated vegetable oil as a diesel substitute.<br>Tyre change e.g., installing higher fuel efficiency rated tyres.<br>Component change e.g., installing a new air filter.<br>Using an additive e.g., fuel system or oil system products |
| **Moderate Invasivity** |
| Accessory retrofit e.g., solar system for a trailer roof<br>Refuelling<br>Liquified Petroleum Gas Conversion<br>Bio Liquified Petroleum Gas Conversion |
| **High Invasivity** |
| SCR<br>Repowering – Engine Replacement<br>Repowering – Hydrogen<br>Repowering – EV Retrofit |

#### 2.5.4.1 Repowering – Engine Replacement

An alternative to improving the emissions of an existing automotive powertrain is to replace it. One of the more common varieties of engine to feature in replacements is a Euro 6 (VI) category diesel. Through the CVRAS, this type of engine replacement is currently only available to buses and includes the engine system and an exhaust aftertreatment system in the form of SCR as part of the same project. Buses that are between 4 and 8 years old are seen as ideal candidates for a replacement engine, with a replacement expected to give the vehicle an additional 7 to 10 years of operation. Repowering to a Euro 6 engine typically takes around 2 weeks to complete but this will depend on the donor bus type. One recent, notable example of Euro 6 engine conversion was a London AEC Routemaster bus conversion. The specific vehicle converted had been placed in service in 1962 [27]. Note that a similar process to engine replacement is engine remanufacturing. This is a prevalent practice in countries such as Germany to extend the lifespan of automotive components. Target customers for this work include taxi fleet operators [138], [139].

#### 2.5.4.2 Repowering – Hydrogen

Retrofit of vehicles to hydrogen fuel is stated to now be offered by firms such as Caigan Vehicle Technologies [140], [141]. There are three categories of hydrogen road vehicle, a fuel cell electric vehicle, a hydrogen internal combustion engine vehicle and a dual fuel internal combustion engine vehicle. All of these vehicle types aim to reduce emissions however they are complex powertrains and are thus likely to be expensive. Furthermore, there is a lack of available evidence relating to the complexity of hydrogen retrofit, a documented retrofit process or any potential cost of the process. This may be due to their rarity of hydrogen vehicles in general.

Only when running on green hydrogen is a retrofitted fuel cell vehicle zero emission, whilst a retrofit hydrogen ICEV still produces nitrogen oxides, and a dual fuel ICEV only has reduced tail pipe emissions. For all vehicle types, fuel tank modifications are required to enable them to hold compressed hydrogen. Dual fuel ICEVs mix hydrogen with diesel fuel directly to displace between 30% and 70% of its energy content. This results in direct emission savings at the tailpipe and air quality improvements. The hydrogen ICEV retrofit is conducted in a similar way to a typical engine replacement and runs on 100% hydrogen content. The fuel cell vehicle requires a fuel cell installation and an electric powertrain for its conversion process.

Despite claims of hydrogen conversion legitimacy, it is unknown if this form of retrofit is viable and useful except for in a limited number of cases. New hydrogen vehicles are also currently not common, the supply chain for this fuel type is underdeveloped and this also extends to hydrogen infrastructure. Furthermore, at scale green hydrogen production is currently not available and hydrogen fuel has lower well-to-wheel efficiency when compared to battery electric powertrains (25% higher fuel consumption and 21% higher emissions per unit distance in [142]). As such, it is the authors view that any benefits of a hydrogen retrofit process are unlikely to be worth the complexities involved at this point in time [143].

#### 2.5.4.3 Repowering – Electric Vehicle Retrofit

In the last few years, a cumulative momentum behind EVs has developed. This momentum has derived from multiple sources, such as the growing number of legacy brands offering EV models, increasing consumer choice [144], and a cultural shift (within the UK) towards a future obsolescence of the ICE, likely inspired by recent regulatory change [63]. The aggregate influence of these factors has created legitimacy for EVs as a viable solution to decarbonise a large segment of road transport. However, EVs are predominantly mass produced and there is not always an available vehicle model to purchase for every vehicle needing to decarbonise within the UK. EV retrofit (also known as an EV conversion) could form a pathway to decarbonise these vehicles.

This retrofit process removes the existing powertrain (typically ICE) and replaces it with an electric alternative (motor and battery combination) [145]. The key components to be introduced to the donor vehicle during a retrofit are the electric motor, its controller, the battery pack, and its battery management system. These components will all be connected via a wiring harness, battery boxes and mounting hardware within the donor vehicle frame [146]. In general, there is no 'typical' retrofit, and components and installation can vary depending on the requirements of each converted vehicle.

The exact origin of the practice is not clear, however, the National Aeronautics and Space Administration cite several retrofits in a 1977 technical report [147], American organisations such as U.S. Electricar are cited to have completed retrofits in the early 1970s, and Chandler H. Waterman completed a retrofit as early as 1968 [148]. Recent resurgence in private car retrofit has stemmed from the classic segment of the automotive market with many new market entrants offering electrification services. Some original equipment manufacturers (OEM's) have also completed retrofit projects on heritage vehicle models [29]. Opinion on the practice is still polarised however, with certain 'purists' not approving of extensive modification; this is countered by a growing number of enthusiasts with old but viable, valuable, vehicles where EV retrofit offers them a path to technological rejuvenation and prevents obsolescence. Retrofit practices are also completed for many other modes of road transport from HGVs to Motorbikes [149], [150].

Each retrofit differs in its complexity and will contain its own subset of specific tasks i.e., chassis modifications, powertrain adaptions and choice of componentry [151]. The budget of a retrofit will be the greatest determinant of its complexity and scale. Low-cost retrofitted vehicles will often not aim to restore the donor vehicle and instead prioritise only the successful operation of the electric powertrain. They may utilise smaller capacity batteries and hence will lack the original driving range of their donor vehicle. More costly retrofits can afford to 'over engineer', focus on a complete restoration of the vehicle and to potentially improve on the original donor vehicle's specification e.g., addition of interior heating/cooling systems. Vehicle owners can necessitate all of these requirements in advance and determine the cost or agenda of the retrofit project [152].

Beyond budget considerations, the integration of new electronic components is another key area of complication for a retrofit. More modern donor vehicles can be more demanding to retrofit as existing electronics and onboard vehicle data communications need to be fully understood/reversed engineered before new electronics can be added. Additionally, the method of incorporating components into the donor vehicle depends on the donor vehicle's physical structure e.g., available space, strength of the donor chassis, original mass etc. The LRD in particular has limited electronics and a chassis design making it particularly appropriate for retrofit. The potential benefits from the retrofit of an LRD beyond reducing running costs and improving its environmental credentials are improving daily operability, reduction in maintenance requirements (e.g., fewer moving parts, no need to replace fluids), improvement in overall efficiency and reductions in noise/vibration. Note that Chapter 4 contains a comprehensive explanation of LRD retrofit.

Once a retrofit has been completed successfully and the methodology codified, standardised retrofit kits for that vehicle model can often follow [153]. The use of kits allows componentry to be made homogenous and bought in larger quantities; increasing economies of scale to drive down the costs of a project whilst maintaining the potential for bespoke design. Furthermore, retrofit kits allow improvement of a specific retrofit process, such as ease of installation and retrofit quality. Vehicle manufacturers work hard to control noise, vibration, and harshness in their products, but petrol and diesel cars often have creaks, groans and rattles masked by ICE noise and vibration. After electrification, when the ICE is removed, users can become aware of previously hidden noise, vibration and harshness and kits can be designed to reduce this. Kits are offered for personal or commercial purchase and installation. Businesses now exist that specialise in retrofit kits, however, despite kit standardisation, each donor vehicle will have its own nuance and so completing a retrofit still requires competence [154].

In terms of legally operating a completed retrofit on UK roads, there remains no legal or significant financial barrier to operating a retrofit, but the process is somewhat uncertain. This is because in the majority of cases the retrofit vehicle does not have to be re-registered as the registration of the donor vehicle can be reused. However, this is only if an owner can prove they have not modified too many parts of the donor vehicle as per the point system requirement highlighted within Table 6.

This requirement is based on a DVLA points system where a vehicle begins with 14 points and a minimum of 8 points are required to retain the original registration. 5 out of the 8 points must be derived from the aforementioned unmodified chassis/monocoque/frame as shown in Table 6. Many retrofits will score between 9 and 11 points due to only requiring engine (1 point), transmission (2 points) and potentially steering assembly modifications (2 points) – hence no re-registration [31], [155]. This is especially true of vehicles like the LRD due to their ladder chassis (also termed body-on-frame) design which makes it much easier to not modify major components. If registration is needed, the completion of an individual vehicle approval test and a built-up vehicle inspection report (V627/1) is likely.

Table 6: DVLA points-based system to determine the level of vehicle alteration [155].

| Unmodified Part | Points |
|---|---|
| Chassis, monocoque bodyshell (body and chassis as one unit) or frame, original or new and unmodified (direct from manufacturer). | 5 |
| Suspension (front and back) - original | 2 |
| Axles (both) - original | 2 |
| Transmission - original | 2 |
| Steering assembly - original | 2 |
| Engine - original | 1 |

Following the previous steps, the retrofit can be complete an MOT (unless its exempt e.g., classic/historic). The lack of an exhaust negates the need for a new emissions test and then the DVLA should be informed about the change in vehicle fuel type via written proof. According to work within [31] this written proof can be in the form of a receipt/garage headed paper stating that a new powertrain has been fitted. To change the retrofits tax class (i.e., VED rate), its logbook (V5C) needs to be submitted to the DVLA alongside an application to change a vehicles tax class (V70), an MOT certificate (unless exempt) and the written proof of fuel type change. As of 2025 VED is no longer zero for zero emission vehicles [156].

Overall, there is not much formal support within the UK from a policy/regulatory perspective to encourage the adoption and use of a retrofit. However, navigating the process is manageable and the development of a formal EV retrofit accreditation scheme could be beneficial [31].

Table 7 contains a non-exhaustive list of businesses currently providing retrofit related services. The list is formed from internet search results and is accurate as of April 2022. It highlights that there are a significant number of businesses operating within the classic car sector, several OEMs that have completed retrofit services, and some specialising in components and alternative vehicle types e.g., heavy goods, industrial or specialist. Firms like EV West now offer provision of parts/kits rather than solely completing retrofit projects. Notably it is difficult to confirm garages/local enterprises providing services due to their smaller online presence, though there are webpages emerging (e.g., HEVRA.org.uk) which state local EV-friendly garages, many of which could be assumed to be comfortable installing a retrofit kit.

Table 7: Sample list of actors operating in the retrofit market.

| Name | Description of Services | Ref. |
|---|---|---|
| Flash Drive Motors | Classic and specialist retrofit, restoration, parts, kits. | [157] |
| Zero Labs | Retrofit/restoration services for classic/specialist cars. | [158] |
| Zelectric Motors | Retrofit/restoration services for classic/specialist cars. | [159] |
| Electric GT | Retrofit kits for several vehicle models. | [160] |
| EV West | Creates retrofit kits, provides parts for several vehicle models. Offers technical advice/servicing. | [161] |
| Electrogenic | Vehicle retrofit, focus on classic cars retrofit, kits. | [162] |
| LUNAZ | Retrofit and restoration of classic cars. Also used to upcycle large vehicles (refuse vehicles/other HGVs) | [163] [164] |
| New Electric | Develops and integrates electric drivetrains. Offers retrofit with a focus on automotive, marine, and industrial sectors. Recently converted a tractor. | [165] |
| Everrati | Retrofit and restoration of classic cars. | [166] |
| Zero EV | Retrofit kits, parts, and business training. | [167] |
| Electric Classic Cars | Largest converter of classic cars to EVs. | [168] |
| EV Europe | Retrofit, parts, and retrofit kits. | [169] |
| Electron Garage | Retrofit, service, repairs, battery replacements. | [170] |
| London Electric Cars | Retrofit for several vehicles. | [171] |
| Netgain | Retrofit electric motor system provider. | [172] |
| Danfoss (UQM) | Retrofit electric motor provider, acquired by Danfoss. | [173] |
| Grid Tractor | Software for EVs to provide energy flexibility. Focus on tractors to charge when energy is cheap then to power a farm when prices are high. | [174] |
| Ford | Selling Mach-E motors to promote custom EV retrofit, especially of classic ford models. | [24] |
| Renault | Facility specialising in automotive circular economy, claimed to also work on EV retrofits. | [175] |
| Aston Martin | Created first reversible EV powertrain concept as a heritage model EV strategy. Aims to mitigate restrictions on classic car usage. | [176] |
| Renault Group | Refactory (Europe’s first circular economy factory) offers retrofit and reconditioning services. | [177] |

In summary, retrofit presents a process that could aid transport emission abatement for certain vehicles through eliminating their exhaust emissions and increasing circularity. Embodied carbon can be reduced through bespoke component selection and achieving secondary mass savings through this more tailored powertrain sizing. Expenditure can also be reduced through bespoke component selection and mass decomposition increasing vehicle efficiency [178], [179]. Furthermore, retrofitting provides an opportunity to customise vehicles intricately e.g., installing a phone changer or Bluetooth to a classic car. Overall, the process has a strong potential to expand the post-production economy. Figure 14 contains an overview of the retrofit market. The depiction focuses on the transition from the vehicle production economy to retrofit post-production economy.

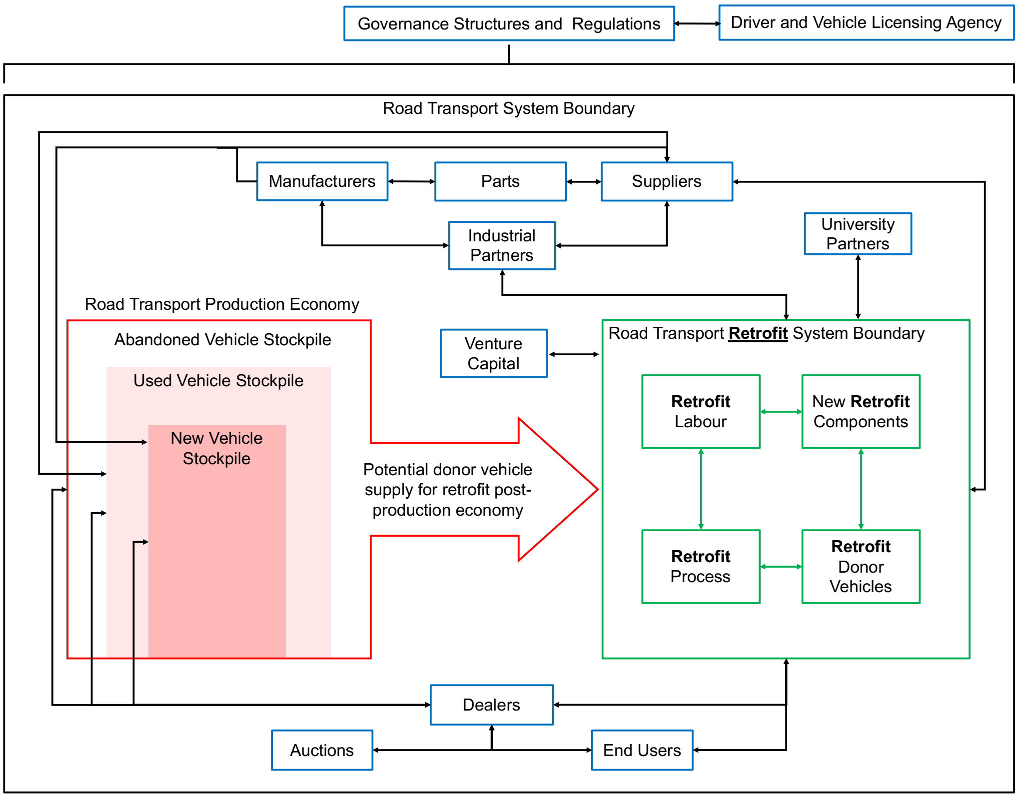


Figure 14: Representation of the retrofit market, inspired by work in [153] and [25].

## 2.6 Summary

This chapter has covered the necessary pre-requisite information to understand, transport systems, their decarbonisation and retrofit as one potential decarbonisation solution. Specifically, it has presented an overview of transport emissions; how emissions are quantified, documented, and reported; an introduction to transport within the agricultural sector and some of its challenges to abate emissions; and how new decarbonisation methodologies are needed to address this issue. This led into the discussion of retrofit methodologies. The discussion of agricultural transport in this chapter provides context to the case study which appraises the role of retrofit in the agricultural sector through the investigation of LRD retrofit. This vehicle and the sector form a useful foundation upon which to consider broader applications of retrofit for decarbonisation. The review of different retrofit techniques highlighted many potential methods that could be used to abate emissions for a number of different vehicle types.

# Chapter 3 Research Methodology

## 3.1 Introduction

To thoroughly appraise retrofit as a transport decarbonisation solution, this research has opted to employ multiple perspectives of analysis. This is due to transport being a complex, socio-technical system [180] interdependent with other sectors [181]. Therefore, in the opinion of the author, determining if transport decarbonisation can be aided or not through retrofit will require a holistic appraisal. This is in line with the narrative of other publications that call for "whole system approaches" [182] which is a commonly used aphorism within decarbonisation literature calling for the advancement of emission abatement through integrated practices [183], [184], [185], [186], [187].

Therefore, to achieve a more holistic appraisal of retrofit in this research, a microscopic, mesoscopic, and macroscopic analysis of the central case study is completed concerning the retrofit of internal combustion engine LRDs to electric. As mentioned in previous chapters, the vehicles studied are operating within the context of the agricultural sector which is considered difficult to decarbonise. The microscopic, mesoscopic, and macroscopic analyses are presented across three technical chapters which are all detailed in Section 3.4. This methodological approach was inspired by several tranches of literature concerning socio-technical theory, socio-technical transitions and in particular the Multi-Level Perspective (MLP). This literature is overviewed within this chapter.

## 3.2 Socio-Technical Systems

Research on systems is broad, dates back decades, and the terminology used to describe the study of systems is diverse. Systems theory and systems thinking are common high level terminologies, but others include systems innovation, whole system design and systems engineering [188], [189], [190]. Many fields of study overlap to a considerable extent in their analysis of systems and, due to the span of this literature, this chapter is narrowed to focus on socio-technical systems theory and socio-technical transitions.

The term socio-technical system was coined by Trist in [191] and dates back to the 1950s. The discipline itself (socio-technical theory) then saw significant development by social scientists at the Tavistock Institute of Human Relations in London. The concept was initially dedicated to the study of production systems and the relationship between human operators and technology [192]. This resulted in the discipline's objective of helping to improve the relationship between technology and social/human systems within an organisation to produce output [193]. The application of socio-technical theory has now grown from this origin to cover a range of disciplines including transport (Figure 15 depicts a socio-technical system for land-based road transport), information systems, organisational studies, business, management and engineering [194].

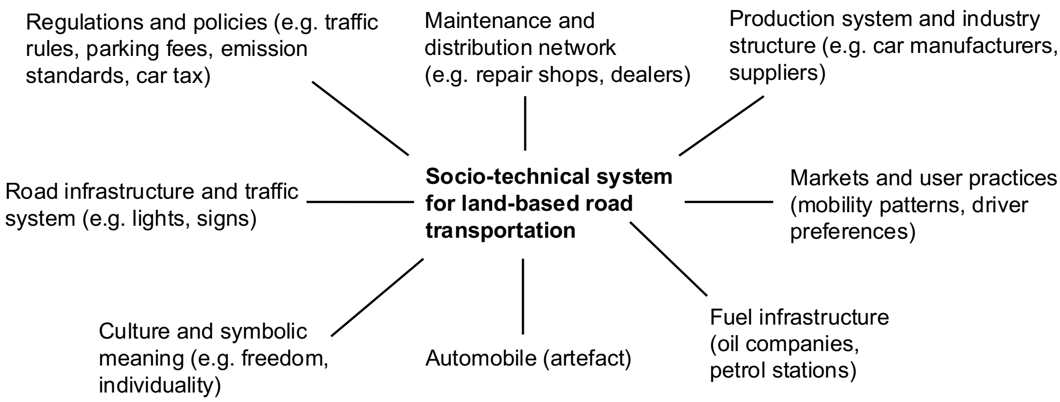


Figure 15: Socio-technical system for land-based road transport [180].

Elements from the figure include the user practices and culture of the people who use, operate, and work within transport systems including their reasons to use transport, attitudes towards it, expectations of it, hierarchies in operational staff and skill levels. Moreover, they use tools, techniques, procedures, skills, knowledge, and devices to accomplish tasks [193]. This human agency plays a role in the transport system's uncertainty and inertia (resistance to change [195]). Change often requires capability, opportunity, and motivation and the existence of an improvement or technological innovation may not result in its adoption [196], [197]. This resistance can be termed 'path-dependence' or 'lock-in' which originates from "the stability of existing socio-technical systems, e.g. legally binding contracts, cognitive routines, core capabilities and competences, lifestyles and user practices, favourable institutional arrangements and regulations" [180]. Path-dependence also relates closely to biases which transport system designers/practitioners must consider e.g., that a person's daily commute to work is more likely to have resulted from habit than a daily rationalisation of the most effective route [198], [199]. This normal situation challenges an axiom that behaviour is a result of conscious, deliberative, rational cognitive processes. In reality, transport system behaviour could be influenced by incorrect mental models, unavailable data, and the structure of the transport system itself [200]. Research has highlighted that convenience, comfort, cost, and habit are all important factors influencing travel decisions [201], but despite this, journey time is often used to justify projects [202]. Overall, socio-technical systems are actively created and are not static but dynamic [180]. Ongoing work by Geels et al. in this field is aiming to understand and conceptualise change (transitions) in socio-technical systems rather than to provide a static description. The next section describes one popular framework to conceptualise socio-technical transitions – the Multi-Level Perspective (MLP).

### 3.3 Multi-Level Perspective

The MLP was put forth by Frank Geels in [203] and a depiction of the framework is contained in Figure 16 [204], [205]. The MLP abstracts a socio-technical transition across three levels. First is the landscape at the macro level, consisting of trends in structural context e.g., the health of the economy, and environmental problems. Next is the regime at a meso level containing existing infrastructures, technologies, skills, cultures, and user practices. Finally, the technological niches at the micro level contain small numbers of actors enabling radical innovations, which are yet to form part of the incumbent regime. Retrofit of vehicles to electric is an example of a niche innovation.

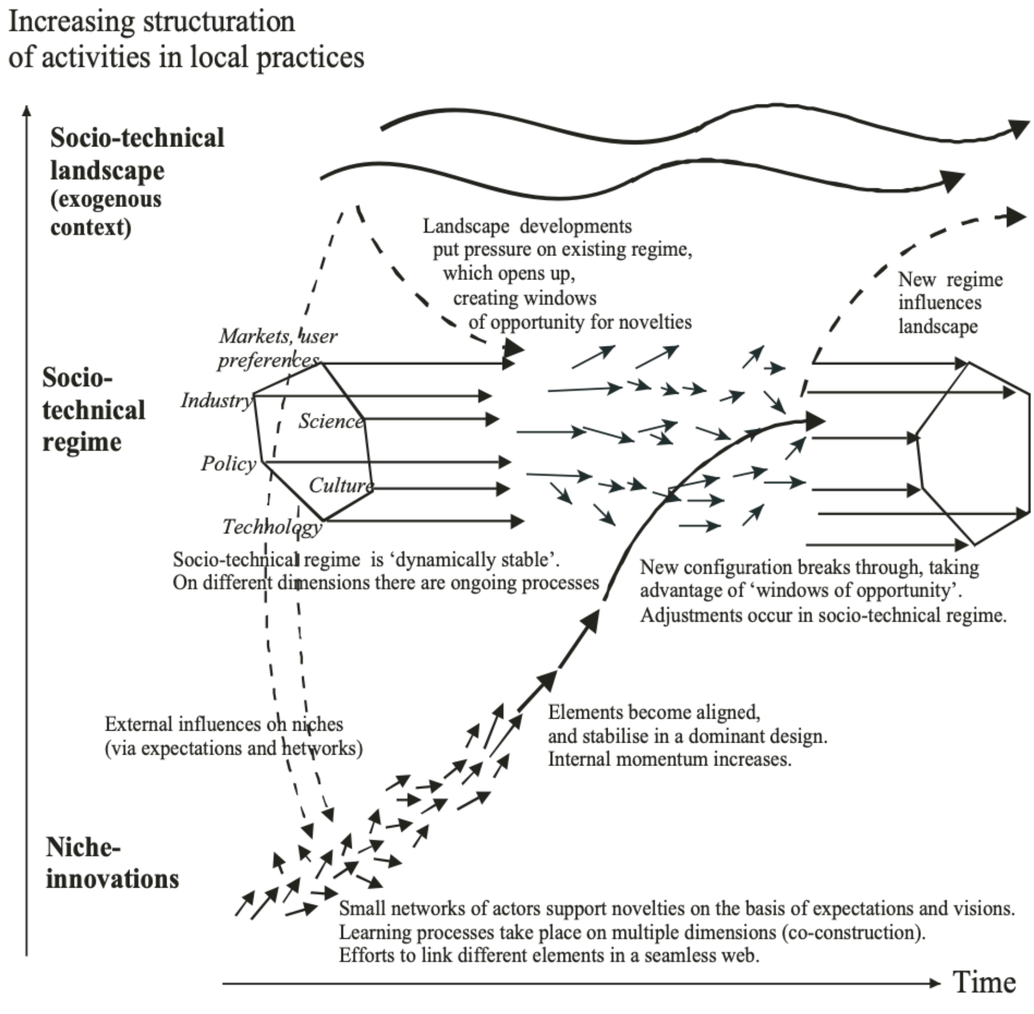


Figure 16: A dynamic multi-level perspective on technological transitions [39].

The various arrows in the figure illustrate dynamics, such as regimes putting pressure on landscapes, and niches on regimes. The landscape is shown to evolve slowly and has large amounts of inertia (arrow length). The shape of the regime is shown to break down creating "windows of opportunity" allowing niche innovations to take hold. At the micro level, and in the early stages of a transition, there are a variety of early innovations/ideas/directions which evolve over time until more dominant designs/ideas stabilise. Note that while landscape developments as a whole are typically slow moving, three dynamics are commonly exhibited within them: factors that do not change (e.g., national geography), rapid external shocks (e.g., oil price/war) and long-term changes/trends (e.g., demographic shifts) [206].

Although the MLP is useful, it can be argued that it contains several drawbacks, such as a bias towards bottom-up innovation, along with an omission of ideology, agency, and politics [39]. Additionally, in early MLP depictions of transitions, there existed a bias towards innovation and techno-optimism [207]. Furthermore, the MLP does not have a clear methodological basis and transition case studies are more aimed towards illustration than systematic research [208]. In more recent literature, the role of the other layers in technological transitions, especially in the decarbonisation of transport, are considered.

Despite these shortcomings, overall, the MLP is a good foundation from which to illustrate the dynamics of a transitioning system, and its inertias [39], [203]. The MLP also forms a useful multidisciplinary framework that can be combined with other techniques [209]. The three-level architecture described within the MLP is also used in other work, for example a depiction of circular economy transitions from [210] is summarised in Figure 17. It highlights example actors at the micro, meso and macro level e.g., individuals, groups of organisations or nations respectively.

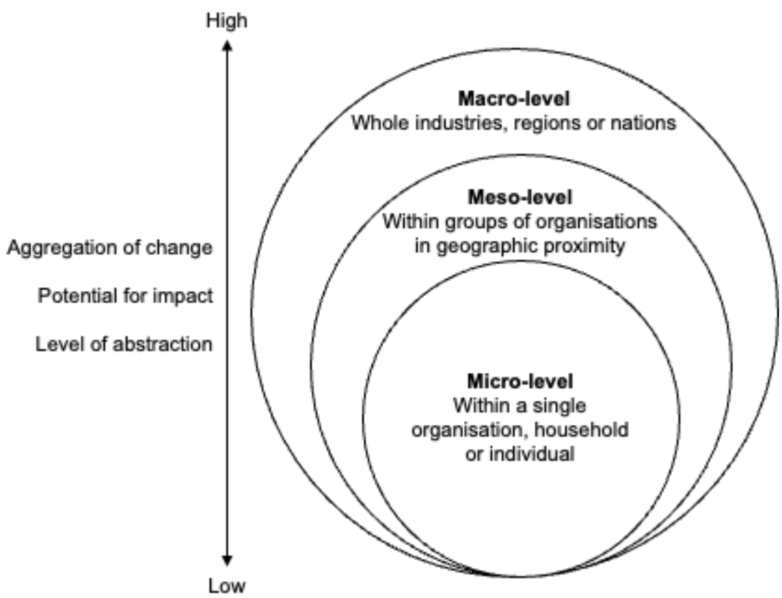


Figure 17: Macro-meso-micro architecture [210].

Based on the aforementioned frameworks, this research also adopts this three-level architecture as a methodological foundation to appraise retrofit in the context of the central case study. The application of the three-levels is presented across three technical chapters termed “bottom-up perspective”, “middle-out perspective”, and “top-down perspective”. These analytical perspectives directly relate to micro, meso and macro levels of abstraction respectively.

Each chapter's specific methodology is explained in Section 3.4 however, in summary and as per Figure 17, the bottom-up perspective appraises retrofit from the standpoint of an "individual" vehicle and its retrofit process, vehicle performance and cost. The middle-out perspective considers how retrofitted vehicles could be successfully deployed and operated. This requires close consideration of other system actors in "geographic proximity" e.g., charging infrastructure, energy supply, users, use cases etc. Finally, the top-down perspective appraises retrofit at a broader scale i.e., as a decarbonisation policy measure. The use of the three perspectives hopes to reduce the trade-off in typical macro vs micro approaches i.e., bottom-up vs top-down [211]. Table 8 provides a general description of retrofit appraisal from each perspective.

Table 8: Appraisal description from each level of abstraction (perspective).

| Perspective | Appraisal Description |
|---|---|
| **Bottom-up (Micro)** | Appraisal at the micro level of the system is ultimately from the perspective of an individual system actor. For example, an individual system user, household, organisation, institution, or vehicle etc. Hence, appraisal of retrofit at this micro level will involve evaluating an individual vehicle retrofit process, its performance, emissions, idiosyncrasies, cost, and ability for the vehicle to be embedded in the future into a broader context (the central case study in this instance). Successful embedment may involve short term retrofit improvement through incrementalism or iterative re-design. The probable success of the retrofit can be enhanced by consistent collaboration with system actors as the specification of the retrofit will stem from their problem definition i.e. from the bottom-up. |
| **Middle-out (Meso)** | Appraisal at the meso level considers changes in the interactions between system actors in geographical/resource proximity i.e., how the deployment and operation of retrofitted vehicles could impact existing system actors. These 'middle actors' could be retrofit users, the local supply chain, retrofit supporting infrastructures like chargers or their associated energy supply. Interactions can be considered to travel outwards from each actor to others (hence the use of the term middle-out). The interactions between retrofitted vehicles and other system actors could impact the performance of the agricultural holding. Appraising retrofit from this perspective should aim to uncover possible operational impacts from retrofit deployment and methods to mitigate impacts and/or improve outcomes. |
| **Top-down (Macro)** | Appraisal at a macro level considers whole industries, regions, or nations i.e., a high-level strategic viewpoint. For retrofit, this is the appraisal of its introduction as a broader measure e.g. as a national policy, potentially targeted at a particular vehicle. Such a policy would proliferate from the top-down, impacting stockpiles of vehicles. Hence, the appraisal of retrofit at the macro level should aim to indicate what impact a retrofit policy could have e.g. on life cycle emissions and what causal relationships could manifest between a retrofit policy and other policy initiatives (e.g., other decarbonisation measures). |

### 3.4 Technical Chapter Overview

This section begins by providing additional context to the central case study. This is followed by details of the particular methodological approaches utilised within each technical chapter to facilitate the microscopic, mesoscopic, and macroscopic appraisal of retrofit in the context of the central case study. Note that the exact proceedings of each technical chapter are not covered as this is provided in their respective introduction sections. This section also outlines some existing uses of bottom-up, middle-out, and top-down terminology to inform how the usage of each term in this research differs.

#### 3.4.1 Additional Case Study Context

The focus of this research and central case study are introduced in Section 1.2 and expanded here. The site of the case study is Worthy Farm (host to Glastonbury Festival) located in Pilton, England. The opportunity to work on this case study arose as part of an Innovate UK project entitled "Low-cost electric Land Rovers for farmers and landowners" grant reference 80658. The two partner organisations involved with Cardiff University were Electrogenic (project lead) and Worthy Farm.

The Worthy Farm site is an agricultural holding which utilises LRDs on a daily basis for general mobility of people/goods e.g., towing trailers of feed/animals, carrying tools or moving people and supplies during the Glastonbury Festival period. Although other agricultural holdings could have been contracted by Electrogenic for participation in this study, Worthy Farm was proposed as they have vocal commitments to sustainability, a good public presence and have an appetite to "host alternative solutions to environmental concerns" [37]. The farm was also enthusiastic to yield fuel savings from the use of their existing renewable energy assets with the retrofits which may not have been possible to study at other sites.

To assess the potential of retrofit for LRD decarbonisation at the site, three LRD vehicles were retrofitted and provided to Worthy Farm by Electrogenic. The key objective for Electrogenic during this project was to develop a marketable retrofit kit for the LRD and to publicise their organisation via this project. Electrogenic were instrumental in providing access to vehicle controller area network (CAN) bus data by Cardiff University (who retrieved this and also collected certain additional data during site visits e.g., floating phone data during vehicle tests). Worthy Farm provided site and vehicle access once the retrofits were deployed. The author of this thesis was the sole analyst of the vehicles and the data presented in this thesis. The author did not collaborate with any other institution or researchers but conducted ad-hoc stakeholder engagement (e.g., with farm staff and retrofitters) to evidence the retrofit process and its success/drawbacks.

### 3.4.2 Bottom-up Perspective

The term bottom-up has been widely used in academia and wider literature as it is well recognised in many fields of research e.g., policy, cognitive psychology, cognitive science, economics, natural science, computing, systems engineering, biochemistry, and social science. In all of these fields the definition of bottom-up e.g., 'bottom-up economics' or 'bottom-up design' varies but a general meaning from social science for bottom-up processing is when sensory data influences observation. This relates to transport in the fact that an individual (e.g., a transport user) can view a problem and this view could influences a potential solution which can spread from a niche to a general practice [212], [213], [214], [215], [216], [217].

Therefore, to apply a bottom-up perspective to the appraisal of retrofit for aiding transport decarbonisation an emphasis is made on investigating an individual retrofit's performance as a niche solution. This should include the analysis of retrofit performance from a technological and economic standpoint, and the retrofit should be investigated in the context of other vehicles. The current state of the retrofit market can also be considered and its potential to be able to develop.

Comparisons of retrofit solutions against other vehicles can be conducted through activity models derived from simulation or primary data. Both simulation and primary data were used within this research. Primary data was provided from a retrofit manufacturer in the form of CAN bus frames and the Future Automotive Systems Technology Simulator (FASTSim) was the selected modelling tool. Drive cycle data was captured during site visits and the use of a mobile device. More information is contained within Chapter 4 on FASTSim and data acquisition. This is an Excel based vehicle analysis tool developed by the National Renewable Energy Laboratory (NREL) which provides an effective way to compare powertrains and estimate the impact of technology improvements on light, medium, and heavy-duty vehicle efficiency, performance, cost, and battery life [218]. FASTSim has also been validated in terms of its accuracy and reliability [219].

To analyse the economics of a retrofit in the context of the case study, a desk study of secondary data was selected as the research method. This method allows for the economic cost of a retrofit to be considered over a period of ownership through estimation of capital and operational costs. Secondary data for capital costs could include donor vehicle cost, retrofit labour cost, and part costs. Operating costs could include vehicle taxation, fuel cost and maintenance. Other impacts such as foreign exchange and deflation are also considered. Retrofit costs are also compared against other vehicles and multiple suppliers are viewed to gather a range of potential prices e.g., for parts.

### 3.4.3 Middle-out Perspective

On the contrary to bottom-up, the term middle-out is not as well conceptualised or recognised in the literature base. The terminology is, however, not novel. One early mention of the term middle-out was in 1979, within visual processing research by Kinchla in [210]. More recently a middle-out assessment has been developed by authors Parag and Janda in [213]. This is in the subject of energy systems, building performance, and low carbon systemic societal transitions. They argue that although systems are complex by nature, and frequently perceived as only having a bottom actors and top actors e.g., the government and citizens, in fact, the middle actors of a system (professionals, communities, organisations and smaller institutions) play a large role in the durability of systemic change [221].

Despite much of the research on a middle-out analytical framing being linked to energy, buildings and efficiency, some literature has shown how middle actors can play a role in demand management and shaping governance [212], [213]. It is also not unreasonable to suggest that findings could be generalised to transport systems. In the end, transport systems materialise as agglomerations of system elements including but not limited to infrastructures, vehicles, operators, supply chains, and institutions etc. which are deeply intertwined. Moreover, each element has its own needs. So, for this research the middle-out perspective is coined as an analysis of these inter-element relationships.

Thus, to successfully appraise retrofit as a transport decarbonisation measure from a middle-out perspective its impact on the "symbiotic associations among system actors in geographic proximity for sharing resources" [210] needs to be completed. This will require the study of interactions between system elements at the meso-transport-system level. One method to incorporate multiple actors into this meso level analysis is through the use of an ABM. Hence, for this section of research an ABM of a group of retrofits was undertaken to determine their interactions with an existing transport system environment and its actors/elements.

Agent-based modelling is a powerful tool to simulate the actions and interactions of autonomous agents to understand the behaviour of a system, specifically human systems. [224]. The agents are entities, notions, or software abstractions similar to objects, methods, procedures, and functions in traditional programming. However, they are intrinsically more autonomous than objects and hence allow for the simulation of more sophisticated intellectual capabilities such as reasoning, learning, and planning etc. into the problem domain [225]. When the interactions of agents are contingent on past experience and adaption to that experience, mathematical analysis is typically limited in its ability to derive dynamic consequences [226]. In this case, ABM is a practical method of analysis [225]. Overall, ABMs allow practitioners to examine the behaviour of a system as a result of micro level properties, constrains, and rules.

There are many uses of ABMs, from attempts to guide policy [227], simulation of complex freight transport chains [228], and charging behaviour [229], to modelling multi-energy networks [230] and chronic diseases [231]. ABMs can vary largely in scale, in transport this can manifest as the difference between a small pedestrian simulation to a large simulation of London in [232]. ABMs however do have limitations mostly stemming from model confirmation bias, especially at high levels of abstraction such as determining policy effects [233]. For these types of problem definition it is recommended that ABM be used for possibilistic modelling rather than probabilistic (forecasting) i.e., to "anticipate the various things that could happen" so that policy can be steered/adapted [234]. Not all the limitations of ABM are currently understood but poor input data, cost of computation, transparency of the model, validation, reproducibility and standardisation are all variables that need to be considered [235]. Ultimately, in an academic setting these limitations are not particularly problematic but, in another institutional setting a poor model could have significant consequences [236].

The software AnyLogic is used in this research to develop an ABM. AnyLogic is a closed source, java-based software package that can produce large scale models for a "moderate" amount of development effort [225]. AnyLogic software contains an intuitive integrated development environment and interactive user interface builder. Simulations produced can be 2D or 3D in style, interactive, and typically focus on manufacturing, business strategy, innovation analysis, transport, healthcare, social science, economics, urban dynamics, supply chains, logistics etc  [237]. This aesthetically appealing method of model delivery is more accessible to a prospective audience who wish to observe the dynamical interactions between agents and the consequences/impact on overall system performance [238]. Additionally, AnyLogic is working to provide the integration of Python in future updates, which will increase its accessibility to other users [239].

### 3.4.4 Top-down Perspective

The term top-down has been utilised in the literature base in a similar quantity and in similar fields to the term bottom-up. This could be due to the fact that the terms are in natural opposition. For comparison, the definition of top-down processing is that background knowledge influences observation. In the context of transport this existing knowledge could be thought of as contemporary transport system arrangements and governance structures which are often distilled at the macro level as a broad generalisation. The usefulness of a top-down approach is that a change at the macro level can have a widespread impact on a system. Transport policy alterations are a good example of a top-down change, for example, the ICE car phase out in the UK.

Therefore, to implement a top-down perspective of appraisal for retrofit, it needs to be considered at a macro scale under a scenario of broad adoption, for example, an assessment of its impact on transport decarbonisation as a policy measure. To consider retrofit as a policy measure, a SD procedure was adopted because it is often used in policy analysis at a high level of abstraction (i.e., an appropriate spatial and temporal scale) [240]. SD is implemented by first mapping the causalities of a bounded system and then representing this map of causalities in a stock and flow model (SFM). To bound the scope of the model so that retrofit as a policy measure can be effectively critiqued, the policy was limited to impacting a fixed population of vehicles and embodied emissions were the sole focus of quantification.

Quantitative inputs for this assessment of a retrofit policy were taken from previous works e.g., a life cycle inventory (LCI) of emission data and real-world estimates of vehicle stockpile size. The CLDs in this methodology aim to identify the dynamics affecting embodied emission flows within a vehicle stockpile. The CLDs are constructed in the software package Vensim which is a popular software for practitioners of SD. The CLD structures were informed from existing, holistic literature such as LCA's, LCI's and works on the circular economy in the automotive sector.

Primary data was used for CLD translation to a SFM, but secondary data was also essential due to the breadth of certain CLDs. This is especially true for the automotive regime where social, economic, and technological factors (to name a few) play a crucial role in the dynamics of the sector. The SFM is implemented in the platform AnyLogic and is then used to quantify a retrofit pathways effects on embodied emission dynamics and to perform multi-variate analysis. Of significant interest are the impact of retrofit adoption rate on emissions, how policy delay impacts emissions and how the attractiveness of retrofit could be impacted by the supply of donor vehicles and subsequently, how this also impacts emissions.

### 3.4.5 Modelling Approaches

All three perspectives utilise modelling approaches. Modelling was preferred in this instance, not due to the overarching methodological approach of this research per se, but due to convenience as the majority of this research was conducted during COVID-19. Therefore, in terms of completing individual research, maintaining research speed, and mitigating the impacts of lockdowns, modelling became an indispensable approach. Furthermore, the middle-out and top-down perspectives were difficult to achieve without modelling, without more research resources (time, labour and fiscal) being available.

The modelling approaches chosen were aligned with the three different levels of abstraction i.e., differing spatial and temporal scales. Figure 18 depicts the modelling approaches used with green boxes and shows how model types differ. Note that a number of the boxes have arrows denoting their possible variability. e.g., system dynamics can be conducted to have a much more local or global applicability depending on model design. Some perspectives utilise a combination of modelling techniques which have been used to enable deeper and more detailed analysis of low-carbon transitions [209].

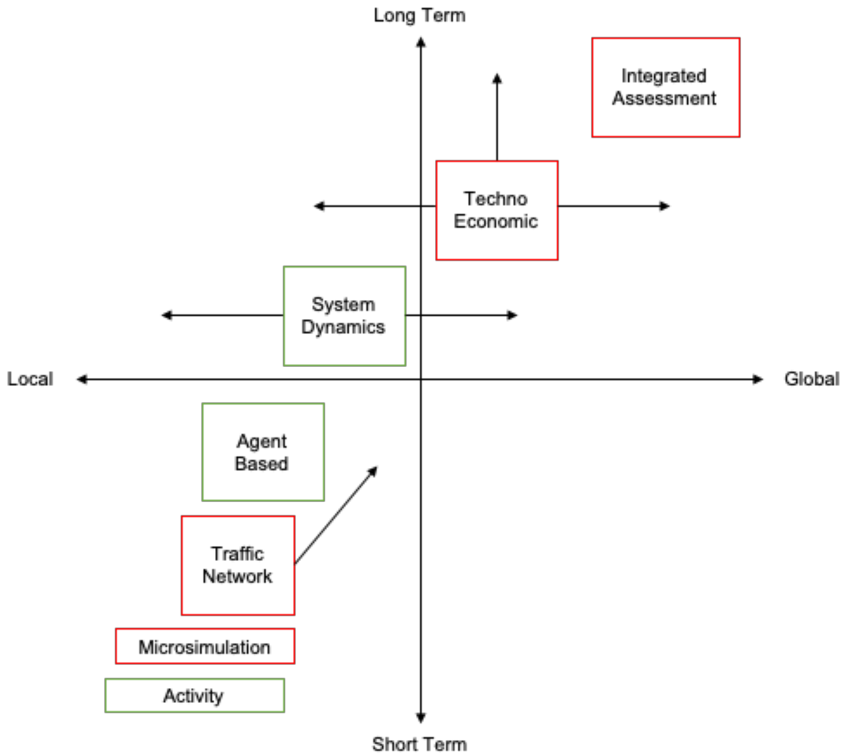


Figure 18: Spatial vs temporal variation in modelling techniques edited from [240].

Similarly, Figure 19 from work in [241] catalogues the variation in agent-based (AB), system dynamics (SD), and discrete event (DE) approaches in the context of their levels of abstraction. Overall, discrete event modelling highlights the complexity emerging from individual decisions, agent based modelling represents the complexity resulting from the decentralised behaviour of individual agents within a common ruleset, and system dynamics facilitates the inclusion of longer-term dynamic complexities.

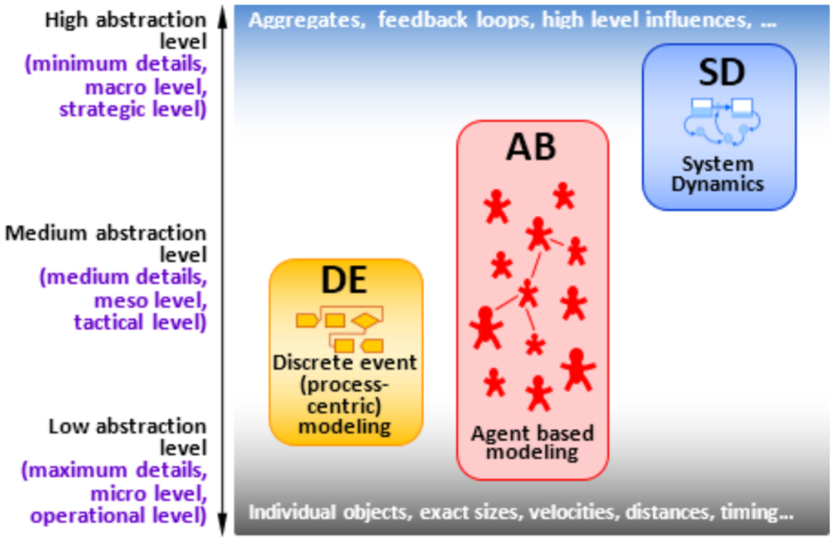


Figure 19: Comparison of DE, AB, and SD modelling abstraction levels [241].

## 3.5 Summary

To the authors knowledge, no microscopic, mesoscopic, and macroscopic analysis has ever been dedicated to facilitating an appraisal of transport decarbonisation solutions such as retrofit in an agricultural context. It is hoped that by utilising the MLP and analogous literature as a foundation for appraisal in this manner, this can form a scaffold for the appraisal of other transport decarbonisation solutions and supplements existing transport appraisal methodologies. For example:

- Treasury Green and Magenta Books for Appraisal and Evaluation [242]
- Welsh Government Transport Appraisal Guidance [243]
- UK Government Transport Appraisal Guidance [244].

To conclude, Table 9 contains a summary of each technical chapter of this research including chapter outputs/insights and how the MLP has inspired a comprehensive analysis of retrofit. The summary also includes the aims and key research methods from each chapter.

Table 9: Summary of methodological approaches in chapters 4, 5 and 6.

| **Chapter** | **Bottom-up Perspective** | **Middle-out Perspective** | **Top-down Perspective** |
|---|---|---|---|
| Aim | Evaluate the performance of a retrofit in the context of the case study at the individual vehicle level against other solutions. | Consider how interfaces between transport system elements are affected by the integration of a number of retrofits at the level of system actors in resource proximity. | Investigate widespread retrofit adoption as a policy measure for transport decarbonisation at a strategic level. |
| Primary Research Method | Activity Modelling and Desk Study | Agent Based Modelling | System Dynamics (CLD and SFM) |
| Outputs and Insights (in line with research objectives) | Description of technique/technical processes for retrofit of an ICEV.<br>Energy consumption of a retrofit, its donor ICEV and a new EV.<br>Emissions of a retrofit, its donor ICEV and a new EV.<br>Estimated costs (capital and operational) of a retrofit, its donor ICEV and a new EV.<br>The viability of an individual retrofit to decarbonise a vehicle whilst being attractive techno-economically in the context of other vehicular solutions. | Operation scenario analysis of retrofits.<br>Effects of retrofit battery capacity variation on operation.<br>Reducing emissions and operating costs through integration with local renewable energy generating assets (middle actors).<br>Impacts of human agency on retrofit solution integration through stochastic modelling. | Exploration of embodied emission dynamics of vehicle stockpiles.<br>LCA of vehicle replacement scenarios.<br>Investigation of factors impacting retrofit attractiveness in the policy context.<br>SFM exploring the dynamics of vehicle stockpile embodied emissions with and without retrofit pathway.<br>Assessment of the impact of other policy measures on retrofit.<br>Ability for retrofit to delay embodied emissions to landfill, save on overall embodied emissions and buy time for future decarbonisation solutions. |

# Chapter 4 Bottom-up Perspective

## 4.1 Introduction

This chapter appraises retrofit as one solution to aid in the decarbonisation of transport from a bottom-up perspective. This is accomplished through conducting a technoeconomic analysis of an individual ICEV converted to an EV through a retrofit process. The ICEV in question for this analysis is a used LRD vehicle operating in the agricultural sector. The chapter begins with a review of the technical requirements for the retrofit of this LRD. This is followed by an analysis of the technical performance of the LRD through the collection and examination of primary vehicle data. The performance metric of significance is the vehicle's energy consumption. This consumption is then compared to the original donor LRD and a new EV through the use of a series of activity models created using FASTSim.

Following the performance comparison, the chapter conducts a desk study of retrofitted EV parts to estimate the capital cost of conducting a retrofit of the LRD. Furthermore, the operational cost based on the previously calculated performance data is also estimated. These capital and operational cost figures are then directly compared against the donor LRD and the same new EV again to provide an economic comparison of choosing the retrofit pathway. The chapter concludes with an introduction to a concept, flexible retrofit tool that could aid the commercialisation of retrofit, a discussion surrounding this bottom-up appraisal and its conclusions.

## 4.2 Electrification of Land Rover Defenders

The LRD is considered a versatile and capable off-road utility vehicle and the first was produced in 1983. There are three main models of LRD, the 90, 110 and 130 which correspond to three choices of wheelbase, 90-inch, 110-inch, and 130-inch (originally named the 127) though in actuality, the value of the wheelbases is not quite accurate e.g., the LRD 90 is actually 92.7 inches. The LRD has a range of body styles including a 3-door, 5-door, 2-door high-capacity pickup and 3-door panel truck [245]. The model of LRD considered for retrofit in this research is the 110 300Tdi. The 300Tdi denotes the model of engine which was in production between 1994 and 2006. The 300Tdi ICE is a 2.5L, 4-cylinder, turbo charged diesel design fuelled by two stage injectors fed by a mechanical injection fuel pump. The 300Tdi engine block is cast iron and the head is cast alloy. It produces 264 Nm of torque and 83 kW of power [246].

Three LRDs of this variant were analysed at Worthy Farm. All three have permanent four-wheel drive systems coupled to their ICEs via front and rear live beam axles with open differentials. These axles are driven by two prop shafts which are connected to two outputs on the transfer case. The 2-speed transfer case is coupled to a 5-speed manual gearbox and then to the ICE via a single friction plate clutch. The LRD has never been built with an alternative powertrain to the ICE and always contains a manual transmission and manual transfer case which were key features to control the vehicle on off road terrain [33]. The particulars of the three LRDs which were retrofitted to EVs at Worthy Farm are detailed in Table 10. During the process a significant proportion of existing componentry was retained. The main change to the vehicles was the removal of their ICEs and the installation of an electric motor coupled to the existing transmission casing via an adaptor plate as shown in Figure 20. These LRDs also utilises an aluminium body on a steel ladder chassis (body on frame design) which is well suited for retrofit. During retrofit, some LRD systems need to be altered. Notable systems include but are not limited to:

- power steering system
- braking system
- climate control system
- driver signals, instrumentation, and lighting systems

Systems that can remain unchanged are the radio, rear glass heating, coolant temperature gauge and clock (as there is no tachometer).

Table 10: Specification of Worthy Farm LRD vehicles utilised for retrofit.

| **Data** | **Worthy Farm Converted Defenders** | | |
|---|---|---|---|
| Registration No | P511 NBJ | M958 POH | J882 FPS |
| Registration Year | 1996 | 1995 | 1991 |
| Registration Colour | Blue | White | Blue |
| Wheelbase | 110 | 110 | 90 |
| Body Style | 2-door pickup | 3-door | 3-door |
| Engine | 300Tdi | 300Tdi | 200Tdi |
| Gearbox | 5 Speed Manual | 5 Speed Manual | 5 Speed Manual |
| Total milage MOT | 154,304 | 185,404 | 139,475 |
| Average annual milage | 5935 | 6867 | 4500 |
| Image |  |  |  |

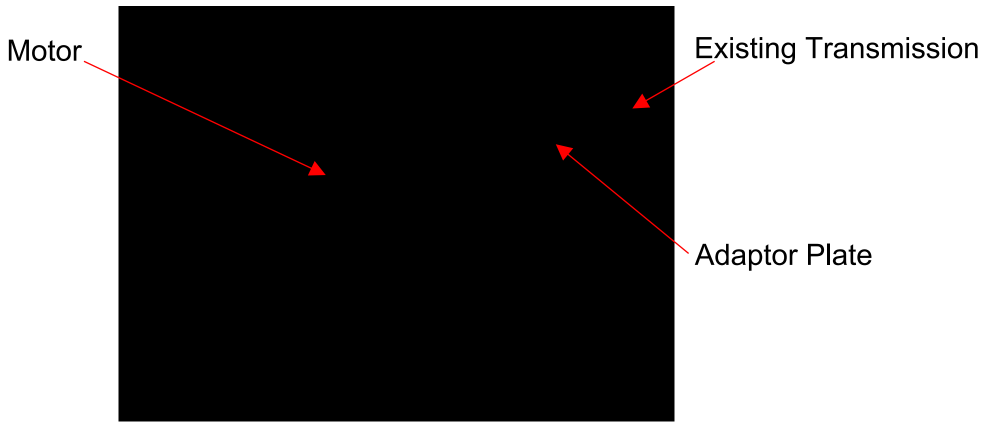


Figure 20: Electric motor connected to existing LRD transmission via adaptor plate.

The power steering system is fed by a hydraulic pump driven by the ICE, this pump is connected to a hydraulic steering box. For the retrofit an electric power steering system can be installed either through electrifying the pump and supplying the existing steering box, electrifying the steering box, or installing an inline electric steering rack. These options are similar for many old ICE vehicles. Power consumption and complexity of installation will influence the choice of option on a vehicle-by-vehicle basis.

The braking system is power assisted through the use of a vacuum pump. The retrofitted EV can utilise a replacement electrical or parasitic pump to save costs by keeping the rest of the existing braking system. However, complexity within the braking system is introduced if regenerative braking from the new motor and controller is desired. This is very useful to assist in overall vehicle control (especially during off road conditions or when pulling a trailer) and helps to simulate the engine braking of the old ICE. Furthermore, the regenerative action recharges the LRD retrofits battery improving its overall efficiency. If this option is chosen, the brake pedal of the LRD will need to be adapted to provide a signal to the motor controller that regen is required, or an additional control input will need to be added to select a fixed amount of regenerative action during zero throttle conditions [247].

The climate control system in a 1990s LRD normally consists of a simple heater utilising the waste heat from the engine cooling system. For the LRD retrofit (and depending on budget) a resistive heater or heat pump can be installed. The heat pump option is preferable from a power consumption standpoint but is more complex and costly. Furthermore, the LRDs at Worthy Farm do not have air conditioning, but this could feasibly be added.

For driver signals, instrumentation and lighting, the speedometer can continue to be driven from the transfer case and the fuel gauge could be used to represent the state of charge (SOC) for the battery pack through use of a small servo or stepper motor. The fuel gauge feedback is derived from a potentiometer in the fuel tank; thus, an equivalent voltage could be simulated for SOC, however in general, it is much simpler to install a new user interface display connected directly to the vehicle's CAN bus which interfaces with the new componentry. Finally, the replacement of all incandescent lighting systems with light emitting diode technology is advised to reduce auxiliary power consumption.

Overall, any retrofit process should aim to produce a retrofitted vehicle that facilitates easy implementation. In terms of the retrofitted LRDs at Worthy Farm the largest change in usage behaviour involves the training of drivers to utilise the clutch pedal of the manual transmission to simply 'select' a gear without applying throttle input. This is because an electric powertrain cannot stall. Figure 21 contains a simplified schematic depicting the changes in LRD architecture after retrofit using colour coding. The colours represent the replacement or reuse of vehicle components. This block diagram should not be taken as the perfect retrofit approach, nor identical to the LRDs of the case study as certain intricacies may be different such as the layout of cables depending on the specific LRD model and specific component selections e.g., the choice of on-board charger (OBC). It aims only to provide a foundational scenario of the retrofit process.

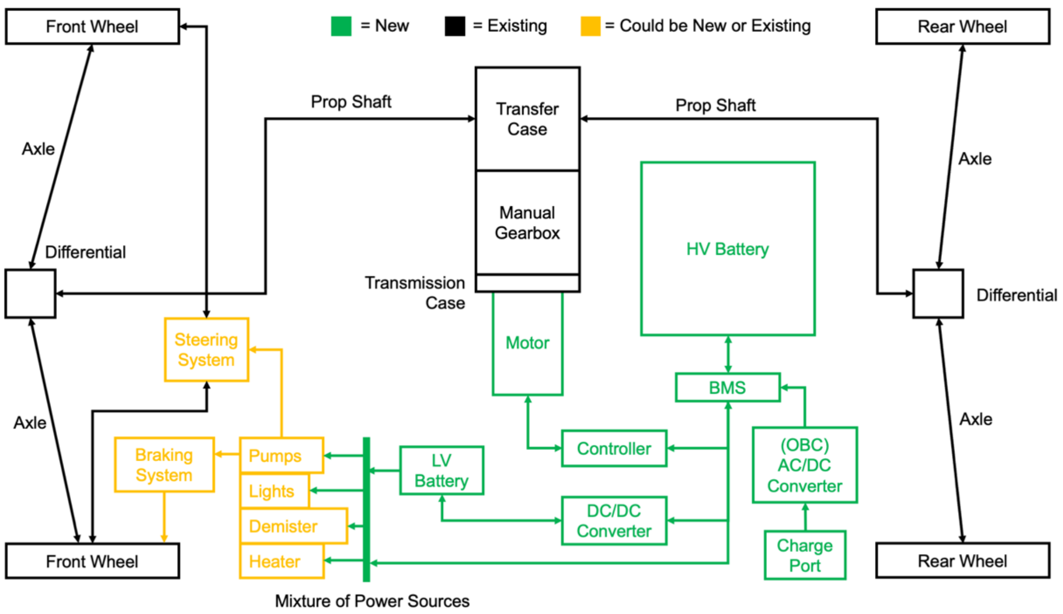


Figure 21: Block diagram of the LRD retrofitted EV.

### 4.3 Energy Consumption Comparison

In this section a comparison of LRD ICEV, new EV and retrofitted LRD retrofit energy consumptions and resultant changes in direct emissions is conducted. Energy consumption was derived from primary data from Worthy Farm or simulated through the use of the FASTSim and an input drive cycle created at Worthy Farm - The Worthy Farm Drive Cycle (WFDC). FASTSim was produced by the NREL and is a tool that supports the comparisons of vehicle performance [219].

The tool aims to provide an effective way to compare powertrains and estimate the impact of technology improvements on vehicles. FASTSim accounts for factors such as drag, acceleration, ascent, rolling resistance, component efficiency, power limits, and regenerative braking. The tool also has many features outside of the scope of this research such as simulation of electric roadway charging technologies, power vs efficiency mapping for individual components, component calibration, shift scheduling and transmission impacts etc. Therefore, an abridged explanation of the tool is provided here with more detailed overviews available in [218], [248] and [249]. It is important to note that the outputs and prepopulated inputs of FASTSim have been validated through comparisons with measured test data, a validation report can be found in [219].

FASTSim was developed in Excel, model calculations reside in the various worksheets, Visual Basic for Applications (embedded in Excel) is used to run/manage these models. The main vehicle input parameters for FASTSim (on the “VehicleIO” tab) include drag coefficient, frontal area, glider mass, cargo mass, centre of gravity, drive axle weight fraction, wheelbase, wheel information (e.g., number, inertia, rolling resistance, radius etc.) and auxiliary loads. Then depending on powertrain type, components such as vehicle fuel storage, battery specifications, motor parameters etc. are also available. Parameter inputs to FASTSim for this research can be found in Appendix B.

To compute energy consumption over a specific drive cycle, this research used the Powertrain Model within FASTSim. This determines if vehicle component limits can fulfil the requirements of the drive cycle i.e., if the drivetrain power required for the drive cycle is equal to the drivetrain power received from vehicle components working, more detail on this process can be found in [248]. The formulae that relate to individual vehicle components are all contained and visible in the “Veh Model” worksheet of FASTSim, they are written in a readable form, for example:

Power to overcome drag =
0.5*airDensityKgPerM3*dragCoef*frontalAreaM2*(AVERAGE(+prevMpsAch,+cycMps)^3)/1000.

Where “airDensityKgPerM3” is the air density in units of kilograms per meter cubed; “dragCoef” is the vehicle drag coefficient; “frontalAreaM2” is the vehicle frontal area in units of meters squared; “prevMpsAch” is the previous vehicle speed achieved in meters per second; “cycMps” is the input drive cycle's current speed in meters per second; and “prevMpsAch” and “cycMps” are arrays where the “+” denotes use of the value in the corresponding row and not the whole array. Note that the division by 1000 produces an output in kW. Information on “Veh Model” worksheet inputs can be found in Appendix B.

FASTSim is then structured to maintain and propagate a consistent set of powertrain calculations as the model steps through a drive cycle second by second. The calculations and results are saved to a new worksheet for each drive cycle.

The WFDC input to FASTSim was created using floating phone data during a LRD movement at Worthy Farm. The floating phone data was captured using the application TrackAddict which measures time, location, accelerometer, and barometric pressure data from a mobile device to derive time varying, speed, altitude, longitude, and latitude datasets. The WFDC route is depicted in Figure 22 and was chosen as it represents a typical route likely to occur on the farm with both uphill and downhill sections. WFDC velocity and altitude profiles are provided in Figure 23 and Figure 24 respectively.

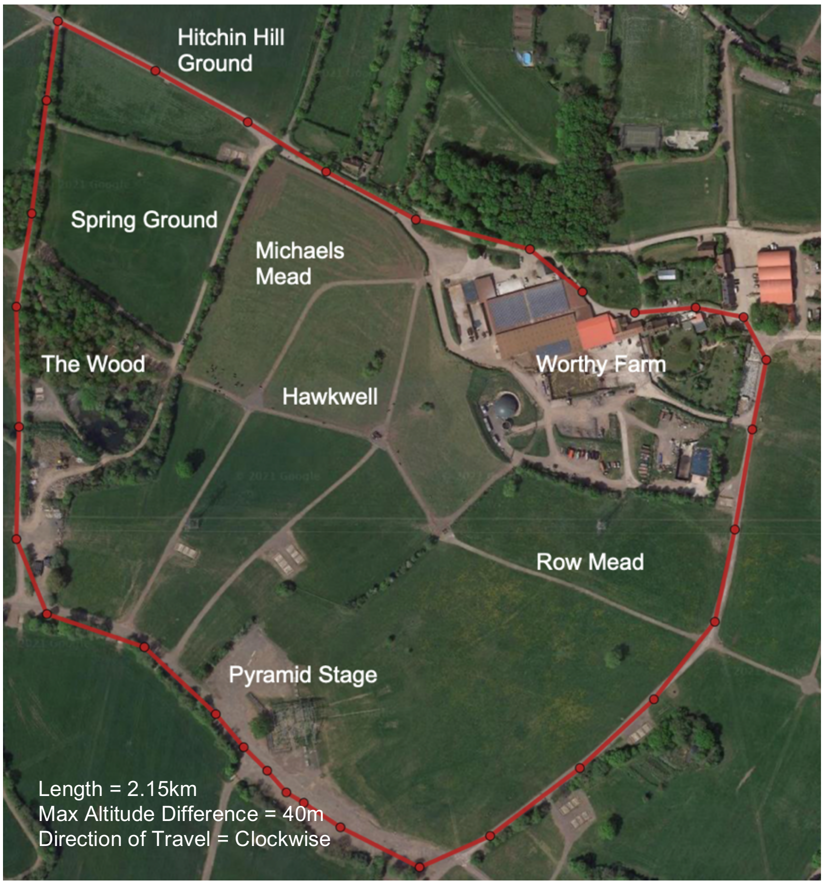


Figure 22: WFDC route (image created using Google Maps).

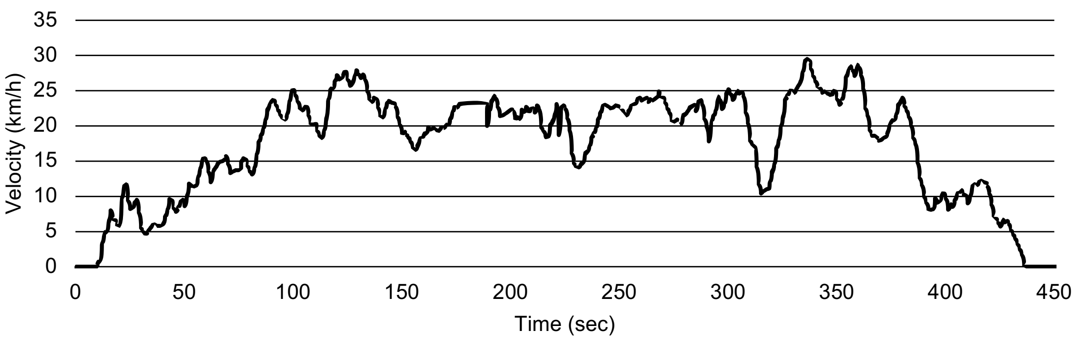


Figure 23: WFDC velocity profile.

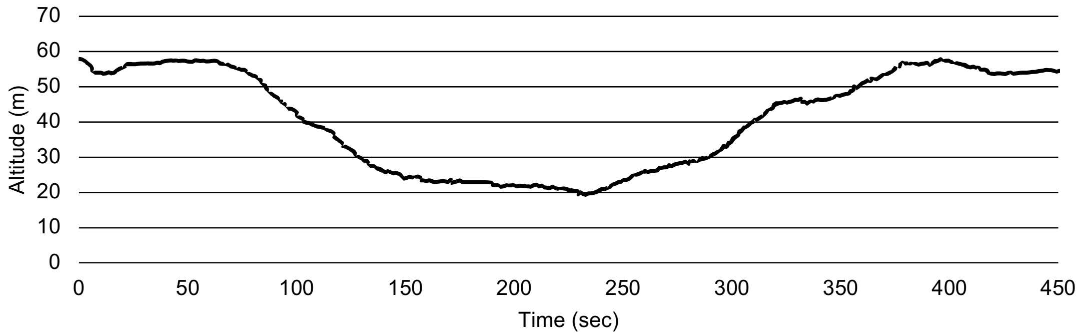


Figure 24: WFDC altitude profile.

### 4.3.1 Internal Combustion Engine Vehicle

To assess an ICEV, manufacturer data for a 1995 LRD 110 300Tdi taken from [246] is presented in Table 11 to examine vehicular performance before retrofit. This manufacturer data was inputted into FASTSim and can be found in detail in Appendix B. After running the simulation, an energy consumption estimate was exported and is plotted in Figure 25. A final energy consumption figure was then derived for the ICE powertrain. It would have been beneficial to obtain primary data from an LRD ICEV on Worthy Farm but unfortunately, due to COVID-19, this was not possible before the retrofits were completed.

Table 11: 1995 LRD 110 300Tdi specifications sourced from [250].

| **Specification** | **Value** |
|---|---|
| Peak power | 83kW |
| Length | 4599mm |
| Width | 1790mm |
| Height | 1996mm |
| Wheelbase | 2794mm |
| Coefficient of drag | 0.65 |
| Frontal area | 2.97$m^2$ |
| Curb weight (no driver) | 1979kg |
| Fuel capacity | 80L |
| Manufacturer energy use[1] | 97kWh/100km |

[1] Figure based on manufacturer claimed urban cycle fuel consumption of 9.7L/100km from [250]. 1L of diesel equivalent of 10kWh [251].

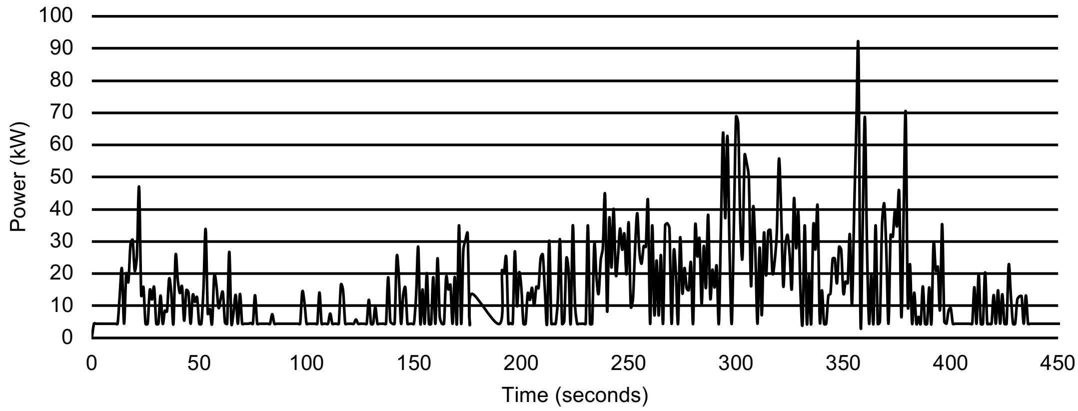


Figure 25: FASTSim fuel system power output for 1995 LRD 110 300Tdi during WFDC[2].

The data used to generate the plot in Figure 25 is recorded at one second time intervals, so the energy consumed at each Y axis data point is a kWs i.e., if at t = 50 seconds the power is 35kW the energy consumed during this second interval is 35kWs. These kWs values can then be summated and converted to kWh to compute the total energy consumption. It is calculated, that over the WFDC, 1.89kWh of energy is consumed equating to an average energy consumption of 87.9kWh/100km. Notably, this is around 10% lower than the manufacturers figure of 97kWh/100km (but well within expected variations in consumptions [252]) the more modest consumption could be due to the lower speeds of the WFDC compared to the manufacturers drive cycle (see Urban Cycle completed as per Annex III of Directive 70/220/EEC in [253]).

### 4.3.2 New Electric Vehicle

Currently, no modern full electric LRD model exists to compare against the retrofitted variant of the case study. The closest offering from Jaguar Land Rover (JLR) is its plug in hybrid Defender which starts from £63,000 [254]. The complexity of the hybrid powertrain, and its non-zero emissions, means it is discounted from this comparison on the grounds that it is an ineffective decarbonisation solution. Instead, the electric Rivian R1T was used to investigate alongside the retrofit. The Rivian was selected as at the time of completing this research, no modern fully electric utility focused off-road vehicle was available on the UK market[3]. This selection is noted as a limitation as, for example, the Rivian has a much higher rated maximum power than the LRD (5x more) and a luxury interior. However, this peak power is not going to be utilised at Worthy Farm and so its energy consumption under low-speed operation should be representative of a vehicle of this category completing a WFDC. The manufacturer data for the 2022 Rivian R1T 135kWh EV from

[2]Using fuel system power output data rather than engine power output data allows for powertrain efficiency to be considered, for more information see Appendix C.
[3] Only ‘pick up’ style vehicle is the Maxus T90 EV Elite which is 2-wheel drive only and has similar rated energy consumption and list price to the Rivian R1T.

[255] and [256] is presented in Table 12 alongside the ICE and retrofit LRD for convenience. This data was used to create the FASTSim inputs (located in Appendix B). Figure 26 shows the resulting power output data for the Rivian R1T 135kWh battery. This data is used to compute its average energy consumption.

Table 12: 2022 Rivian R1T 135kWh specifications [255], [256].

| **Specification** | **Rivian R1T** |
|---|---|
| Peak power | 562kW |
| Length | 5537mm |
| Width | 2007mm |
| Height | 1829mm |
| Wheelbase | 3429mm |
| Coefficient of drag | 0.3 |
| Frontal area | 3.09m$^2$ |
| Curb weight (no driver) | 2670kg |
| Battery capacity | 135kWh |
| Fuel tank capacity | N/A |
| Manufacturer energy use[4] | 28kWh/100km |
| Range | 483km |

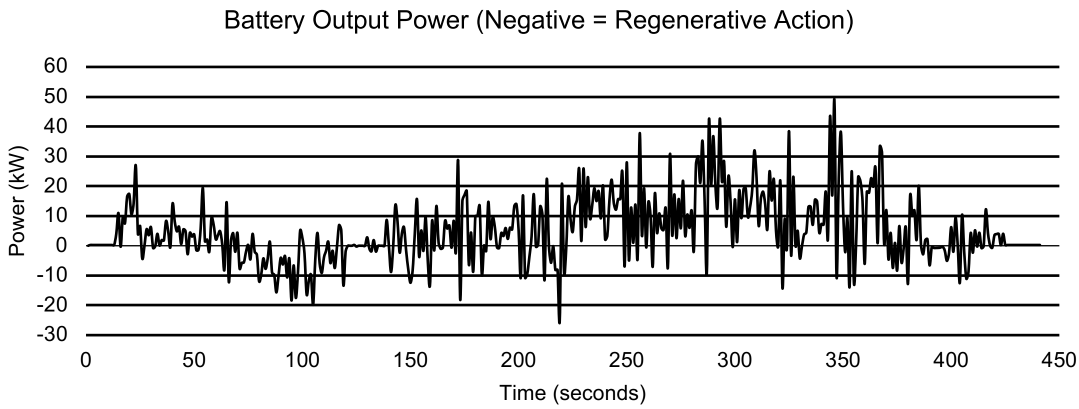


Figure 26: Rivian R1T battery power output (negative values indicate regen).

From this plot it was estimated that the Rivian R1T's total energy consumption during the WFDC is 0.62kWh (28.8kWh/100km), this is similar to the manufacturers figure of 28kWh/100km.

### 4.3.3 Retrofit Electric Vehicle

The final powertrain in this comparison is of the 1995 LRD 110 retrofit at Worthy Farm. This retrofit has an approximate battery capacity of 52kWh and utilises a Hyper-9 electric drive unit and controller producing a peak power of 102.8kW and 235.1Nm of torque at 120V (41.5kW and 88.8Nm continuous at 108V) [172]. Ten used 5.3kWh Tesla modules supply electrical energy to the powertrain [257]. Performance data on the motor can be

[4] Figure based on manufacturer claimed range of 483km and a battery capacity of 135kWh.

found in [172]. Data on this vehicle was collected in operation through use of an onboard microcontroller-based data logger connected directly to the vehicle's CAN bus. This data has been correlated with a WFDC route completed in the vehicle through use of data timestamps. The vehicle CAN bus consists of two dedicated conductors (CAN high and CAN low). When the bus is in idle, both conductors sit at the same voltage, when data is being transmitted, the CAN high and CAN low wires generate a voltage differential. This differential results in the bus not being sensitive to inductive spikes, electrical fields, or other noise. CAN protocols use baud rates up to 1 Mbit/s with the most common being 125 kbit/s (CANopen) and 250 kbit/s (J1939) [258]. To view the messages recorded by the retrofit, the recorded CAN frames are replayed using a virtual CAN in MATLAB Simulink. One channel replays the frames with another receiving and decoding the frames. The Simulink model used can be found in Figure 27. As the CAN frames are replayed, a database file (.dbc), created in Kvaser Database Editor, decodes the frames.

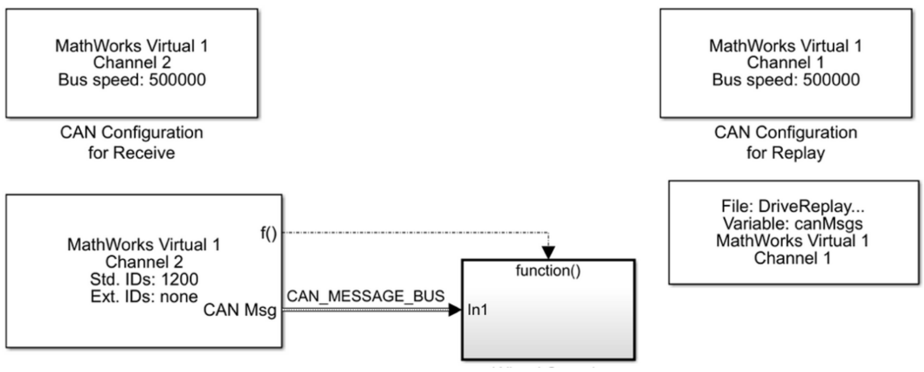


Figure 27: Simulink model to replay CAN frames, adapted from example model [51].

Through viewing the CAN frames corresponding to the "Controller Supply Voltage" and "DC Bus Current" the power output of the LRD retrofit was estimated. The CAN frames were selected over the time period of a WFDC to determine its energy consumption. Selection of the frames was based on matching the timestamps of floating phone data recorded by the TrackAddict mobile application and CAN frame timestamps of the retrofit. From the data it can be estimated that the retrofit consumed 0.66kWh during its completion of the WFDC route which equates to an average energy consumption of 30.7kWh/100km. This figure is similar to that of the Rivian and based on this figure and the 52kWh battery pack, the LRD retrofit has an estimated range of 169km, which will vary depending on operating conditions.

It must be noted that, as per the motor controller manual, depending on the retrofits hardware configuration the DC Bus Current is either estimated or sniffed from the battery management system. Hardware configuration was not confirmed by Electrogenic so this potential for an estimated DC Bus Current could affect the validity of the energy consumption estimate. Accordingly, it should be treated as indicative but very useful given that it provides an indication that the energy consumption of a retrofitted EV could be similar to a new EV. Moreover, the energy consumption figure is only for a singular operational scenario and will vary day-to-day, across weather conditions, driver behaviour and drive cycle.

For completeness, the retrofit LRD energy consumption was also estimated using FASTSim (using inputs documented in Appendix B). Note that a Hyper 9 motor power of 41.5kW under continuous usage at 108V was selected as the most representative input. Over one WFDC the energy consumption of the retrofit was estimated to be 0.67kWh or 31.1kWh/100km which is comparable to the result from primary data. For convenience, Table 13 contains a summary of the vehicles considered in this section, to reiterate, more details on specification/model inputs can be found in Appendix B.

Table 13: Summary table of vehicles in this section [250], [255], [256], [172].

| Specification | Rivian R1T | ICE LRD | Retrofit LRD |
|---|---|---|---|
| Peak power | 562kW | 83kW | 102.8kW[5] |
| Length | 5537mm | 4599mm | 4599mm |
| Width | 2007mm | 1790mm | 1790mm |
| Height | 1829mm | 1996mm | 1996mm |
| Wheelbase | 3429mm | 2794mm | 2794mm |
| Coefficient of drag | 0.3 | 0.65 | 0.65 |
| Frontal area | 3.09m$^2$ | 2.97m$^2$ | 2.97m$^2$ |
| Test mass (for simulation) | 2830kg | 2139kg | 2700kg |
| Battery capacity | 135kWh | N/A | 52kWh |
| Fuel tank capacity | N/A | 80L | N/A |
| Energy use (claimed/observed) | 28kWh/100km | 97kWh/100km | 30.7kWh/100km |
| Energy use (simulated) | 28.8kWh/100km | 87.9kWh/100km | 31.1kWh/100km |
| Range | 483km | 825km | 169km |

### 4.3.4 Vehicle Usage Emissions

Table 14 summarises the energy consumptions of the different vehicle types and also derives the $CO_2$ equivalent emissions from this consumption through utilisation of the 2021 emission conversion factors in [86]. Emissions are estimated over one WFDC, 100km of WFDC and 9282km of WFDC (9282km is the mean average annual milage of all three LRDs summated from Worthy Farm). In terms of specific conversion factors, the net calorific value (Net CV) of an average biofuel blend diesel has been used to compute diesel ICE emissions as it represents the realistic amount of energy which may be realised from the diesel at atmospheric (constant) pressure from the ICE [259]. Furthermore, the UK electricity emission factor for 2021 was used to estimate the

[5] 41.5kW continuous – voltage dependent.

emissions of the LRD retrofit and Rivian. Note that the retrofits primary data has been used for the comparison.

Table 14: Summary of vehicle energy consumptions and emissions.

| Vehicle | Original Defender | Rivian R1T | Defender Retrofit |
|---|---|---|---|
| Energy Consumption (kWh/100km) | 97 (Manufacturer)<br>87.9 (FASTSim) | 28 (Manufacturer)<br>28.8 (FASTSim) | 30.7 (Primary Data)<br>31.1 (FASTSim) |
| Energy Consumption during WFDC (kWh) | 1.89 | 0.62 | 0.66 |
| Emissions ($kgCO_2e$/100km) | 22.12 | 6.12 | 6.52 |
| Emissions during WFDC ($kgCO_2e$) | 0.48 | 0.13 | 0.14 |
| Emissions based on average annual LRD milage at farm ($kgCO_2e$/9282km) | 2053 | 568 | 605 |
| Conversion factors: 0.25165 $kgCO_2e$/kWh (diesel), 0.21233$kgCO_2e$/kWh (electricity). | | | |

Overall, the retrofits emissions are approximately 29.5% of the original ICE LRD. This is a significant improvement and is in line (but potentially a slightly lower reduction) when compared to other studies use phase emissions estimates comparing diesel to modern battery EVs [260], [261], [262]. However, this slightly poorer reduction in use phase emissions could be due to retrofits lack of a bespoke EV platform. Note that Section 6.4 expands on this section to complete a retrofit life cycle emissions estimate.

### 4.4 Economic Comparison

In this section a comparison of the capital and operational costs is conducted for the three vehicles. EV retrofit capital costs have been estimated through creating an estimated list of parts using a collection of secondary data sources. Additionally, indicative labour and donor vehicle costs are also added for completeness. Details can be found in Table 15. Note that within the table is an assumption of a five-module battery pack configuration rather than a ten to reduce costs. Five modules are estimated to produce a high enough range LRD retrofit at Worthy Farm given that the three LRDs in the case study average 25.4km per day according to their MOT data. The costed parts include common components that are major in function to the vehicle e.g., motor, charger, and battery but exclude smaller parts and costs that vary between retrofit projects such as lengths of cable, tubing, cabin heaters, small fittings, or electrical connectors. The cost of the tools necessary to complete installations was also excluded. It must also be noted that the parts are considered to have been purchased individually, but a future LRD retrofit kit could lower these costs significantly through bulk purchasing and reducing labour etc.

Table 15: LRD retrofit estimated capital costs[6].

| Part | Quantity | Unit Cost | Ref. |
|---|---|---|---|
| NetGain Hyper 9 Motor and Controller | 1 | £3683 | [167] |
| NetGain Hyper 9 Mounting Bracket | 1 | £200 | [167] |
| Tesla 5.3kWh 22.8V 74p6s Battery Module | 5 | £949 | [263] |
| 5-Module Battery Box | 1 | £1529 | [264] |
| Orion 2 36 Cell Battery Management System | 1 | £822 | [167] |
| Orion 2 Cell Tap Wiring Harness 6ft | 1 | £60 | [167] |
| Tesla Battery Management Replacement Board | 5 | £18 | [167] |
| Tesla Module Busbars | 4 | £12 | [167] |
| GIGAVAC Contactors | 2 | £136 | [167] |
| HV Connector 2-3 Way Generic Budget | 1 | £250 | [167] |
| HV Service Disconnect Generic Budget | 1 | £100 | [167] |
| Fuses Generic Budget | 1 | £200 | [167] |
| Key Switch Relay | 1 | £22 | [167] |
| Elcon TC HK-J 6600W Charger | 1 | £627 | [265] |
| Charing Port Locking Solenoid Pin | 1 | £27 | [167] |
| Type 2 32A 3-Phase Socket + Internal 3m Cable | 1 | £110 | [167] |
| External 32A 3-Phase 5m Type 2 Charging Cable | 1 | £110 | [167] |
| DC/DC Converter 74-162 Volts DC | 1 | £319 | [167] |
| Brake Vacuum Pump Kit | 1 | £228 | [167] |
| Hall Effect Throttle | 1 | £202 | [167] |
| Electric Power Steering | 1 | £600 | [161] |
| Coolant Pump (Bosch Electric Water Pump) | 1 | £69 | [167] |
| Radiator 190x235x26mm | 1 | £108 | [167] |
| Radiator Fan 190mm | 1 | £82 | [167] |
| Tesla Battery Module Coolant Manifold | 2 | £27 | [167] |
| Netgain Hyper Drive Compact Display | 1 | £136 | [266] |
| **Total Cost Excluding Labour** | **£14693** | | |
| Estimated Labour Cost Hourly[7] | 200 | £60 | [267] |
| **Total Cost Including Labour** | **£26693** | | |
| Used Donor LRD Cost[8] | 1 | £11645 | |
| **Total Cost Including Labour and Donor Vehicle** | **£38338** | | |

Operational costs considered are fuel, tax, and depreciation. Table 16 contains the summary of costs for each vehicle. Note that vehicle insurance, maintenance and servicing were excluded due to their variability based on personal circumstance and poor data availability. Details on depreciation calculations can be found in Appendix E. All prices in foreign currencies ($ and €) are converted to pound sterling at an exchange rate of £0.80/$ and £0.84/€. All prices presented include value-added tax (VAT) and are rounded to the nearest pound.

[6] Costs based on a 26.5kWh LRD retrofit (5 modules) and single-phase charging system.

[7] Figure based on a one-month retrofit with part lead times ignored, mounting hardware designed, and the retrofit is familiar. Garage mechanic labour rate is £60/hr [267]. Mechanic works 200 hours [268]. Note that if garage is used then retrofit parts could be marked up, this is not considered in this analysis.

[8] Based on the average price of two comparable used LRDs on Autotrader (Autotrader filters: 1995, 110, 300TDI, 150,000 miles+ completed on 03/05/2022). Autotrader valuation tool was not used as vehicle ages are above 15 years.

Table 16: Summary of vehicle operational and capital costs.

| Vehicle | LRD ICEV | Rivian R1T EV | LRD Retrofit |
|---|---|---|---|
| New Vehicle Cost | £39267[9] | £54000[10] | £38338[11] |
| Used Vehicle Cost | £11645 | Unknown | Unknown |
| Annual VED[12] | £360 | £0 | £0 |
| Annual Fuel Cost[13] | £2013 | £535 | £570 |
| Annual Depreciation[14] | £1023 | £1774 | £1272 |
| **First Year Total[15]** | **£42663** | **£56309** | **£40180** |

From the analysis it is clear that with the desired specification suited to an agricultural context, a LRD retrofit can be as/more attractive economically than a new EV even when purchasing the donor vehicle and paying for the retrofit labour. The use of an already owned donor vehicle, a 'do-it-yourself' retrofit, and even stricter component selection could reduce costs significantly. Popular vehicle models such as the LRD (that do not vary significantly in terms of their design over a significant number of years) can likely be converted using kits which allow for bulk component purchase and greater accessibility to self-installers. Kits could also reduce contracted labour costs as professional installers become more familiar with specific vehicle retrofit processes and access to instruction manuals with proven methods.

It should be noted that the cost of retrofit plus labour excludes an additional profit margin as the component prices referenced are retail rather than wholesale/cost price. Electrogenic (the manufacturers of this LRD retrofit) claim a target price of £24,000 + VAT (£28,800) excluding the donor vehicle which is similar to the estimate of this research of £26,693 [38]. To contextualise commercial retrofit offerings further, Table 17 highlights a range of prices from other retrofit companies (note than Lunaz and Everrati focus on the high-end luxury restoration and retrofit market) sourced and reproduced from [31].

[9] Based on starting retail price in [269] of $30000 (this is £19196 at GBP-USD exchange rate on 01/01/1995). GBP is adjusted for inflation using Bank of England tool [270].

[10] US price of $67500 to pound sterling (£0.80/USD), price likely to be higher after import taxes.

[11] Price includes donor vehicle and estimated labour cost. Would be £15324 excluding donor vehicle and labour or £24924 including only labour, for detailed breakdown see Table 15.

[12] VED is based on 2021 rates and 221g/km $CO_2e$ for the ICE LRD. Rules are convoluted for older vehicles so this price could vary or potentially be zero as SORN vehicles are exempt from VED. Retrofitted EV donor vehicles registered post 1st March 2001 cannot alter original VED rate [271].

[13] Fuel costs are based on energy consumption over 9282km of the WFDC at £1.90 per litre of diesel or £0.20 per kWh of electricity. ICE consumes 11.4L/100km.

[14] LRD annual depreciation based on used price subtracted from new inflation adjusted price divided by 27 years (1995 to 2022). R1T and LRD retrofit depreciation based on Tesla Model S depreciation data over 10 years and exponential extrapolation to 27 years see Appendix F.

[15] Based on new vehicle cost price.

Table 17: Sample of retrofit prices from retrofit companies reproduced from [31].

| Company Name | Vehicle Type | Cost (£) |
|---|---|---|
| Electric Classic Cars | Classic cars | From £22,000 |
| Zero EV | Cars | Kits from £15,000 |
| Falcon Electric | Classic cars | From £18,000 + VAT |
| eDub Conversions | VW campervans and classic cars | From £40,000 |
| Electron Garage | Classic cars | From £20,000 |
| London Electric Cars | Mini, Land Rover, Morris Minor | From £20,000 |
| RBW Classic Electric Cars | Classic sports cars | From £90,000 |
| Everrati | Classic and iconic cars | £150,000 - £295,000 |
| Lunaz | Classic cars | £245,000 - £500,000 |

In terms of operational costs, the use of a new EV or retrofitted EV in this study resulted in a significant reduction in fuel costs and potentially VED. In the absence of red diesel or other ICEV subsidies this operational cost saving will be even more attractive. Furthermore, ICE LRD performance is likely to be worse than manufacturer claimed data due to efficiency decline over time, making fuel consumption worse.

EVs can also be charged by distributed energy generating assets such as solar, wind or anaerobic digestors. These installations could eliminate/reduce direct fuel costs and are well suited to spacious agricultural settings. Surplus energy could also power the agricultural holding itself and could form an additional revenue stream to asset owners. Though farms will need to conduct a cost-benefit analysis to determine if the capital to purchase this equipment is appropriate. This cost-benefit question extends to the initial specification of any retrofitted vehicle when compared to a new EV which is likely to have more modern features which may have economic benefit to an individual.

### 4.5 Concept Retrofit Tool

To aid the commercialisation of retrofit from a bottom-up perspective. This section covers a concept application which has the potential to utilise floating phone data from a client's donor vehicle in the agricultural sector to aid in the specification of a future retrofitted vehicle. The flexible tool/application would provide a hypothetical client with the confidence that a retrofitted vehicles performance will meet their needs and an estimated cost figure. Such a tool could turn retrofit into a more bespoke, demand-side decarbonisation solution and could aid in increasing the adoption of retrofit. The tool could also be utilised to increase a retrofit projects benefit to cost ratio before physically beginning the retrofit.

To aid in the conceptualisation of this tool, an example was built within the MATLAB Simulink environment and specifically through use of the MATLAB Simscape add-on. The tool has been exported as a standalone executable application through MATLAB App Designer for easy accessibility by retrofit stakeholders. Figure 28 presents a concept user interface and installation of the tool.

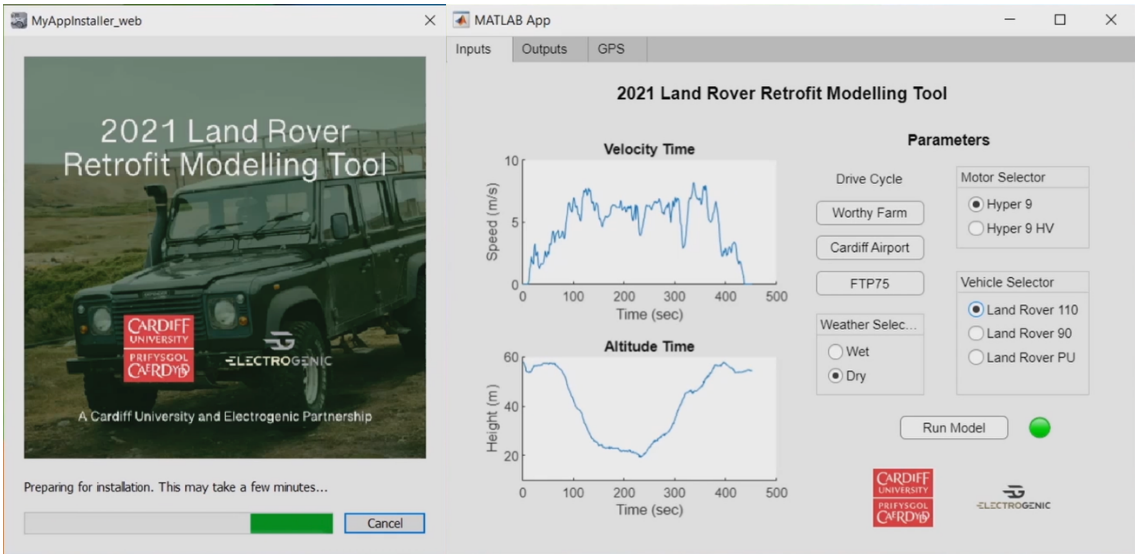


Figure 28: Tool installation and first page user interface.

In the figure the selection of a drive cycle is depicted which represents the use case of a potential donor ICEV inputted from floating phone data. The drive cycle of the donor ICEV can be collected through use of an application on a mobile device mounted inside the donor ICEV. The application collects location, barometric pressure, accelerometer, and weather data to formulate the drive cycle. If more accurate data is required for a future tool, a bespoke telematics unit could also be installed in the donor vehicle. Once the drive cycle, ICEV vehicle type, weather condition and other preferences are selected in the tool a simulation can be completed to determine the high-level specification of a retrofitted version of the donor vehicle (available parameter selections are subject to change depending on this tools validation). Figure 29 shows an indicative back end Simscape model at a system level which computes the donor vehicles retrofitted specification.

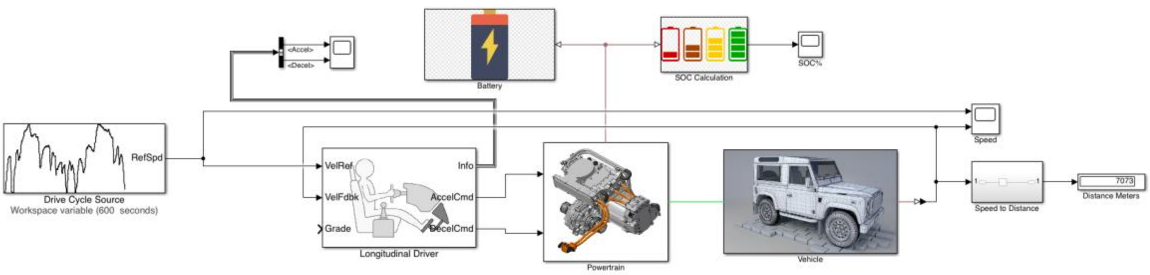


Figure 29: LRD retrofitted EV back end Simscape model.

The Simscape model utilises the floating phone input data and parameter selections to estimate the required specification for the specific use case. This bespoke specification could be used to inform a client of predicted retrofit capital cost, performance, and operational cost. Indicative tool outputs are depicted in Figure 30. The figure shows a sample of performance data (change of state of charge of the retrofitted donor vehicle over time) and a global positioning data trace from operational data to confirm that the mobile device generated drive cycle has captured donor vehicle usage correctly.

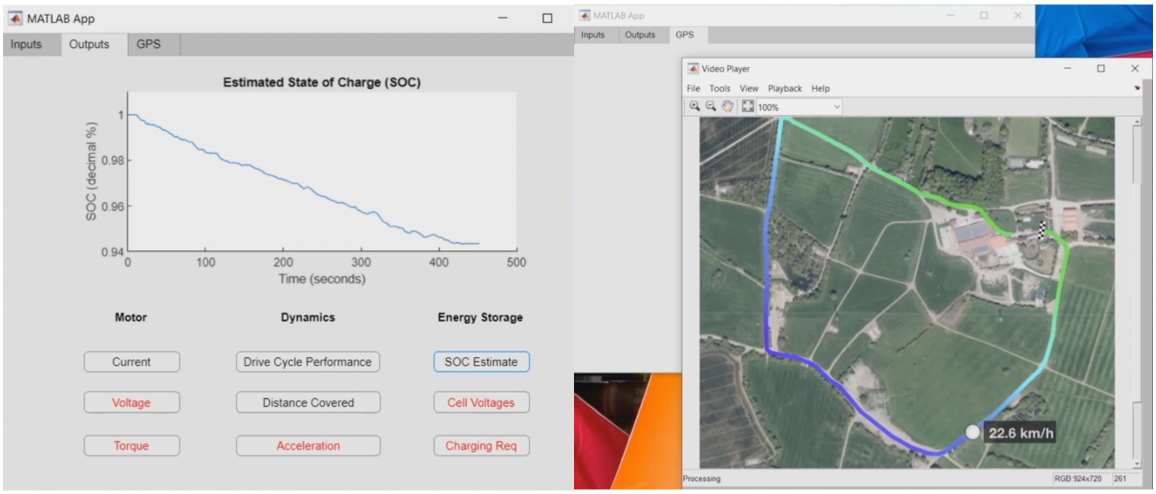


Figure 30: Example of model outputs from the tool.

Currently this example tool takes drive cycle and gradient data to compute retrofit performance figures through a pre-parameterised model. In the future, more detailed variables such as weather data need to be added along with costing elements. The tool will also conduct a sequence of model runs to portray a range of specification options and/or to provide a sensitivity analysis. Outputs of the tool should be validated against previous retrofit project datasets; so that this tool can be validated. The tool should also consider presenting emissions savings as a value add.

### 4.6 Discussion and Limitations

Firstly, from the examination of LRD retrofit in this chapter, it has been found that the retrofit of donor LRD ICEVs at Worthy Farm can significantly lower its donor vehicles direct emissions. When compared to the original donor LRD ICEV, emissions reductions could be as high as 70% through use of 2021 UK emission conversion factors. Also, direct emissions have the potential to fall much further as the grid continues to decarbonise or if cleaner electricity generating assets, such as the solar already installed at Worthy Farm are utilised as part of the LRD retrofits charging energy mix. The LRD retrofit also has similar potential for direct emissions abatement to the modern Rivian under the conditions of this specific study.

Secondly, through the economic evaluation of the LRD retrofits, it was found that the direct emissions reductions could be achieved for a lower capital cost than a new EV. This is very beneficial for sectors such as agriculture where funds for capital investment in decarbonisation could be harder to generate than in other sectors. Additionally, with careful consideration of specification, self-installation and ownership of a donor vehicle, the capital cost of retrofit could be significantly lower than ICEV replacement with a new

EV. The advent of retrofit kits for popular donor vehicle models could be a key enabler of this capital cost reduction.

Other exogenous factors such as a reduction in labour cost (typically a function of geographic variation) can also heavily influence the total capital needed for a retrofit project. In the future manufacturers could take several steps to make retrofit easier. These steps could include but are not limited to publishing details of vehicle CAN message IDs so that integration of retrofitted hardware can be simpler, and vehicles could be designed more consciously for disassembly. These steps could be introduced under similar legislation to the right to repair, which is now becoming ever more prevalent in the consumer electronics space which aims to reduce the technical capability required to repair products.

In terms of the methodological assumptions, limitations, and constraints of this chapter, it is noted that the Rivian is not an exemplary vehicle to analyse alongside the LRD ICEV and retrofit. When an appropriate mass-produced vehicle analogous to the LRD becomes available this should be compared to the retrofit. Furthermore, more duty cycles need to be considered under different conditions (e.g. temperature, weather, cargo capacities including trailers which will impact vehicle traction) to more comprehensively determine LRD retrofit performance. Supplementary research is also needed in other contexts beyond a retrofitted LRD to determine if retrofit has broader utility with other vehicle types, duty cycles and markets e.g. internationally.

Unfortunately, access to vehicles and vehicle data received during this particular study was limited mainly due to external factors such as COVID-19, but also hardware constraints of this project’s industrial partner. This should be overcome in subsequent investigation however, the outputs of this first investigation within the agricultural context are promising.

### 4.7 Conclusion

In this chapter the use of retrofit as a transport decarbonisation method has been appraised from a bottom-up perspective. This being from a microscopic level of abstraction considering the performance of an individual retrofitted vehicle in terms of its energy consumption, emissions, and economics. The appraisal utilised the central case study in which an LRD retrofit was considered in an agricultural context.

First the chapter described the methodological approach to convert an LRD ICEV to an EV through a retrofit process. This model of retrofitted vehicle was then evaluated from an energy consumption, emissions, and economic standpoint against comparable vehicles. This was specifically through the direct comparison of the retrofit to an LRD ICEV and a new EV. This work fulfilled objective one of this research to “evaluate quantitatively the energy consumption of a retrofit, its donor ICEV and a new EV to determine how it compares technically to its donor vehicle or a new EV operating under a similar use case". The chapter also provided estimated capital and operational costs for this specific retrofitted vehicle to conduct an economic comparison. These estimates satisfied objective two of this research, to quantify the cost of the retrofit of one donor ICEV to determine if it is attractive economically (e.g., capital/operational cost) when compared to its donor vehicle or a new EV with a similar purpose. To the knowledge of the author at the time of writing, the documentation of a retrofit process, and the appraisal of an individual retrofit has never been completed in the academic literature within an agricultural context.

From the results of the chapter, it has been demonstrated that retrofit could form a solution for the decarbonisation of some transport assets, especially within this specific agricultural context. Furthermore, emissions abatement could be achieved more economically whilst maintaining the suitability of a vehicle when compared to legacy ICEVs or a new EVs in the same context.

The bottom-up perspective employed in this chapter is useful as it has shown that retrofit could form a useful demand-side decarbonisation pathway i.e., a solution instigated from the perspective of system actors, though these types of solutions need to be publicised. Retrofitted vehicles can be developed and integrated directly by an actor who is immersed in the problem space, this is a key benefit. Demand-side development allows a vehicle specification to be tailored to its owners needs and this can act to lower capital costs and increase vehicle efficiency, which in turn reduces direct and embodied emissions, raising decarbonisation potential.

# Chapter 5 Middle-out Perspective

## 5.1 Introduction

This chapter appraises retrofit for transport decarbonisation from a middle-out (mesoscopic) perspective. This perspective of appraisal is conducted by analysing how three retrofitted LRDs within the context of the central case study could be deployed and operated. Successful deployment will mitigate disruption to Worthy Farm and increase benefits yielded from the introduction of the retrofits e.g., emission abatement. Worthy Farm contains several key transport related actors within its boundary including but not limited to infrastructures, vehicles, operators, and institutions. These are all deeply reliant on one another or as is succinctly written in [210], change at the meso level in systems occurs due to “symbiotic associations among system actors in geographic proximity for sharing resources”. To investigate this, an agent-based model (ABM) of the central case study's retrofitted vehicles is presented in this chapter.

This type of computational model allows for the concurrent simulation of multi-disciplinary actions and interactions of autonomous agents in order to understand the behaviour of a system. This could include but is not limited to:

- varying vehicle specification e.g., battery capacity;
- operating time constraints;
- environmental constraints e.g., fixed traffic routes;
- seasonal variation e.g., on EV efficiency;
- power system dynamics e.g., grid carbon intensity; and
- decision-making heuristics e.g., learning rules or randomisation.

The transport system at Worthy Farm contains many system elements such as the retrofitted vehicles, their human operators, PV electricity generating assets and charging infrastructure. To capture representative vehicle usage patterns, a hypothetical transport network with nearby farms is simulated using an ABM during a busy period at the farm – the week of Glastonbury Festival. The simulation is used to conduct a scenario analysis that considers several ways to operate the retrofitted vehicles at the farm[16].

The outputs of this chapter are insights on how to operate the LRD retrofits more effectively within the farm’s environment so that decarbonisation can be increased, and operational costs reduced. Central to this aim will be the alignment of the solar generation of the farm with the charging scheduling of the vehicles. Additionally, the potential for

[16] Note that there will be instances outside of this simulation where conclusions regarding retrofit operation could differ including where ICE LRDs may be a better solution than a retrofit e.g., long-distance operation off-site (no charging) but this was not considered in this analysis.

varying the battery capacity of the vehicles is tested in the interest of further reducing their cost within their duty cycle requirements.

## 5.2 Worthy Farm Agent Based Model

The ABM of Worthy Farm was created in the software AnyLogic and represents a hypothetical supply chain network between Worthy Farm and six local farms. The ABM is run over the week of the Glastonbury Festival (24$^{th}$ – 30$^{th}$ June 2019) to represent a period of high demand on Worthy Farm's retrofitted EVs[17]. During this period over one hundred thousand people attend the farm holding and the vehicles normally used at the farm are utilised comprehensively for festival support purposes (e.g., movement of supplies) across the site on a segregated network of routes. Analysing the vehicles during this period will ensure that any improvements uncovered have the most impact on the farm's annual emissions and operating costs.

The supply chain is investigated through a scenario analysis to determine a favoured operating scenario for the LRD retrofits during their hypothetical operations over the week of the festival with nearby farms. The reason that nearby farms were chosen as part of the scenario was that they all are located within the festival boundary and correspond with potential destinations for the retrofitted vehicles during that period. Crucially, the farms are clearly defined on the geographic information system (GIS) functionality embedded within AnyLogic so that the routes to and from them and Worthy Farm can be simulated. For the ABM to be realistic it needs to utilise this GIS module for vehicle routing. Table 18 contains the GIS input data used to model the farm's key festival locations. From the use of the GIS locations, clear routes could be devised for vehicles to utilise during a run of the ABM. Figure 31 depicts these routes.

Table 18: GIS coordinates for hypothetical Worthy Farm logistics network.

| Farm Name | Festival Location | Longitude | Latitude |
|---|---|---|---|
| Steanbow Farm | Yellow and Bronze entry gates | 51.159451 | -2.604165 |
| Stickleball Hill Farm | Sticklinch car park and campsite | 51.148403 | -2.609244 |
| Park Farm | Glade and BBC festival stages | 51.153187 | -2.594459 |
| Pennard Hill Farm | Worthy View campsite and Park Stage | 51.142163 | -2.598625 |
| Cockmill Farm | Staff area and Shangri La stage | 51.148257 | -2.572767 |
| Clover Hill Farm | Blue gate entry point | 51.156091 | -2.568657 |

[17] Other periods at the farm are also particularly strenuous i.e., immediately after the festival for clear up and when the farm reverts back to a productive agricultural holding and cares for livestock.

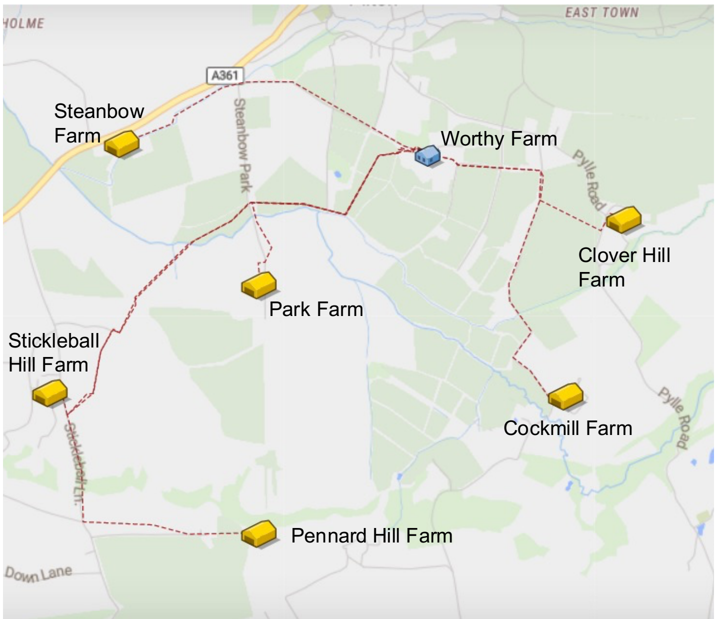


Figure 31: Routes (red) between destinations (yellow) and Worthy Farm (blue).

Within the AnyLogic ABM four agents are defined which represent: the vehicles, Worthy Farm, destination farms and the energy system. The Worthy Farm and destination farm agents constitute only a set of location nodes associated with GIS data points; these points are represented graphically through use of 2D identifiers as shown in Figure 31. The vehicle agent utilises a truck as its 2D identifier, and its initial location is set at Worthy Farm. The parameters for each of the retrofitted vehicles at the farm use some of the results of the bottom-up perspective chapter. Specifically, the retrofitted EVs are set to have an average speed of 17km/h and a constant energy consumption of 30.7kWh/100km. This performance is applied to all routes. If more data becomes available with which to improve the results of the bottom-up chapter, then more accurate speed and energy consumptions could be added. The vehicles are assumed to operate every day over the period of 24$^{th}$ – 30$^{th}$ June 2019 as the festival runs constantly from Wednesday to Sunday, and Monday through Tuesday are considered as days used for festival preparations. The three vehicles operate during each day over an eight-hour workday. During workhours, the LRD retrofits have no downtime and follow a decision path based on the state chart depicted in Figure 32.

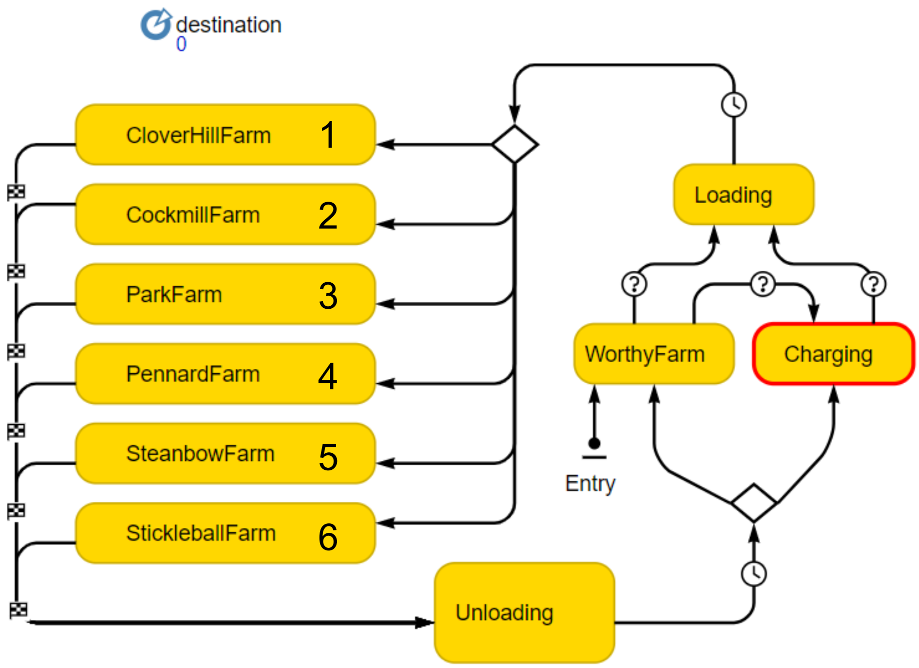


Figure 32: State chart defined within each LRD retrofit agent.

Figure 32 depicts the states completed by each LRD retrofit. The states consist of a 'Loading' event each time the origin location (Worthy Farm) is reached by one of the vehicles and an 'Unloading' event each time a destination (one of the 6 local farms) is reached. The durations of loading and unloading events are determined by a randomised time delay, this delay is based on a uniform probability distribution created in AnyLogic between 10 and 30 minutes. This unform probability distribution is algebraically represented in Equation 3 where P($x$) is the probability of delay $x$ in minutes, max = 30 and min = 10 and its realisation in AnyLogic is described in [272]. Note that a uniform distribution is frequently called a rectangular distribution.

$$P(x) = \frac{1}{\max - \min} \quad (3)$$

This probability distribution was chosen to simplistically generate a variation in vehicle loading and unloading times between 10 and 30 minutes that could naturally occur as a by-product of human behaviour. Variations in loading time could form due to different working speeds, cargo sizes, cargo types and weather conditions etc. It is noted that other skewed distributions such as log-normal or gamma would have been more accurate probabilistic representations of delay (i.e. for vehicle loading/unloading) and in future work this limitation should be addressed. Similarly, route selection is also determined by a probability distribution. After the loading process is complete, the destination and associated route selection is made by each vehicle through the selection of an integer corresponding to the index of each route i.e., routes 1 to 6. To achieve this a discrete uniform probability distribution between 0 and 5 which represents an index of each of the six possible destination farm locations is called in the agent's state chart to select a random destination farm using the AnyLogic function "uniform_discr(int min, int max)" where int min is 0 and int max is 5. This probability distribution, as per [273], follows Equation 4 below.

$$P(x) = \frac{1}{\max - \min + 1} \tag{4}$$

This randomised route selection aims to simulate the impromptu usage of the vehicles during the festival period. The supply chain will follow no particular operational routine as destinations are assumed to require supplies at random throughout the festival as their resources deplete. As the vehicles are used, and vehicle batteries discharge they eventually will require recharging. In terms of charging and discharging, each vehicle is permitted to charge whenever they are outside of their designated work hours or if their SOC falls below 20%. This figure of below 20% was selected to ensure battery health and to mitigate range anxiety. The 'checking' of work hours for each scenario is completed by a set of event blocks in the ABM. Whenever charging is permitted i.e., outside of work hours, or required i.e., below 20% SOC the charging process begins automatically upon the vehicle agents return to the GIS node of Worthy Farm.

Whenever charging begins, it will be conducted until an SOC of at least 80% has been reached before the charging state will allow an LRD to be released of back to work. If charging is conducted during a non-work period, then the LRD will continue to charge until 100% SOC. This represents a vehicle being left to charge outside of work hours i.e., overnight. The charge rate of all LRD retrofits in the model is 7kW. For context, the chargers at Worthy Farm are located next to a large rooftop solar installation on one of the farm buildings.

To dynamically adjust each of the LRD's SOC as it performs its functions at the site, a SFM is contained within each agent. The model's primary function is to 'check' if the LRD is moving or stationary and if it is charging. During a true condition for either movement or charging, a discharge or charge rate is applied to a stock which represents the vehicles battery capacity. This adds or removes energy from the particular agent's battery pack at a rate of either the 7kW charger or the vehicles designated energy consumption rate (determined in the previous chapter) respectively. The default battery capacity of the LRD agent is 26.5kWh, despite the actual farm LRD retrofitted EV being approximately 52kWh. This choice is explained in detail in section 5.3.2.

The Energy agent has no 2D identifier as its purpose is solely to determine the LRD agents' interactions with the farm's electricity supply (PV or grid). This task is completed through the introduction of two datasets within the Energy agent's definition, these being

Worthy Farm's estimated solar generation and the UK national grid's carbon intensity to estimate grid-based emissions from any grid-based electricity consumption. Both data sets were for the period between the 24th and 30th June 2019.

The PV installation at Worthy Farm consists of a 250kWp, 1112 panel, 1500m$^2$ rooftop solar array [274] and the array is claimed to produce 235,100kWh of electricity per year [36]. To determine estimated energy output during the last week of June 2019, an irradiance dataset from a Centre for Environmental Data Analysis archive was utilised in [275]. This dataset contains irradiance values in hourly kJ/m$^2$ corresponding to a nearby measuring station in Lyneham Wiltshire. From this irradiance data a conversion was made to an hourly kWh/m$^2$ of solar irradiance and passed into the formula represented in Equation 5 to estimate the installations electricity generation $E$ in kWh each hour.

$$E = A \cdot r \cdot H \cdot PR \tag{5}$$

Where $A$ is the total panel area of 1500m$^2$, $r$ is the solar panels yield as a % which is computed as a division of the installation's 250kWp and 1500m$^2$ = 16.67%[18], $H$ is average irradiance, $PR$ is the performance ratio where $PR = 0.75$[19] and thus from each hour's kWh value an equal power value in kW can be estimated. This variation in solar power output over the week's 168 hours is graphed in Figure 33.

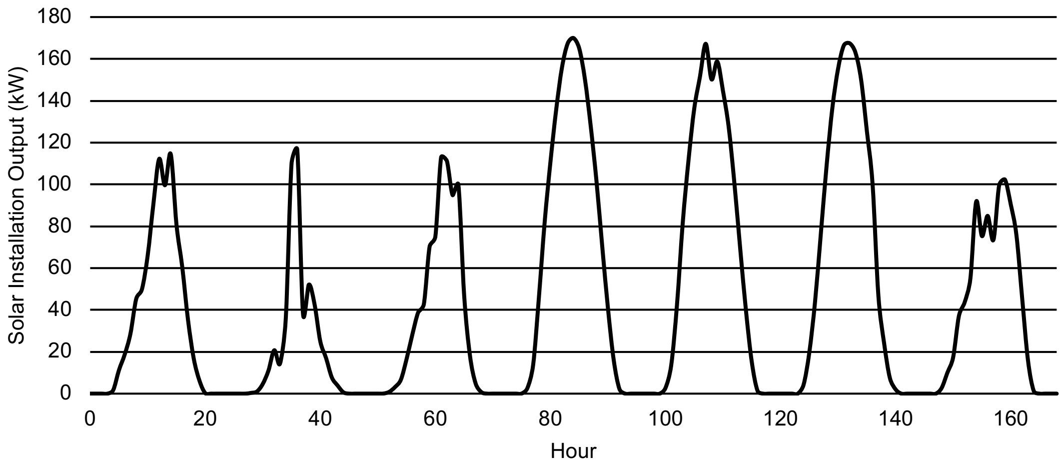


Figure 33: Estimated Worthy Farm PV installation power output 24th to 30th June 2019.

[18] This ratio is only for standard test conditions of 25°C and 1000W/m2 irradiance, wind speed 1m/s, air mass coefficient =1.5. For Worthy Farm the average temp when irradiance is greater than 0 is 15.1°C based the same dataset of the weather station in Lyneham Wiltshire [275]. As this temp is lower than 25°C, panel efficiency is likely to be higher, so the assumption stands.

[19] According to the NREL, the standard performance ratio for a new solar system is 77%, and over time, the performance of the system is assumed to degrade, so 75% was set as an appropriate value [276].

Following calculation of the estimated solar output, the carbon intensity of the UK grid was taken from a National Grid ESO archive in [277]. This carbon intensity variation over the week's 168 hours is graphed in Figure 34. Note that this carbon intensity is in $gCO_2/kWh$ not $CO_2e$ (carbon dioxide equivalent) which has been preferentially used in this document so far. So, emission results from the ABM are therefore provided in grams of $CO_2$.

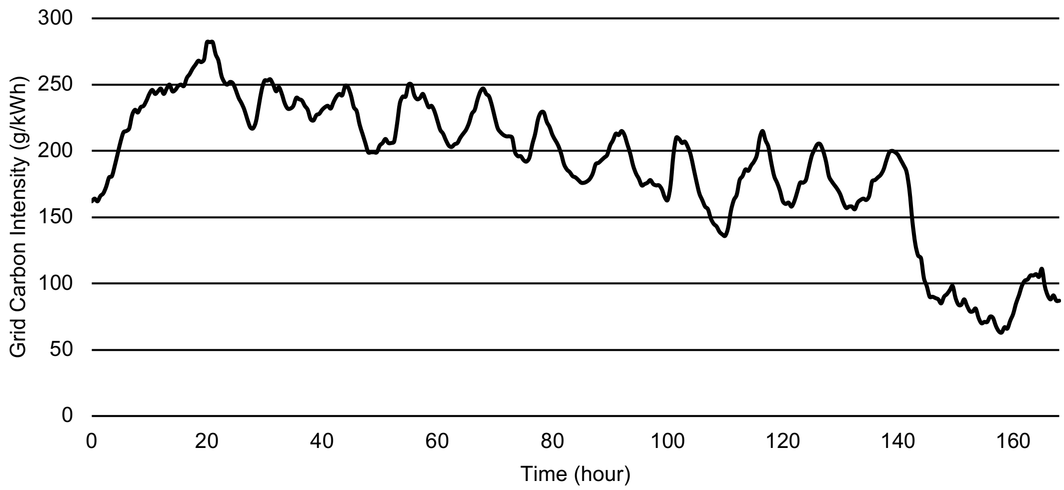


Figure 34: UK National Grid Carbon Intensity from 24th to 30th June 2019 [277].

## 5.3 Scenario Analysis

To investigate how best to integrate the retrofitted vehicles onto Worthy Farm, scenario analyses were conducted using the ABM with the aim of determining:

1. What are the best periods to operate the vehicles so that decarbonisation can be increased, and operational costs[20] reduced?
2. Will a reduction in retrofitted vehicle battery capacity, with the aim of reducing capital cost, affect their operation at Worthy Farm, and can any impacts be mitigated?

### 5.3.1 Operation Time Variation

To investigate the best time to operate the vehicles, five operational scenarios were defined. Within the time frame of each scenario, the vehicles can conduct work and all scenarios are based upon a variation of an 8-hour workday to mimic typical UK employment contracts. Table 19 contains the name and description of each scenario. During each scenario the vehicles have no downtime and only return to charge if their SOC falls below 20% or they outside of the operational period.

[20] Operational costs are considered to be the price of electricity used to recharge the vehicles.

Table 19: Name and description of each LRD operational scenario simulated.

| Scenario Name | Description |
|---|---|
| Normal | LRDs are only allowed to operate within one operational period of 9am to 5pm. |
| Morning | LRDs are only allowed to operate within one operational period of 6am to 2pm. |
| Early | LRDs are only allowed to operate within one operational period of 4am to 12pm. |
| Early Late | LRDs are only allowed to operate within two operational periods of 4am to 8am and 4pm to 8pm. |
| Morning Evening | LRDs are only allowed to operate within two operational periods of 6am to 10am and 2pm to 6pm. |

### 5.3.2 Battery Capacity Variation

Currently, all LRD retrofitted EVs deployed on the farm have ten used Tesla battery pack modules installed within them. This results in an estimated 52kWh of energy storage capacity for each vehicle from these Tesla modules. This total capacity is an estimate as the capacity of individual modules will vary based on differing levels of degradation, manufacturing tolerances and the day-to-day conditions at the farm. To investigate potential reductions in installed battery capacities, 5, 4 and 3 module installation scenarios were investigated. Any reduction in battery capacity could benefit Worthy Farm through reducing each retrofits capital cost, using old/removed/replaced batteries as stationary storage, and lower embodied emissions per vehicle. Each vehicles efficiency could also be increased through a reduction in its mass from a smaller battery. Note that this change in efficiency and/or the use of batteries as stationary storage at the farm was not factored into the model due to a lack of data on this subject.

One Tesla module has a 5.3kWh manufacturer claimed capacity and a nominal voltage of 22.8V which can range from 18V to 25.2V [257]. The reason for considering 5, 4 and 3 module battery configurations is that a reduction in pack number, reduces the maximum voltage that can be supplied to the powertrain. Based on a maximum Hyper 9 powertrain operating voltage of 132V and a minimum of 62V [172] pack configurations below 3 will not produce an appropriate voltage for the motor setup without additional componentry, this is highlighted in Table 20 which contains the power and torque sacrificed when operating a reduced module count.

Table 20: LRD retrofit powertrain and battery capacity options [172], [167].

| Battery Modules | Total Capacity | Maximum Voltage | Hyper 9 Operating Voltage, Peak Torque (and Power) | Estimated Range |
|---|---|---|---|---|
| 5 | 26.5kWh | 126V | 120V, 235.1Nm (102.8kW, 138hp) | 86km |
| 4 | 21.2kWh | 101V | 96V, 235.1Nm (81.3kW, 109hp) | 69km |
| 3 | 15.9kWh | 76V | 72V, 235.1Nm (60.3kW, 80.9hp) | 52km |

Although more than 5 modules could be installed, it is in the opinion of the author that 5 modules are sufficient to produce the required range for an EV at Worthy Farm given that the three LRDs in the case study average 25.4km of usage per day according to their MOT data. The ABM will support or contradict this assumption, and as this simulation is conducted during the farm's most demanding operational period it is likely that a successful reduction in battery capacity would be applicable to all other time periods at the farm. More simulation/real world testing would be necessary to confirm this for a final retrofit design as other variables such as temperature need to be considered along with potential efficiency gains from lower battery pack masses.

### 5.4 Results

Each variation in the total number of battery pack modules (5, 4 and 3) was simulated across each operational scenario for each LRD to generate a selection of results from the ABM. Firstly, the variation in LRD SOC was explored purely through the random behaviours of the model, namely, loading/unloading delay and random route selection. It was found through investigating the variation in maximum and minimum SOC across any simulated week for every LRD agent, battery capacity and operational scenario that random route selection and delays can result in SOC variations from 14% up to 47%. This is significant and highlights the difficulty in improving the operations of vehicles used arbitrarily. Examples of the SOC results for the normal operation scenario are contained in Figure 35, Figure 36 and Figure 37. The figures clearly demonstrate the difference in daily SOC across a week of usage for each of the three LRD agents at three battery capacities.

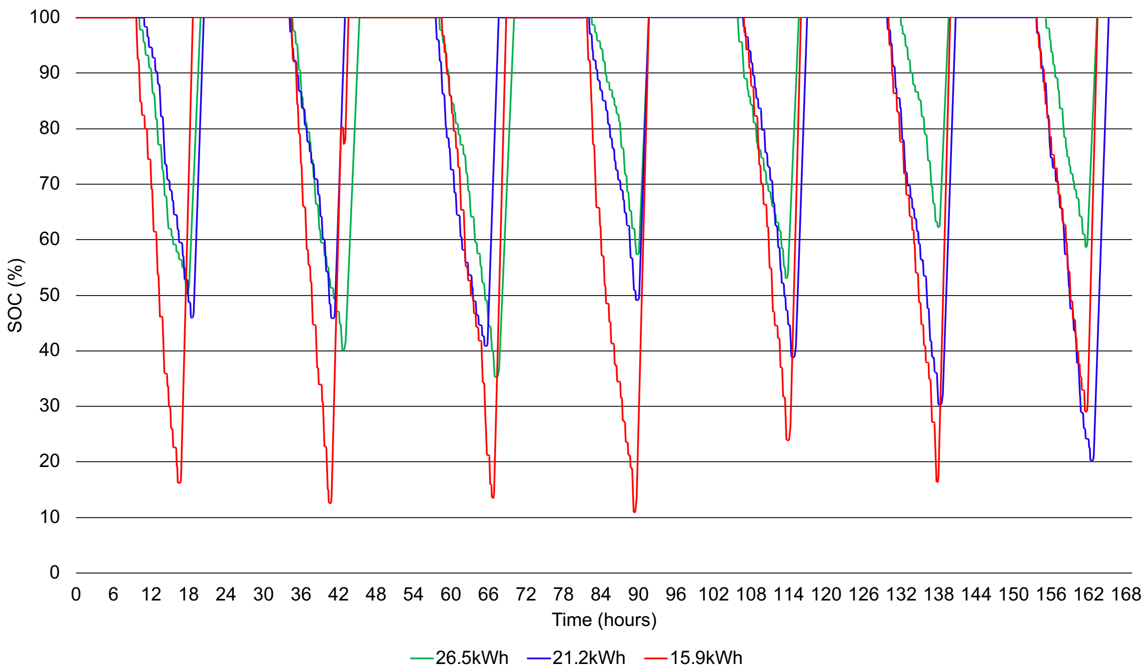


Figure 35: LRD1 agent SOC at varying battery capacities for Normal scenario.

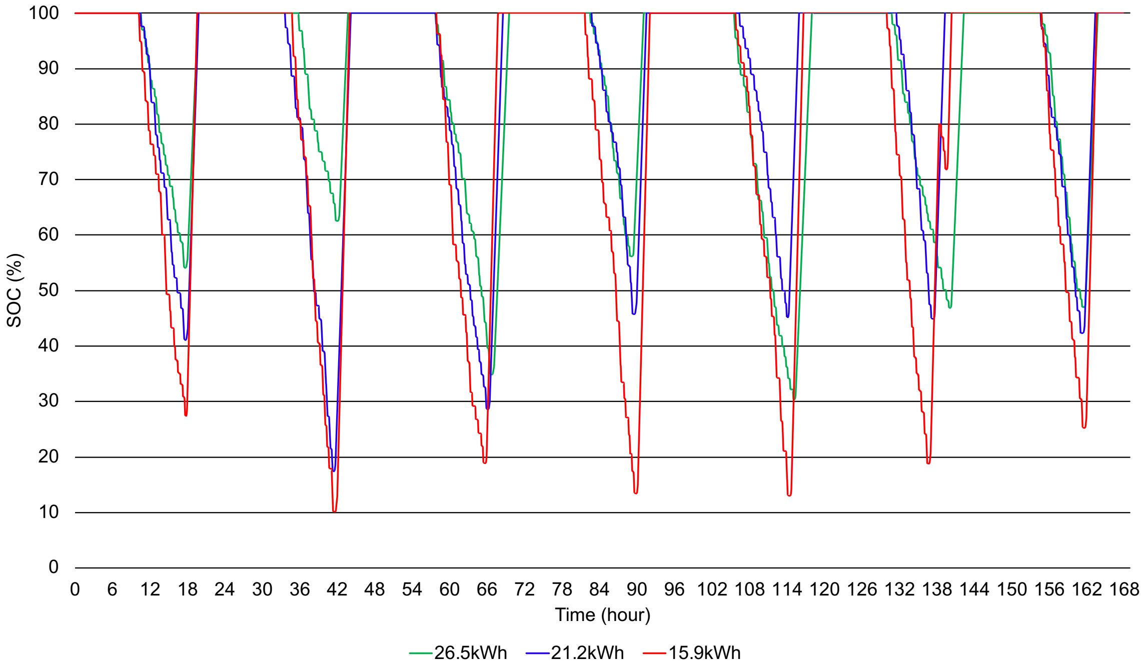


Figure 36: LRD2 agent SOC at varying battery capacities for Normal scenario.

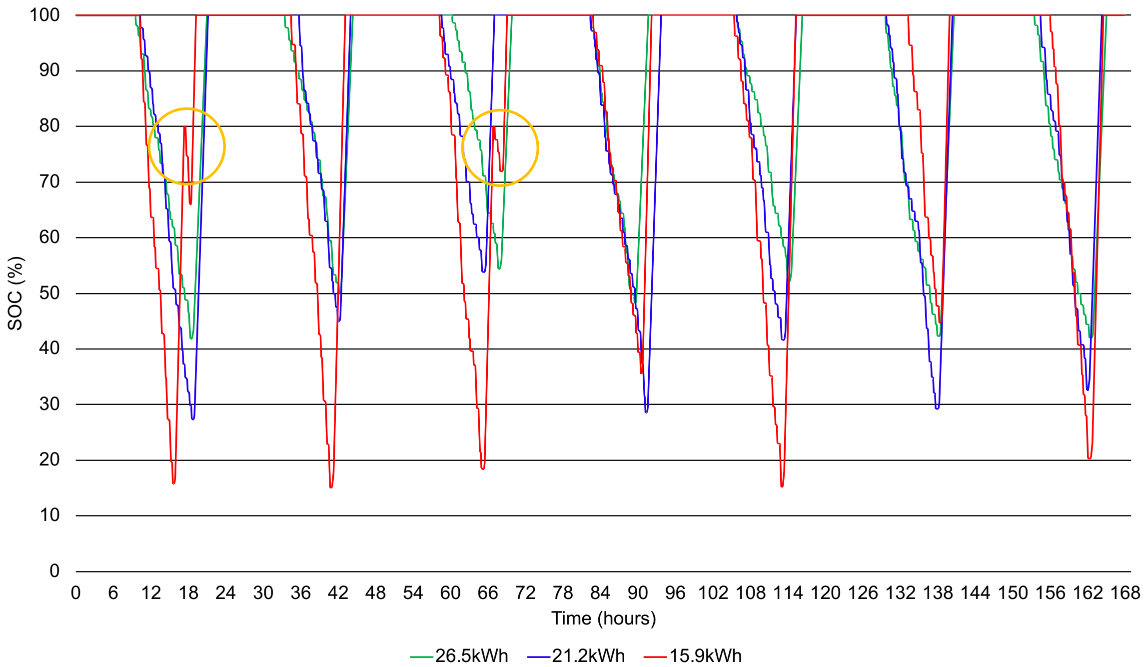


Figure 37: LRD3 agent SOC at varying battery capacities for Normal scenario.

Secondly, the impact of reducing battery capacity was investigated. It was found that as battery capacity is reduced from 5 or 4 modules down to 3 there is an increased probability of an inter-operational charge by a vehicle, however this was only seen for the Normal, Morning and Early scenarios i.e., continuous 8-hour operational conditions without downtime. These inter-operational recharges are circled in orange in Figure 37. During the Early Late and Morning Evening scenarios lower battery capacities had no effect on the operational ability of the vehicles during simulations conducted as the interim charging period between 4-hour shifts seems to allow for an appropriate recharge. To combat these inter-operation recharges, opportunity charging could be utilised (in a similar fashion to electric bus fleets with smaller batteries/long operational duties) to provide a fast top-up of energy at specific planned intervals.

To quantify the first circle in the recharge example of Figure 37, the inter-operational charge begins at 3.47pm on day one of the simulation at a SOC of 15.8% (t = 56831 seconds or 15.79hrs) until 5.20pm at a SOC of 80% (t = 62397 seconds or 17.33hrs), an addition of 10.2kWh. The vehicle then continues work to its first day's operational finish time of 6.23pm at 66% SOC (t = 66185 seconds or 18.39hrs). This interim charge cost the LRD at least 1.5 hours in lost operational time even though the vehicle only potentially required an additional SOC of 14% (2.2kWh) to complete its tasks. This reduction in output could reduce the payback time of the retrofit through lost revenue and can frustrate operators. This type of situation needs to be avoided though improved charging scheduling, operator training or through tailoring battery capacity. Additionally, the rate of occurrences of any inter operational recharging could be reduced by allowing the SOC at which a charge is requested to fall below 20% e.g., 10% which would have eliminated problems for LRD3 in Figure 37. However, this high depth of discharge could result in larger rates of battery degradation and further the range anxiety for vehicle operators and may not be appropriate during alternative farm conditions such as in low temperature winters. This trade off would need to be considered in a further multi-variate analysis. Moreover, in reality, it is likely that a break during the 8-hour operation is required by a vehicle operator e.g., for food or comfort. This window of time for an opportunity recharge could alleviate operational issues at smaller battery capacities. However, this type of opportunistic charging in the middle of the day may increase operational costs due to the higher unit costs of electricity when compared to overnight if alternative sources of cheap electricity (e.g., PV) are not available. In the case of Worthy Farm, paradoxically, it is probable that the requirement of this early recharge will reduce operational costs and emissions due to the availability of PV.

Thirdly, the total direct emissions of the vehicles were simulated at each battery capacity across the scenarios using the ABM. The results are presented in Figure 38. Emissions from the vehicles are calculated by the quantity of grid electricity used and the carbon intensity of this grid electricity at the point it was used in grams of $CO_2$ per kWh. It is assumed that PV energy generated at Worthy Farm is free, zero emission, is transferred to the vehicles with no losses and it is not utilised by any other load on the farm's electricity network. The farm also has a gas turbine connected anaerobic digestor, but this was not considered as an energy resource for the retrofitted vehicles.

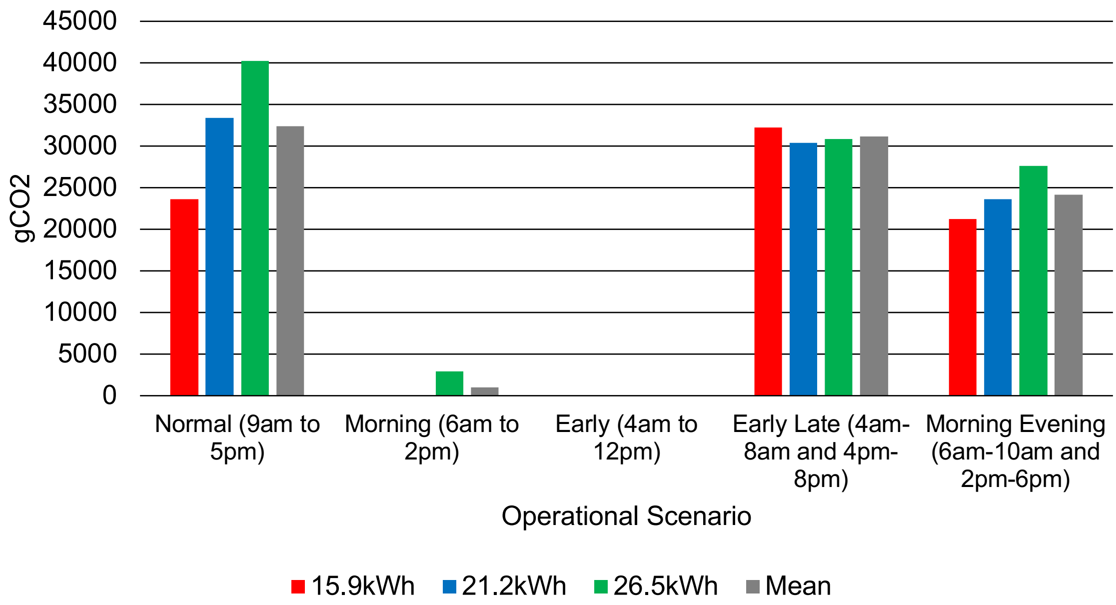


Figure 38: Vehicle emissions by operational scenario / battery capacity.

From the figure it is clear to see that the Morning and Early scenarios yield the lowest potential emissions for the vehicles over the week. This is due to the recharge period of the vehicles occurring during the daytime where the 250kWp solar array can be utilised. It is also apparent that there is variation in direct emissions as a function of battery capacity though this variation is heavily affected by the volatility in daily SOC change as a result of the random elements of the ABM. Furthermore, as shown clearly in the Morning Evening and Normal scenario a lower battery capacity can often reduce emissions by forcing a premature, unplanned inter-operational charge which ends up coinciding with daytime solar energy generation. It must be noted that this model does not account for the mass related efficiency changes of the vehicles when using different sized battery packs and incorporation of the more dispatchable anaerobic digestor energy supply at the farm could significantly impact these results.

Next, the weekly grid energy consumption from the vehicles is presented in Figure 39. This plot follows a similar trend to the figure on emissions though variations can be observed due to grid carbon intensity variations through the simulated week e.g., Morning Evening scenario has equal energy consumption across 15.9kWh and 21.2kWh battery capacities in Figure 39 but differing emissions in Figure 38.

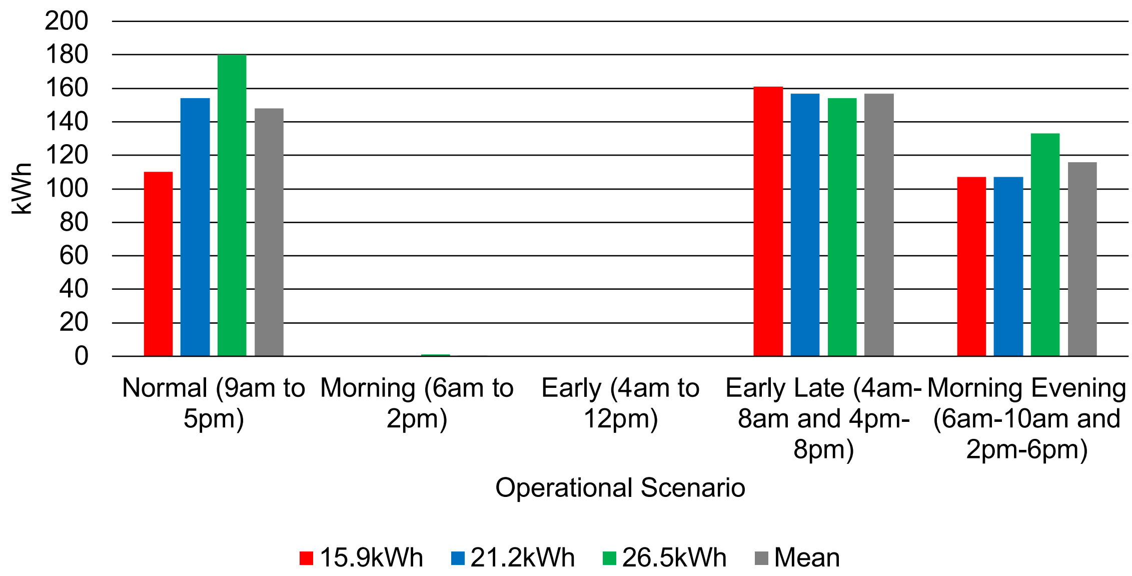


Figure 39: Grid-electricity used for charging by operational scenario / battery capacity.

Finally, in terms of illustrating the potential effects of battery capacity and operational scenario selection on annual costs Figure 40 contains an estimation of yearly electricity costs from grid energy consumption if this week simulation was to occur concurrently for 52 weeks. Naturally, over the course of one year, vehicle usage, renewable energy generation and unit costs of electricity will vary, and this is acknowledged as a limitation. However, due to simulation run time constraints this scenario is presented for completeness. An average per unit (kWh) electricity cost of 28.4p in the South West of England (2022) from [278] was chosen to make these estimates. Also included in the figure is potential capital savings from retrofitted battery module reductions for comprehensiveness. As per previous results, the best operational scenario was found to be Early (4am to 12pm), though Morning is comparable.

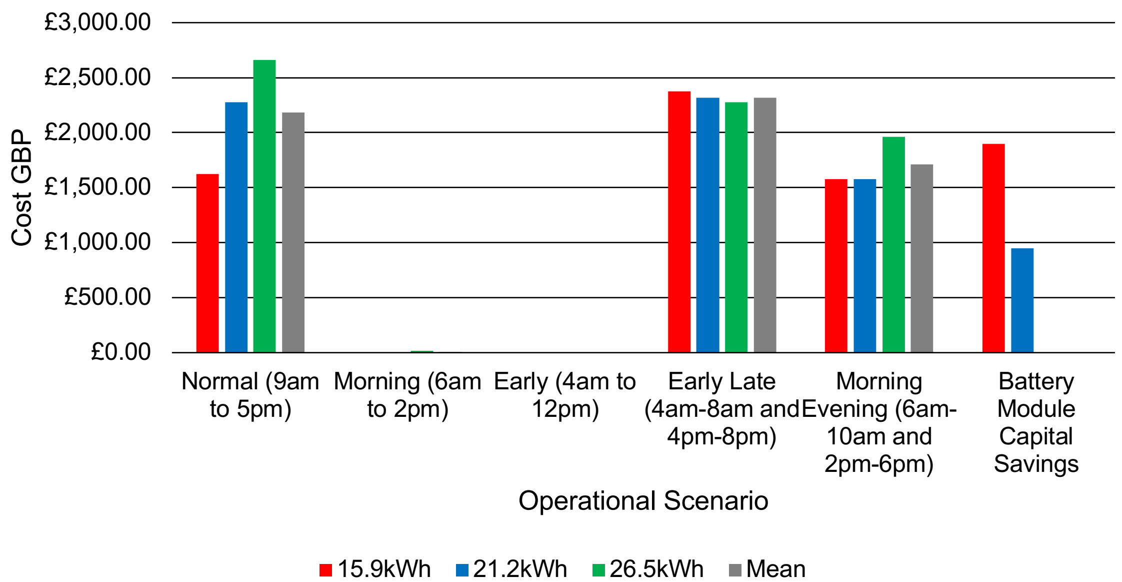


Figure 40: Annual electricity cost estimate by operational scenario / battery capacity.

### 5.5 Discussion and Limitations

This chapter has presented a mesoscopic appraisal of retrofit as a decarbonisation solution through simulating the LRD retrofits at Worthy Farm. The simulation was an ABM which centred around the deployment of three retrofits for use in a hypothetical transport network and analysing their interaction with grid and solar electricity supplies. The use of an ABM has allowed for the exploration of stochastic model elements which imitate the types of decision making and unpredictability of vehicle operators in the logistics networks and reflects the arbitrariness of the transport systems usage at the time of the Glastonbury Festival (a period of heavy vehicle usage at this location). This investigation aimed to capture the interfaces between key transport related actors at Worthy Farm.

From the ABM simulations, it was determined that use of lower battery capacities than those installed in the currently deployed LRD retrofits could be possible for their expected duty cycles at this time of year. This possibility is dependent on the operating conditions of the vehicles i.e., uptime vs downtime, route selection, temperature, weather, time of year etc. Reductions in range beyond 20% can be expected when comparing EVs operating in summer vs winter [279]. The three-module battery pack configuration (15.9kWh) may not be capable of avoiding premature charging events during a continuous 8-hour operating window with no planned downtime. Though if this could be mitigated through allowing downtime (for opportunity charging) or deeper discharge cycles etc. then the use of three module configuration would save significant amounts of battery capital cost (around £1000 per module as per Chapter 4) and embodied emissions per vehicle at the farm whilst still being within the voltage supply limits of the powertrain. This reduction in battery capacity could also reduce other expenditures such as mounting hardware costs and increases vehicle efficiency due to the associated mass reduction. It must be stressed that further investigation into this battery capacity would be required before a final retrofit design decision is made. Preferably, one three module prototype vehicle should be tested on site, or within an ABM of increased fidelity to confirm that vehicle performance could be maintained. Voltage drops on the Hyper 9 powertrain could prove problematic under different driving behaviours or vehicle loads, for example, towing a trailer. Regardless, it is highly advantageous that retrofit battery capacities can be tailored in this way.

In terms of increasing decarbonisation and reducing operating costs, earlier operating windows were found to be the most beneficial in the farm's current configuration. Specifically, the Early scenario was most preferred in terms of outright results, but the Morning scenario could be easier to implement and be favoured amongst vehicle operators due to its later start (6am). Earlier scenarios came out ahead of others in terms of emissions and cost due to the sole inclusion of the farm's solar assets. Coupling lower battery capacities, early operational scenarios and an opportunity charge is likely to be the most effective method to deploy retrofitted vehicles at Worthy Farm.

It is noted that the model did not account for the effect of different battery pack masses on vehicle energy consumption or weather conditions impact on energy consumption e.g., through ground traction changes from rain (i.e., terramechanics [280]) or temperature effects on the battery pack. There is the potential for smaller packs to provide a noticeable efficiency gain and further work needs to investigate seasonal variation. Furthermore, the stochastic elements of this ABM caused significant variation in daily SOC across the vehicles. When interpreting these results, the reader must be cognisant that this variation means that no operational scenario/battery capacity choice is perfect, and a preferential scenario may change between model runs.

Notable idiosyncrasies of the local energy system at Worthy Farm included that smaller battery capacities decreased emissions on a few occasions due to a premature charge event utilising solar. Furthermore, there is a significant amount of solar available at the farm (250kWp). This easily satisfies the peak recharge load of 21kW from the three vehicles across the day and this is unlikely to change meaningfully at different periods of the year. This is arguably much more solar availability that would typically be available. Moreover, it is assumed that no other loads are present, a future retrofit deployment could be much larger and currently there is one charger per vehicle available. If these assumptions were to change, the results of the ABM could be significantly different. Likewise, if an alternative energy mix was studied (i.e., inclusion of gas based anaerobic digestor), a more complex ABM implemented, or if different random destination selections were made in an alternative model run, other scenarios could be more beneficial. Hence it is advised that on a case-by-case basis, similar techniques are used to inform retrofit designs, especially for facilitating the adoption of lower battery capacities.

In terms of other limitations, assumptions, and constraints in this chapter. As previously mentioned, the stochastic elements of the ABM e.g., use of a uniform distribution for delay was simplistic and it is noted that other skewed distributions such as log-normal or gamma would have been more accurate representations of vehicle loading/unloading delay to use. The overall lack of farm access and data (mainly due to COVID-19) constrained the scope of this ABM, for example, more information on farm electricity consumption (which was also not representative during lockdowns) would be beneficial to understand the Worthy Farms spend on utilities and other demands on the solar installation or grid electricity supply. If retrofit energy consumptions under different cargo scenarios and the use of a trailer were understood this could have added further depth to the ABM. Similarly, factors such as driving style, charging behaviour (e.g., forgetting to charge) and inclusion of anaerobic digestor energy consumption were also excluded due to lack of data, but would be insightful future additions to the model. Sensible figures for model inputs were used in this analysis such as delays, minimum desired SOC, origins, destinations, and energy consumption etc. but longer-term study of the LRD retrofits would have facilitated a more representative ABM. Finally, the length of the simulation should be extended beyond a seven-day period to preferably one year to view operational scenarios in different seasons/agricultural use cases.

### 5.6 Conclusion

This chapter has covered the appraisal of retrofit from a mesoscopic perspective. This was conducted through use of an ABM of a representative (though hypothetical) transport network at Worthy Farm. The ABM investigated the retrofitted LRD vehicles interface with the farm's energy system, geography, charging infrastructure, and the irregularity of its vehicle operations. The analysis aimed to determine how much of an impact operational procedure and battery capacity could have on the success of the vehicles deployment whereby success was defined as reducing direct emissions and cost. Moreover, simulating battery capacity variation also helped to indicate any potential reductions in retrofit capital cost, highlighted any operational issues and allowed for the testing of required mitigations.

It was found that earlier operational periods starting between 4am and 6am were most beneficial in terms of reducing direct emissions and costs. This was due to the increased utilisation of Worthy Farms on-site solar. It was also determined that a reduced battery pack capacity for the EVs in this case study was likely to be possible but two 4-hour operational periods are needed to avoid premature charging events. These findings work to realise objective three of this research which was to "consider qualitatively and quantitatively the operational changes that may be required to better integrate retrofitted EVs into transport operations".

The incorporation of multiple middle-actors as a result of this appraisal perspective was particularly useful in demonstrating how the success of a retrofit project could be reliant on the exploitation of the opportunities in geographic proximity to the retrofits. The deployment of vehicles will require additional considerations and the uncertainty of human agency must always be appreciated. Overall, it is now easier to comprehend as a result of this middle-out investigation that transport decarbonisation solutions will never be right or wrong but instead they exhibit a spectrum of suitability entirely dependent on context.

# Chapter 6 Top-down Perspective

## 6.1 Introduction

This chapter appraises retrofit as a transport decarbonisation solution from a top-down (macroscopic) perspective by considering the impact of the practice being adopted broadly e.g., as a decarbonisation policy measure. The assessment of this broad adoption is conducted through a combination of life cycle assessment (LCA) and system dynamics (SD) methodologies. First, an overview of system dynamics is provided and its previous use in policy evaluation. Next, a multi-scenario LCA is completed to determine how the flow of embodied emissions manifests across differing vehicle replacement scenarios and what potential there is to achieve embodied and direct emissions savings across varied ICEV replacement scenarios. The three vehicle replacement scenarios are:

- ICEV with another ICEV
- ICEV with a new EV
- ICEV with a retrofitted EV

Each LCA scenario is underpinned by life cycle inventory (LCI) data in [281] as well as the results from the previous chapters. Following the results of the LCA, this is used inform the SD procedure. The first part of the procedure involves the production of three causal loop diagrams (CLDs) relating to retrofit. These depict the dynamics of:

- embodied emissions of a stockpile of road vehicles without the introduction of the retrofit pathway.
- embodied emissions of a stockpile of road vehicles after the introduction of the retrofit pathway.
- factors that could influence the performance of a retrofit policy i.e., the overall attractiveness of the retrofit pathway.

Next, a correlated SFM is created which quantifies the dynamics of vehicle stockpile embodied emissions and how they change under the presence of a retrofit policy and variations in that policy. Note that the SFM aims to inform practitioners of the possibilities for change in embodied emission dynamics. This is sometimes referred to as 'possibilistic' modelling. Quantifying the ability of a retrofit policy to potentially 'delay' embodied emission wastage is overall, a valuable contribution. Furthermore, the combinational use of LCA and SD in this chapter is advantageous as the static LCAs ensure a representative SFM which in turn can be used to simulate a longer timeframe to assess policy effects [282]. The results of the SFM provide suitable quantification of the change in embodied emission dynamics of a vehicle stockpile as a result of retrofit including if retrofit policy is delayed or if a future reduction in donor vehicles affects the attractiveness of the policy.

## 6.2 System Dynamics and Retrofit Policy Evaluation

There is a tendency to view policymaking as a linear procedure in which problems are identified, research or evidence gathered, and then policymakers map a route to a solution. However, this is an oversimplification. Evaluation of policy and strategy is complex, and this is especially true for the UK where transport governance structures mean that control over UK transport is segmented [283]. See the breakdown for transport responsibilities in Wales as one example in Figure 41.

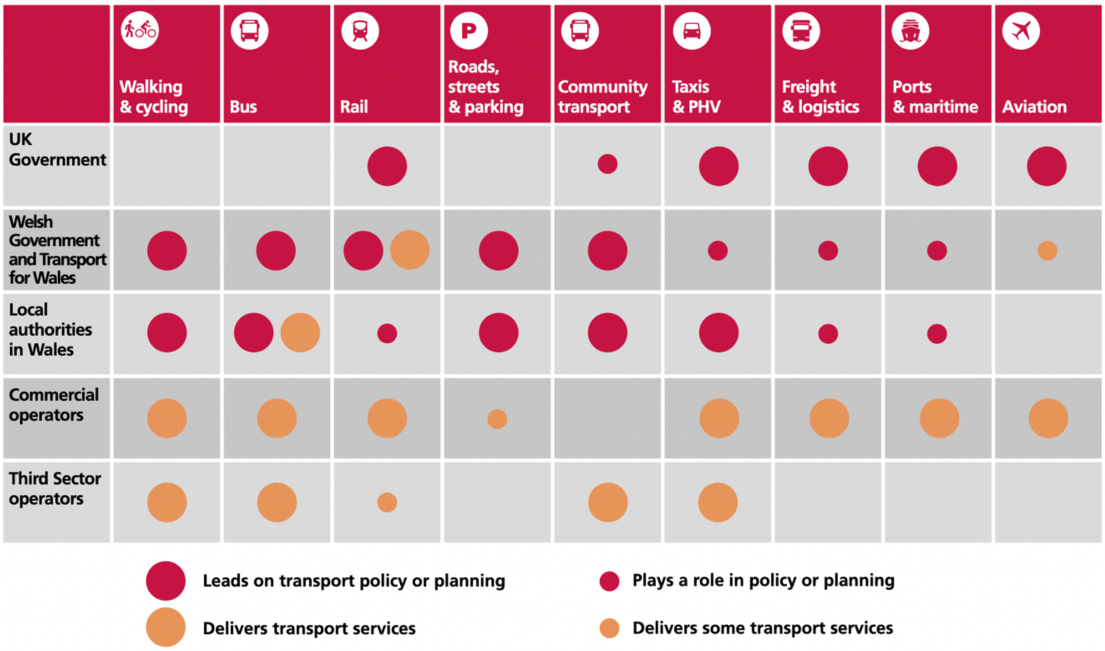


Figure 41: Transport responsibilities in Wales [284].

Policymaking can thus involve a complex navigation of competing interests, personal biases, and existing sector specific structures. This complexity is difficult to manage, so the use of decision support tools for policymakers is becoming ever more prevalent, especially tools based on SD [285], [286], [287], [288], [289]. SD was proposed by Forrester of Massachusetts Institute of Technology [290], [291]. SD is grounded on the principle that a system's structure generates its behaviour and as such, a lot of effort in SD research is expensed on describing system structures through CLDs [292]. These mapping exercises contain many feedback structures which directly depict the interactions between system elements. An example of a CLD is provided in Figure 42.

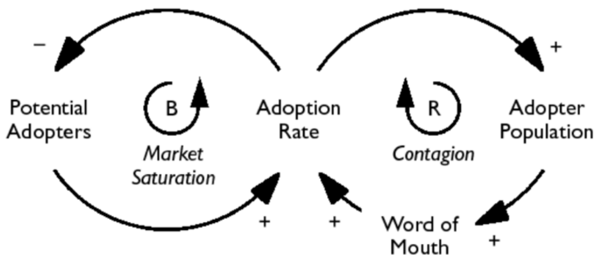


Figure 42: Example of a causal loop diagram [293].

Figure 42 is a simple example of a CLD that contains a balancing loop (B) and a reinforcing loop (R) representing two effects on adoption rate. The balancing loop shows how market saturation reduces adoption rate as the supply of potential adopters is reduced (arrow and negative polarity). Similarly, the reinforcing loop represents contagion (communication by close contact) showing how as adoption rate increases, more adopters exist in the population and hence the probability of word-of-mouth communication about the adoption increases (arrow and positive polarity). CLD causalities e.g., adoption rate can be considered system elements and arrows with polarities the interfaces (relationships) between system elements. The CLD can be developed further by adding additional causalities. Furthermore, the CLD can be combined with SFM elements, this stage is shown in Figure 43.

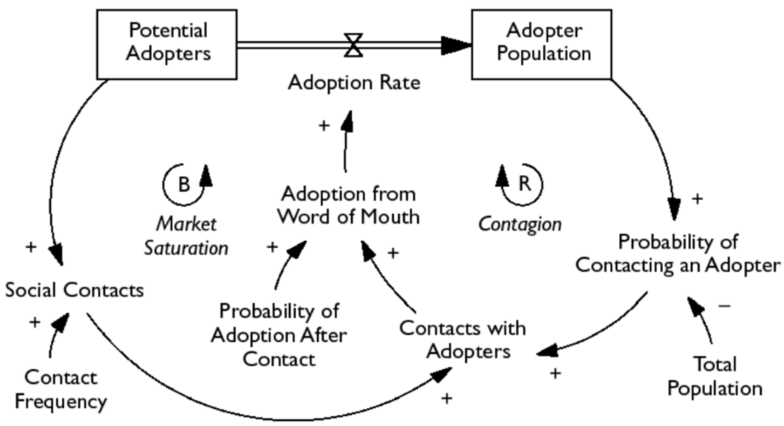


Figure 43: Causal loop diagram combined with SFM elements [293].

The addition of two stock and one flow element has acted to parameterise three variables in the system (potential adopters, adoption rate and adopter population). This also allows for the addition of constraints to the system such as ‘total population’, ‘contact frequency’ and ‘probability of adoption after contact’. The addition of SFM elements allows for the original CLD to be used in more formal quantitative studies. To simplify the visualisation of the dynamics of stock and flow, the bathtub and tap analogy is often used where the faucet/tap represents the inflow, the stock is the level of water, and the outflow is the drain [285]. Mathematically this can be described through the balance equation below in the context of material flow where $K_m(t)$ is the stock amount of material $m$ at time $t$ and $I_m(t)$ and $O_m(t)$ are corresponding inflows and outflows respectively.

$$K_m(t) = I_m(t) - O_m(t) \tag{6}$$

From the balance equation, stock and flow time series can be derived through a flow driven or stock driven approach. The flow driven approach is more simplistic and is used when the inflow and outflows are known/easy to model e.g., modelling the use of short life consumable objects. The stock driven approach is more appropriate when in-use dynamics are more complex e.g., the deployment, operation and decommissioning of infrastructure where there is a long period between inflows (deployment), uncertain intermediate inflows/outflows (operation/maintenance) and outflow (decommissioning) [294].

Overall, the use of SFMs has added a quantitative facet to SD and has been used in a number of projects. One example is the development of the World series of models which culminated in the now famous, but often misinterpreted, Limits to Growth report of 1972. This report was one of the first studies to utilise quantitative approaches in SD to investigate relationships between economic growth, population, and planetary boundaries (limited resources). It concluded that within the earth and human system, without change in resource consumption, there is probable chance of sudden and uncontrollable declines in population/capacity [295]. Since the report, SD has continued to develop into a notable field of systems research due to its capacity to handle multiple disciplines with many applications to transport systems, sustainable supply chain management and the circular economy [296]. Broadly, SD has become an application of control theory to social systems [292].

It is worth noting however that, although SD allows for the production of formal simulations, there is debate as to if SD should be used as a forecaster. Forrester argues that SD models “should be used for determining the character of a system but not its specific state” [291] and that “one should examine models in the context of how different policies within the model change the nature of ongoing behaviour” [297], furthermore, forecasts are likely to be wrong [233]. On the contrary, work in [298] suggests that SD models can provide more reliable short to medium term forecasts than statistical models, a means to understand underlying causes, and thus better decision making/policy design than more traditional forecasting.

In general, to employ SD for the purposes of policy design the following steps from [292] can be taken[21]:

1. Articulate the problem to be addressed e.g., embodied emissions within automotive vehicle stockpiles are being sent to landfill.
2. Once the problem is articulated, typically, SD is used to represent the interactions between factors within the system containing the problem. These interactions are initially conceptualised using CLDs which allow for the presentation of feedback through their arrows, polarities and delays (lagged effects) which give rise to overall system behaviour [285]. This conceptualisation is known a dynamic hypothesis.
3. Dynamic hypotheses are then tested through use of models such as a SFM to evaluate solutions or in this instance, policy design.

The accessibility of the causal loop mapping process allows for future model inputs to be built with stakeholders through collaborative development of CLD's. Model development as a collective is beneficial in terms of encouraging future usage. Participatory systems mapping is one codified methodology for conducting CLD development with stakeholders [300], [301], [183].

Once the CLDs are outlined, these directly inform SFM's which form the backbone of the quantitative analysis within SD. This computation is often presented in the form of dashboards for the input of variables by stakeholders. These interactive dashboards are one of the main means by which SD became a significant decision support tool. The tools allow policymakers, at a high-level, to input data to short run time models which quickly indicate probable policy impacts on complex systems.

One prominent decision support tool relating to decarbonisation which is openly available is En-ROADS in [302]. This highly publicised model is a global climate simulator that allows users to rapidly explore the impact of 30 policies such as transport electrification/carbon pricing on global temperature reductions long-term. En-ROADS is also flanked by smaller efforts such as the work in [303]. Decision support tools like En-ROADS are extremely useful but they need to be considered credible, salient, and legitimate by decision makers to be taken seriously. Credibility is dependent on the tool's accuracy and validity. Salience relates to the applicability/relevance of a decision tool to the decision at hand. Legitimacy is founded upon the use of multiple perspectives within an analysis in an unbiased manner [304]. From the UK perspective, government tools most comparable to En-ROADS include the recently withdrawn Department of Energy and Climate Change calculator [305] and its replacement, The MacKay Carbon Calculator [306].

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[21] additional detail on conducting SD can be found in [299] described by Forrester.

Overall, the holistic approach of the SD methodology and its ability to integrate data from various disciplinary sources is very applicable to socio-technical transport system problems and policy making which also typically cross many disciplinary boundaries. Some examples of multi-disciplinary inclusions within SD work include but are not limited to human factors, engineering and psychology e.g., solar data and solar adoption rates in [307], policymaking and logistics e.g., mandating shore power and seaport activity in [308], economics and transport planning e.g., fuel cost, choice and modal choice in [309], health and agriculture e.g., COVID-19 impact and UK food provision in [310].

Despite the ability of SD to incorporate considerable complexity, it must be noted that it is very difficult to completely model an entire system. This is mainly because causal relationships can arguably continue endlessly, and data is not always available to incorporate every causality effectively into a comprehensive SFM. In a recent systematic literature review of 50 studies of SD, limitations were found in strategy, combinations of variables and a lack of clarification as to how time-dependant behaviour was determined [311]. However, in the opinion of the author, no more developed a method of collaborative, multi-disciplinary modelling for policy evaluation has been presented to date than SD and hence its chosen as the methodology for this analysis.

### 6.3 Retrofit and Vehicle Stockpile Embodied Emissions

To analyse how retrofit could affect the embodied emission dynamics of vehicle stockpiles the life cycle of an individual vehicle from the perspective of its embodied emissions must be understood. This is because the embodied emission dynamics of the stockpile will manifest as a function of these individual vehicle life cycles. Generally, Figure 44 depicts the life cycle from vehicle production to end-of-life.

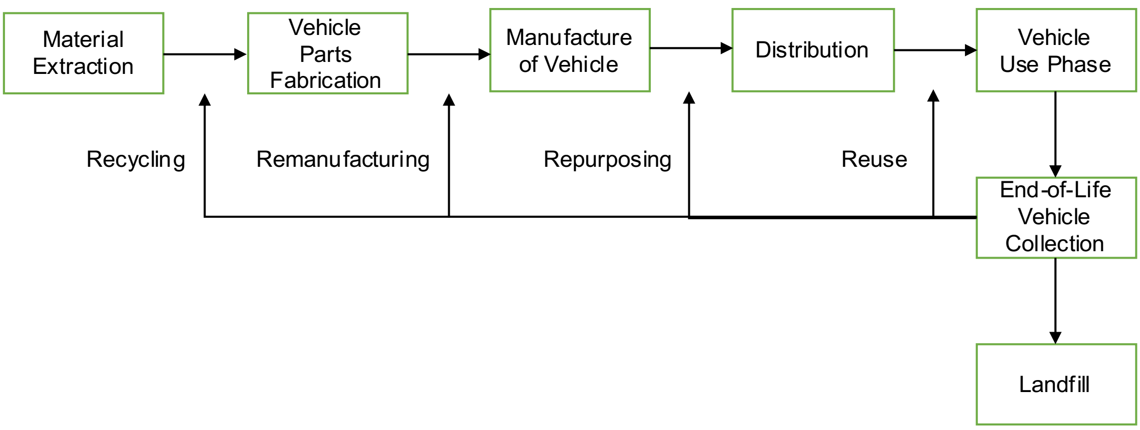


Figure 44: Vehicle end-of-life circularity pathways reproduced from [312].

The figure can be interpreted as a flow of materials and hence a flow of embodied emissions. The flow contains several return paths to various points previously in the life cycle which demonstrate potential points of circularity. Encouraging the development of end-of-life processes to reinforce paths of circularity can be known as a circularity strategy. Such strategies help to further establish/improve a future circular economy [313].

In the figure, the path of recycling represents a dismantling and shredding of the vehicle for its raw material only. This material is then returned to a manufacturing facility where brand new parts/vehicles are produced. Remanufacturing involves a full restoration back to factory condition in which a retrofit could also play a role. This type of process is very common in the classic car industry. Repurposing is the adaption of a vehicle for a new purpose, this is the most applicable pathway for retrofit in the agricultural setting discussed in the case study of this research. Components such as the interior or suspension are left in their original state, with other components such as the powertrain being replaced. Recovery of used parts for repurposing can also fall into this category. Reuse denotes undertaking a repair and/or simply recovering an existing working vehicle and bringing it back into its in-use phase. This could be as simple as a used car sale or the removal of a vehicle's SORN.

Of all of the paths of circularity, retrofit is most likely to most influence repurposing or remanufacturing. Repurposing is the most important pathway where an ICEV to EV transition fundamentally occurs. To diagrammatically represent the effect of retrofit on embodied emission flows through repurposing, Figure 45 contains a component level depiction of a retrofit, including lumped component removal and addition. Red boxes indicate removal, green boxes indicate addition/retention. Nuanced auxiliary system removals/additions are excluded from the diagram due to their smaller effects on embodied emissions and their variability between retrofit projects e.g., power steering is not always electrified, transmissions are sometimes kept/removed.

Complexities could also arise in quantifying embodied emission flows in relation to vehicle components when vehicles are designed so components can be continually swapped (or retrofitted) throughout a life cycle e.g. battery swapping EVs such as the NIO or Renault Zoe. It should also be noted that, in the case of an LRD retrofit, its ladder chassis and body on frame design allows for more simplistic removal and addition of retrofit componentry whilst leaving the chassis, and by extension chassis embodied emissions unaffected, this may not be the case for all vehicle types.

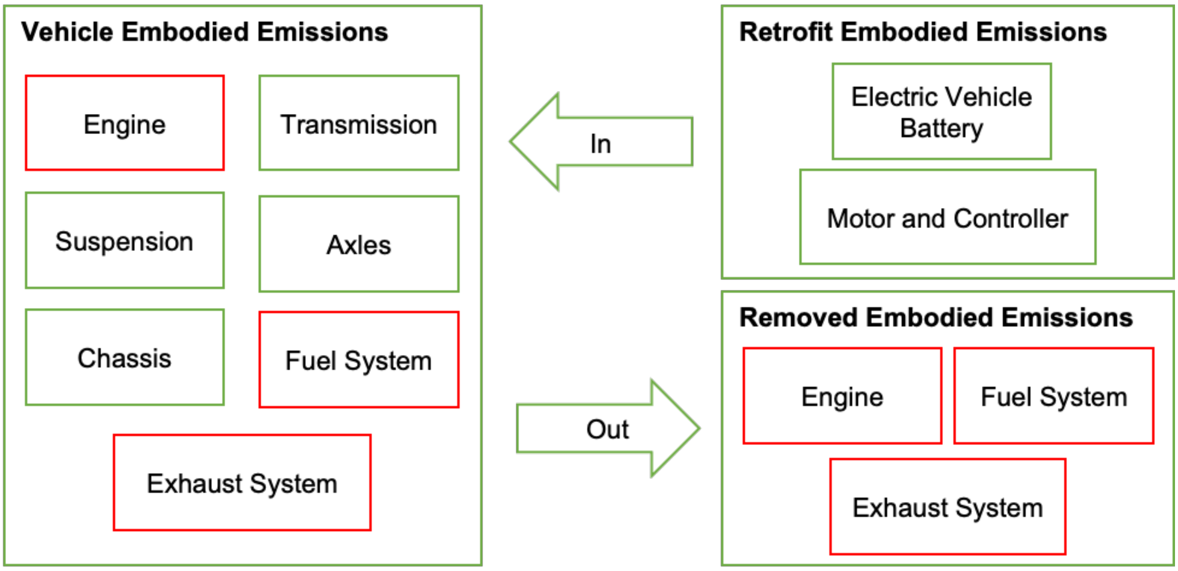


Figure 45: Component embodied emissions added or removed during retrofit.

### 6.4 Life Cycle Assessment of Vehicle Replacement Scenarios

The goal of any LCA is to evaluate the environmental impact of a product or service throughout its entire life cycle. Stages of a life cycle can include the extraction of its materials, its manufacture, operation, maintenance, and disposal. LCAs quantify emissions within these stages through the analysis of life cycle events, for example, the energy and subsequent emissions from a products manufacture, the embodied emissions from its raw materials, the fuel used for transport within its supply chain and any end-of-life ecological costs [314]. LCA results are often provided in the form of equivalent $CO_2$ emissions.

The datasets underpinning a LCA is termed a LCI which records the input and output flows for a product system. Flows can include water and energy consumption, raw material use etc. Inventories can be based on literature analysis or on process simulation and are incredibly useful particularly in investigating embodied emissions. This section estimates and compares the total emissions across three vehicle replacement scenarios i.e., two vehicle life cycles. The emissions data used to complete the estimations are from the LCI in [281] and the emissions data from Chapter 4.

The three scenarios considered are of two, back-to-back, vehicle life cycles. LRDs used in an agricultural setting generally have very long-life cycles. LRDs manufactured in the 1990s and 2000s are especially capable, durable vehicles and the average age of the vehicles involved in the central case study was 28 years with no indication of them being near end-of-life. Therefore, this age is assumed to form the initial part of the life cycle of an LRD before replacement or retrofit. Then the replacement vehicle will continue to be used for this length of time i.e. a total period of 56-years. For each LCA scenario, production, in-use, and end-of-life recovery emissions are considered. The replacement scenarios are:

Scenario 1 – ICEV being replaced with another ICEV.

Scenario 2 – ICEV being replaced with a new EV.

Scenario 3 – ICEV being retrofitted into a retrofitted EV.

It is noted that a limitation of this scenario analysis is that achieving the second life cycle of 28 years through retrofit could be unrealistic when considering potential future obsolescence from technological advance, maintenance costs or component failure. Also, if this research was generalised to other vehicles, they may not achieve this second life cycle. To compute production emissions, the LCI data is used as it contains vehicle components and their kg$CO_2$e emissions value for both EVs and ICEVs. The LCI is based on passenger cars and thus the results of the LCA should be interpreted with this context in mind i.e., it can only describe the asset replacement of vehicles of a comparable nature. Detailed information on the emissions data from the LCI can be found in Appendix G.

Most of the LCI data could be used at face value but some values needed additional consideration. For example, battery embodied emissions data was provided across multiple potential different chemistries in an EV, and so the most applicable for a retrofit needed to be selected. It was decided that the Li-NCM embodied emission data would be used and scaled linearly based on pack capacity for these LCA scenarios. This was on the basis that the LRD retrofits in the case study utilised Tesla battery modules which could contain Panasonic NCR18650B cells [315]. These cells are likely to be of an NCA chemistry so contain mostly nickel and cobalt along with aluminium [316]. Based on this information, the most closely related LCI data was of Li-NCM chemistry although the aluminium is replaced by manganese. Table 21 contains the total production embodied emissions for the three LCA scenarios.

To estimate in-use emissions, averages of the usage and age of the three vehicles at Worthy Farm (annual milage of 9283km and a 28-year life cycle) were taken. The vehicle energy consumption and conversion factors utilised to infer emissions were the same as in Chapter 4 (electricity = 0.21233kg$CO_2$e/kWh and diesel = 0.25165kg$CO_2$e/kWh). Manufacturer energy consumptions were used for this part of the LCA as the analysis is for a generic scenario rather than for the specific case study drive cycle at Worthy Farm. Transitory dynamics, such as a vehicle being in long term repair/storage or usage dropping significantly were excluded from the analysis but could be included in a future sensitivity analysis. Additionally, the per litre, or per kWh emissions were assumed to be constant, which is unlikely to be the case in reality as the grid will likely decarbonise over time [317]. In-use emissions are presented in Table 22.

Finally, end-of-life emissions for the vehicle and battery from the LCI data were introduced. These values were based on Ecoinvent v2.2, a LCI database in [318] where the battery treatment involves a dismantling and cryogenic shattering process, and the vehicle recovery process involves impacts associated with material recovery and disposal. The vehicle recovery process emits 510 kg$CO_2$e and the battery recovery 193 kg$CO_2$e. This results in Scenario 1, 2 and 3 totals of 1020 kg$CO_2$e, 1213 kg$CO_2$e and 1213 kg$CO_2$e respectively. Scenarios 2 and 3 are highest due to two vehicle disposals and a battery disposal. Though the battery recovery process should vary based on battery size, this data was not included. Also note that the second ICEV was assumed to have the same end-of-life, component, and in-use emissions as the first. This is unlikely to be the case as technology improves both in terms of part production, energy consumption, and recovery processes. Final LCA results including end-of-life emissions are presented in Table 23.

Table 21: Total production embodied emissions across three scenarios[22].

| Scenario | First Vehicle kg$CO_2$e | Second Vehicle kg$CO_2$e | Total kg$CO_2$e |
|---|---|---|---|
| 1 | ICEV = 6429.1 | ICEV = 6429.1 | 12858.2 |
| 2 | ICEV = 6429.1 | New EV = 33736.4 | 40165.5 |
| 3 | ICEV = 6429.1 | Retrofitted EV = 7749.6 | 14178.7 |

Table 22: Total in-use emissions estimate for three scenarios (28 years per vehicle).

| Scenario | First Vehicle kg$CO_2$e | Second Vehicle kg$CO_2$e | Total kg$CO_2$e |
|---|---|---|---|
| 1 | ICEV = 74567.3 | ICEV = 74567.3 | 149134.6 |
| 2 | ICEV = 74567.3 | New EV = 15453.1 | 90020.4 |
| 3 | ICEV = 74567.3 | Retrofitted EV = 16943.2 | 91510.5 |

Table 23: Total LCA emissions (kg$CO_2$e) for each scenario.

| Scenario | Production | In-use | End-of-Life | Total | Reduction (%) |
|---|---|---|---|---|---|
| 1 | 12858.2 | 149134.6 | 1020 | 163012 | 0% |
| 2 | 40165.5 | 90020.4 | 1213 | 131398.9 | 19.4% |
| 3 | 14178.7 | 91510.5 | 1213 | 106902.2 | 34.4% |

From the data it is clear that significant reductions in emissions across a two vehicle LCA are possible through utilisation of retrofit. Mapping the dynamics of this reduction is explored in the next section.

[22] Within the production emissions estimate, the retrofitted EV was based on a 26.5kWh battery capacity with 1024.8 kg$CO_2$e of parts removed from the original ICEV and 5404.3 kg$CO_2$e of emissions transferred to the retrofitted EV. The retrofitted EV had 7749.58 kg$CO_2$e of emissions added from the retrofit process creating a total embodied emissions for this vehicle of 13153.88 kg$CO_2$e.

## 6.5 Causal Loop Mapping

This section presents three CLD's that aim to outline the possible dynamics of embodied emissions within road vehicle stockpiles. The three diagrams present vehicle stockpile embodied emissions dynamics without the introduction of a retrofit pathway and after the introduction of a retrofit pathway and explore how the retrofit policy itself irrespective of emissions can interact with other decarbonisation policy. This third diagram centres itself around influences on the attractiveness of the retrofit methodology. The judgement of the author, anecdotal evidence from the central case study and studies in [319], [320], [321], [322], [323] led to the derivation of the three CLDs in this chapter. These studies cover automotive recycling, material usage, technological adoption, strategic niche management and embodied emissions within the transport system respectively. To create the three CLD figures the software package Vensim was utilised. This is a popular software choice for practitioners of SD. The CLDs attempt to include a comprehensive number of causalities and variables to depict the desired dynamics but aim to strike a balance between readability and complexity. Naturally more causalities could be added for further nuanced effects to be represented if required.

Figure 46 contains a CLD of the dynamics of embodied emissions within a generic vehicle stockpile without any retrofit pathway. The CLD focuses on average embodied emission (AEE) from the perspective of a vehicle stockpile (not an individual vehicle) and covers elements from the manufacture (pre-production) of a vehicle to its in-use phase, scrappage, and recovery. Work in [162] and [255] heavily inspired the design of this CLD. To retain simplicity the CLD excludes several causalities. Firstly, nuanced processes of manufacture and recovery such as assembly, dismantling, and shredding are excluded. Secondly, causalities that have a broad influence such as energy and material/labour cost are removed. Thirdly, factors including but not limited to vehicle attractiveness, vehicle reliability, sales rates, incentives (e.g., to recycle, shred or dismantle a vehicle etc.) and potential losses from the automobility system are excluded at this stage to reduce complexity of the mapping.

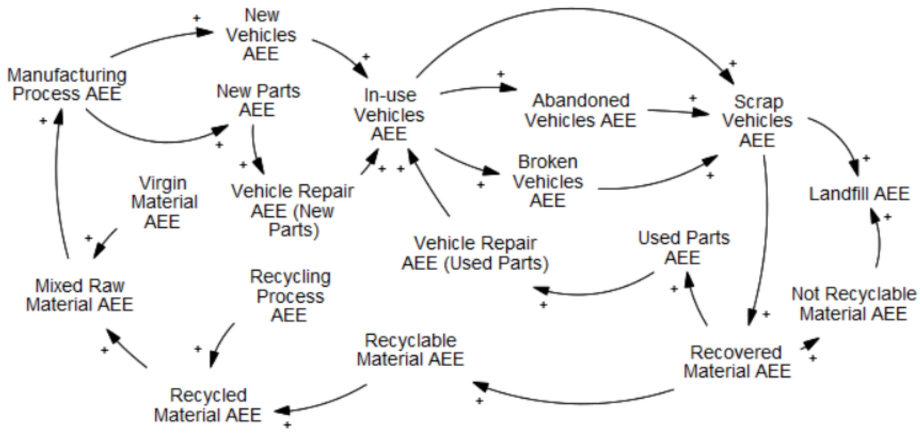


Figure 46: Vehicle stockpile embodied emission dynamics.

One of the key dynamics retained in the figure is the choice between vehicle repair using used parts or new parts. New parts will add their entire embodied emission value to a vehicle's life cycle, whereas used parts contain a mix of existing embodied emissions from a recovered part and potentially some new embodied emissions from the process of repurposing/remanufacturing said used part. It must be stressed that used parts may have shorter service lifespans than new and this must be factored into the decision but is not explicitly represented in the CLD. Building on the first CLD the second introduces the retrofit pathway and is illustrated in Figure 47. The retrofit pathway is highlighted in green.

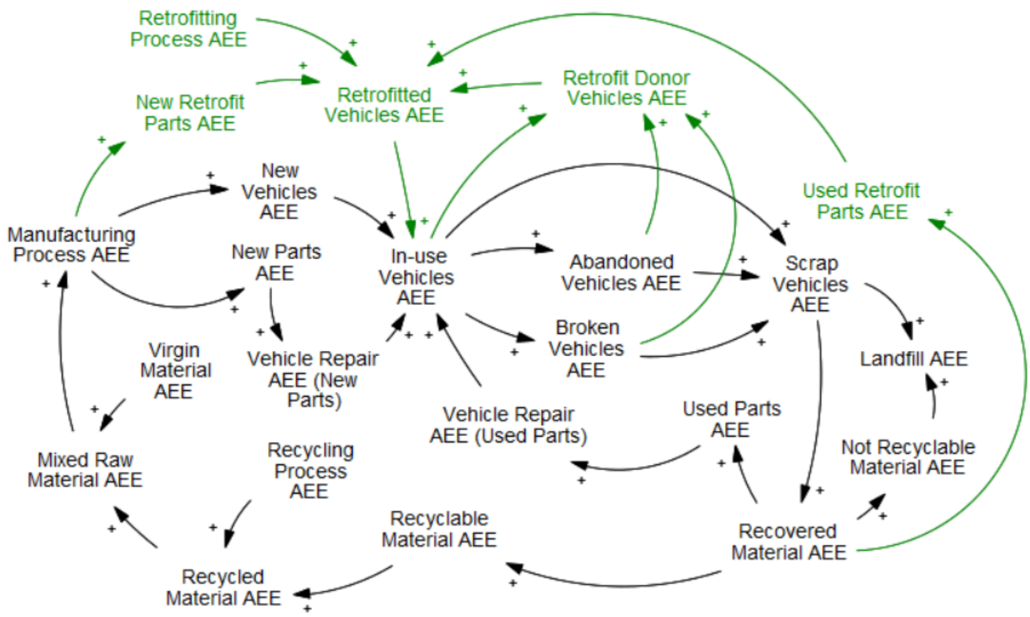


Figure 47: Vehicle stockpile embodied emission dynamics with retrofit pathway.

Key features represented in this figure are that retrofit donor vehicles AEE are coupled directly with in-use, abandoned and broken vehicle AEE causalities as a retrofit donor vehicle can originate from in-use, broken or abandoned stockpiles. Additionally, in the retrofit process AEE is added as a separate element along with new and used parts to create complete separation of the pathway in the diagram. The AEE of used parts are driven directly by the AEE of recovered parts from old vehicles, similarly the AEE of manufacturing processes drive the AEE of new parts to be used in a retrofitted EV. Completed retrofitted EVs will then contribute to AEE of the in-use vehicle stockpile.

Moving away from the dynamics of emissions, alternative causalities are likely to have a significant impact on the attractiveness of retrofit itself. The third CLD in Figure 48 attempts to explore some of these potential links to 'retrofit attractiveness' in the policy context. Policy components are outlined in the figure in blue and although the list of policies is not exhaustive, it represents common choices by policy makers to control emissions. The policies included are emission zoning, road pricing (aka road user charging), VED, carbon taxation, and subsidy in the form of vehicle scrappage, purchase, and retrofit) purchase or manufacture [325], [326], [327]. These policy actions are covered in detail in the next section.

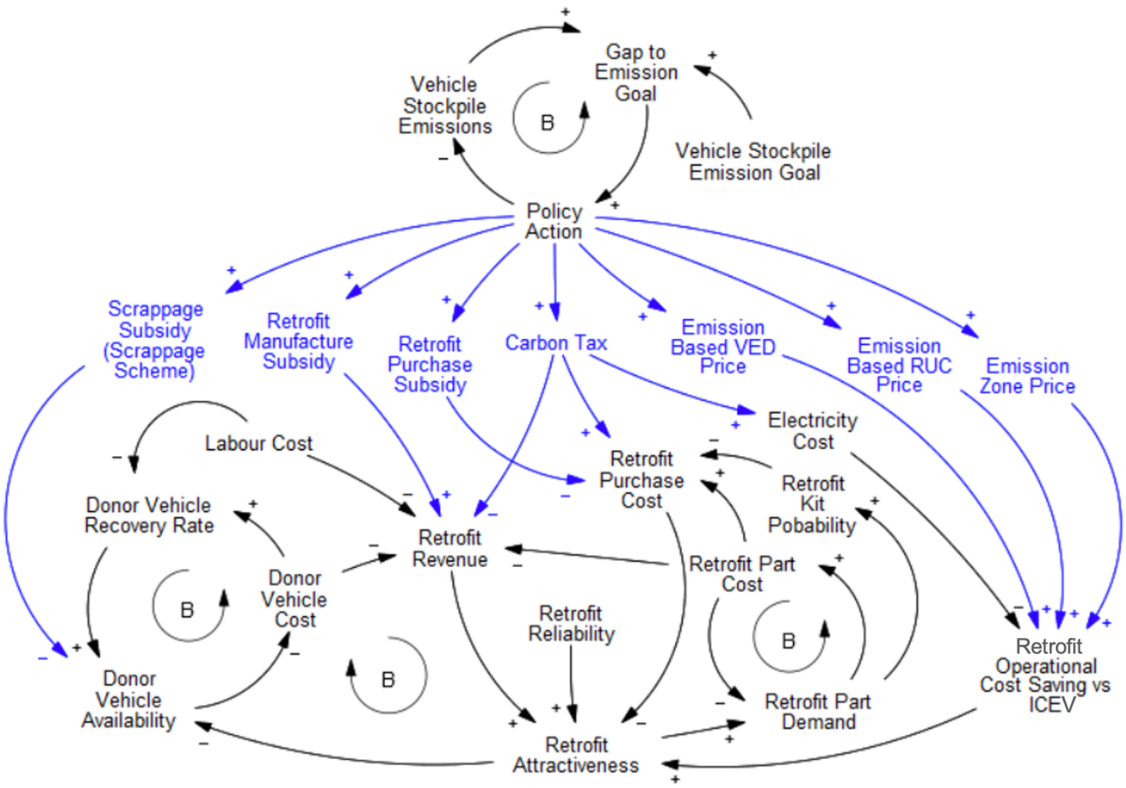


Figure 48: Dynamics of the attractiveness of retrofit in the policy context.

In terms of the links between causalities in the figure, it is worth noting that dynamics such as labour cost, carbon tax and energy cost will likely link to many more parts of the diagram, but this would make the figure less readable, and its focus is on the links to retrofit attractiveness. This third CLD includes social elements such as incentives to recover donor vehicles, reliability, and the potential of retrofit kit development. These causalities are difficult to quantitatively measure but useful to feature. Some key exclusions from this CLD are causalities under the theme of logistics, such as the cost of transport, recovery, collection, storage, and fuel which could affect retrofit revenue.

As with most CLDs, exclusions are common as reality involves a high number of sophisticated interfaces between economic, regulatory, and societal factors [328] though it is hoped that the three CLDs presented offer insights despite certain simplifications.

## 6.6 Policy Actions

This section outlines the specific policies included in the third CLD to provide background and explain their potential impact on retrofit attractiveness. It should be noted that individual policy impacts on retrofit should not be considered in isolation, it should be appreciated how policy choices work together (or not). Also, not all of these policies will directly impact the agricultural sector at this present time such as emissions zones and/or road user charging/vehicle excise duty e.g. due to SORNs. However, the exploration of broad policy impacts was completed to support objective four of this research outlined in Section 1.3. which was to "consider how potential UK policy may benefit and/or hinder retrofit adoption more broadly as a transport decarbonisation pathway". For a broader resource on policy measures for emission mitigation the Committee on Climate Change provide a comprehensive overview in [329].

### 6.6.1 Emission Zones

This is a vehicle access regulation scheme that restricts access to an area by the most polluting vehicles. The naming convention differs from place to place i.e., clean air zone or low emissions zone etc. but the general function is the same. Most schemes operate through enforcement mechanisms e.g., number plate recognition. In the context of retrofit such schemes could increase its attractiveness through forcing compliance of vehicles within the zone [325]. Compliance is normally centred around achieving certain emission standards in $gCO_2$/km which are commonplace in the UK [330]. Several emission zones also extend their compliance rules to NRMM [115] which is another potential reinforcement pathway for the adoption of retrofit.

### 6.6.2 Road User Charging

Road user charging (RUC) also known more generally as road pricing and involves levying a direct charge for use of roadways. This is typically achieved in the form of road tolls, distance/time-based fees, or congestion charges. Schemes can be enforced through systems including vehicle monitoring gantries and in-vehicle electronics [331]. Singapore was one of the first nations to deploy road pricing systems but now many nations are following in their path to counter emissions, congestion, and future reductions in tax revenues through the advent of EVs. Retrofit could be more attractive if road pricing becomes the norm, as vehicles which lack a low carbon alternative become ever more expensive to operate on a per mile basis [332], [333].

### 6.6.3 Vehicle Excise Duty

VED is already utilised in the UK alongside fuel duty as the two principal motoring taxes. VED is levied on vehicle registrations and fuel duty is levied on fuel consumption. There is a potential for these policies to shift from a focus on emissions/fuel consumption as the transport network is electrified to alternative categorisations e.g., a VED based on vehicle value or embodied emissions. Regardless of changes, the taxes place an additional financial burden on operating an ICEV and this could potentially become more burdensome towards 2050. This burden of cost on ICEVs acts to increase the attractiveness of retrofit [334], [335].

### 6.6.4 Carbon Tax

Carbon taxation in short puts a price on carbon emissions on a per unit of mass basis. This can be extended to equivalent emissions and can capture both embodied and direct emissions sources. The UK was involved in the European Union emissions trading system pre-Brexit, and it has now adopted a UK emissions trading system. In the future, these types of schemes could extend to vehicles and/or individuals' emissions which would act to increase the price of operating an ICEV hence raising the attractiveness of retrofit [336].

### 6.6.5 Subsidies

Subsidies can manifest in many forms, and even indirectly from the policy measures already outlined e.g., reduction in VED. The types considered in the third CLD are new vehicle purchase subsidies either through a scrappage scheme or direct payment and retrofit subsidies towards the retrofit manufacturer or purchaser. Note that retrofit subsidies are hypothetical and, to the knowledge of the author, have never been formally trailed.

In terms of direct new vehicle purchase subsidy, the most common in the UK is the 'plug-in grant'. More details on this subsidy scheme can be found in [337]. Grants can be provided in lump sums that are fixed or based on a percentage of the list price of certain vehicles. These types of subsidies also sometimes cover some/all of the cost of a charge point (in the case of electrification) and in recent years, grants have shifted from passenger cars to commercial vehicles. Overall, subsidy is mostly a catalyst for vehicle replacement and so it is assumed that the impact on retrofit attractiveness will be negative.

For a less direct subsidy option, scrappage schemes are available which typically involve government backed funding to encourage the scrappage of eligible old vehicles for replacement with new, with the new vehicle being offered at a discount. The schemes are typically facilitated by manufacturers and local councils. As of 2022, motorists can expect to save several thousand pounds on the list price of a new vehicle. Certain schemes have diverged from this norm. Birmingham council offers a scrappage scheme which provides £2000 of travel credit to use public transport and London offers a scheme which focuses on the scrappage of vans, minibuses, and heavy vehicles. Ultimately, scrappage schemes are mostly encouraging vehicle replacement and so act to reduce the attractiveness of retrofit [338], [339]. It should also be noted that other subsidies exist that act towards lowering or increasing operational costs for retrofit vehicles, for example, diesel subsidies (i.e., red diesel) – discussed in chapter 2, could act to reduce retrofitted EV operational cost savings vs ICEVs reducing the attractiveness of the pathway.

### 6.7 Stock and Flow Model

To provide a quantification of the retrofit pathway's effect on the landfill of embodied emissions of a vehicle stockpile, the CLDs developed are used to inform an SFM. The detailed structure of the SFM variables can be found in Appendix H. The creation of the SFM closely follows the methodology utilised in [294]. The SFM is restricted to exploring the embodied emission dynamics of three vehicle types (ICEV, new EV and retrofitted EV) within a fixed stockpile of vehicles during the initial transition to BEVs. The specific stockpile quantified is based on a lower bound (conservative) estimate of all agricultural road vehicles similar to that of LRDs i.e., sports utility vehicles. The stockpile size is based on a lower bound estimate assuming that one vehicle for retrofit exists per commercial farm holding in the UK. Currently, there are 212,000 farm holdings in the UK, of which 105,220 are considered commercial farms (supporting data and definition can be found in Appendix F). This results in a population of 105,220 ICEVs. This population is assumed to remain constant between the year 2000 and 2050 (simulated period).

The SFM is split into different sectors, the first, depicted in Figure 50, uses a stock driven approach to simulate the transition of the stockpile from ICEVs to battery electric vehicles (BEVs). This is due to the lack of inflow/outflow data regarding BEV transitions which would hinder a flow driven approach. This sector utilises National Grid's Future Energy Scenarios (FES) from 2022 to simulate the transition. Note that each sector's depiction is a general overview and changes slightly depending on the specific analysis conducted e.g., if additional causalities are required.

The FES aim is to explore how the energy system could evolve towards 2050. It focuses on decarbonisation and the choices that could transition the system to a Net Zero state. Choices include making changes to infrastructure and technology, implementing new innovations, and pushing behaviour/societal adjustments. Within the FES framework there are four scenarios, Consumer Transformation, System Transformation, Leading the Way and Falling Short. Each scenario provides data on the uptake of EVs. The philosophy behind each scenario is as follows:

**Consumer Transformation** represents a pathway to reach Net Zero by 2050 which centres its approach around the way energy is used. This focus on high consumer engagement involves disruption to the domestic consumer through the adoption of new technology such as EVs and participation in flexibility services such as demand side response and smart energy management.

**System Transformation** considers an alternative pathway which focuses on achieving Net Zero by 2050 through altering the way in which energy is generated and supplied. This is so the domestic consumer experiences less disruption. The scenario does rely on less established technologies such as carbon capture and storage or hydrogen boilers.

**Leading the Way** describes the fastest credible decarbonisation pathway which is achieved through combining higher consumer engagement, technology deployment and investment. This scenario could result in Net Zero before 2050.

**Falling Short** is the slowest credible speed to achieve Net Zero, falling short by 2050. It involves minimal behaviour change, decarbonisation of power and transport but not heat. EV take up is slow, with HGVs continuing to rely on diesel.

The scenarios applied to the SFM can be found in Figure 49. The System Transformation scenario from the FES has been excluded due to its decrease in BEV penetration towards 2050 due to the adoption of other zero emission vehicle types [340]. This would require the simulation of alternative zero emission vehicles which is beyond the scope of this SFM to investigate retrofit [63].

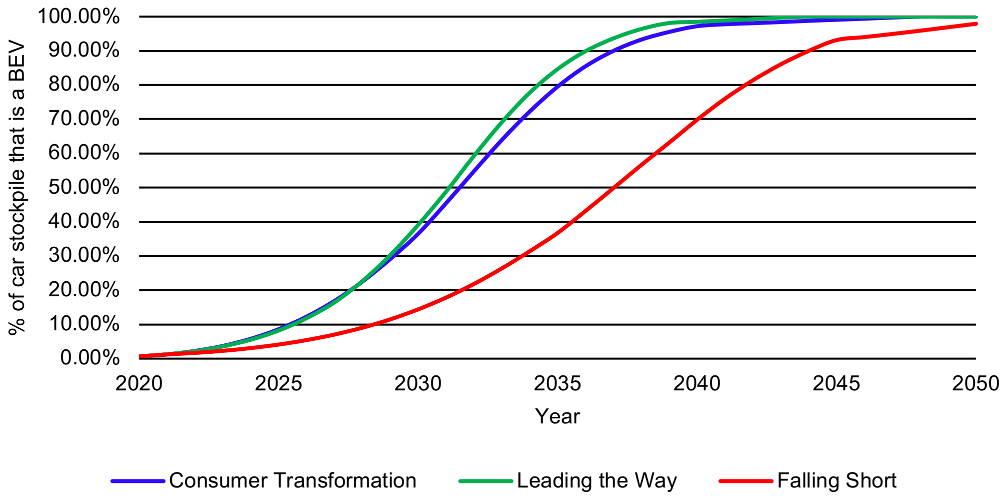


Figure 49: Change in car BEV penetrations to 2050 based on 2022 National Grid FES.

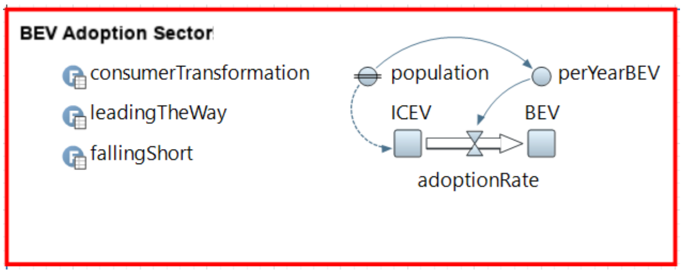


Figure 50: SFM 1st sector which applies FES to the ICEV to BEV transition.

The second sector, contained in Figure 51, considers the probability of an ICEVs replacement during the transition to either a new electric vehicle (NEV) or the adoption of a retrofitted electric vehicle (REV) based on the “attractiveness” of retrofit. This probably of retrofit is explored across all of the included National Grid FES in Figure 49 from a fixed percentage perspective using the CLD in Figure 48.

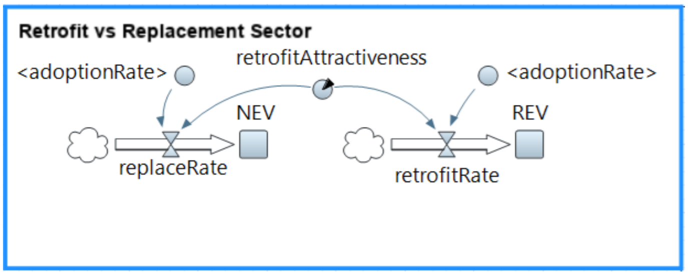


Figure 51: SFM 2nd sector computes ICEV replacement with new or retrofitted EVs.

The third sector of the SFM computes the total embodied emissions of each vehicle type within the stockpile and the scrappage of ICEV based embodied emissions based on the vehicle’s replacement by new EVs and removal of components during the retrofit process. The embodied emission stocks utilise component LCI data from the previous LCA in this chapter and the calculations of the stockpile’s vehicle breakdown in parent sectors one and two. This sector was originally inspired by dynamic material flow analysis in [294], but should be termed a component flow analysis as each vehicle type’s stock of embodied emissions is based on a combination of its sub components calculated in the LCA. Figure 52 is an overview of this third sector.

It should be noted that, as shown within Figure 52, the embodied emission stock of each vehicle does not factor in the impact of component lifespans and their ongoing replacement during a vehicle life cycle. This was mainly due to a lack of data on individual component degradation. It is also not known if modern EV or retrofit EV components will fail over the 30-year simulated period at significantly different rates. Furthermore, the overall aim of this SFM is to visualise the embodied emission dynamic changes within a vehicle stockpile, and so, in this instance, this particular simplification was not deemed inappropriate. For an accurate forecast of embodied emissions, a comprehensive material flow analysis would have to be undertaken which would also have to include individual material life cycles, emissions from waste management techniques and industrial production processes.

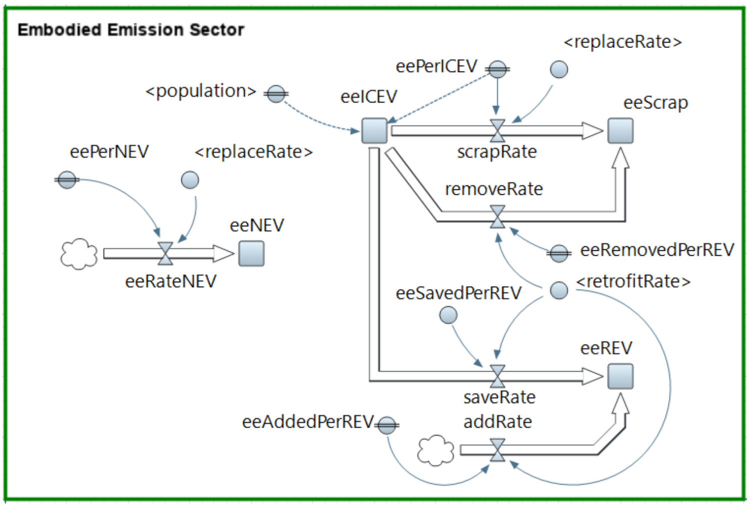


Figure 52: SFM 3rd sector which computes stockpile embodied emissions.

The fourth sector considers the end-of-life processing of ICEVs as they are replaced. It does not consider the end-of-life processing of new/retrofitted EVs as these are assumed to not be replaced over the simulated 30-year period[23]. The treatment of the ICEVs in this model is based on data from end-of life vehicle statistics from [341] where across the European Union 95.1% of vehicles were reused/recovered and 89.6% were reused/recycled. This leads to an 89.6% recycling rate of scrapped embodied emissions, a 5.5% recovery and a 4.9% landfill rate. Although for the purposes of this model these headline figures are useful to indicate end-of-life processes, it should be noted that reporting of these figures by individual nations within the European Union are still impacted by methodological and definitional inconsistencies, and limited information is available regarding loss of vehicles before end-of-life.

More complex end-of-life processes that could add to embodied emissions before landfill such as dismantling, and shredding are excluded due to lack of data. The European Union consistently mandates for high levels of end-of life processing of materials to be achieved. This extends to retrofit where the end-of-life battery directive in 2006 requires manufacturers to take responsibility for the collection and recycling of post-used batteries. It sets a minimum recycling target of 50% by average weight for general batteries, 65% for lead-acid and 75% for nickel-cadmium (European Union Directive, 2013/56/2013)[24] [343]. The fourth sector is depicted in Figure 53.

[23] Assumption based on average 28-year lifespan of LRD ICEV in case study. There is a lack of data on new/retrofitted EV lifespans due to their recent introduction to the automobile market.
[24] Note that EU directives can be indirectly applicable via secondary legislation in the UK [342].

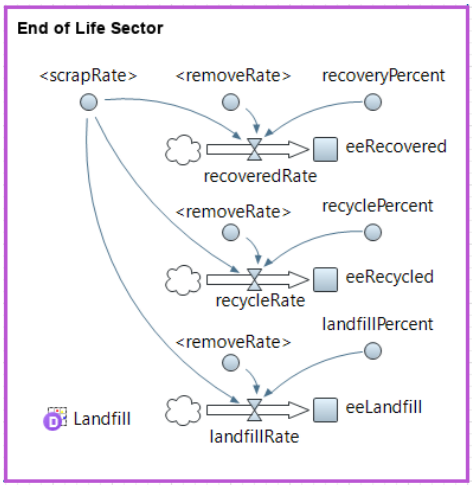


Figure 53: SFM 4th sector computes scrap embodied emission pathways.

## 6.8 Results

The results in this section contain the impact on embodied emissions to landfill from the vehicle stockpile as a result of varying the retrofit rate during the FES BEV transition pathways from 0% to 50% in 5% increments. The percentile rates are applied to the transition via a sensitivity analysis function within AnyLogic. This means, for example, that in a 5% simulation, as the ICEVs are replaced with BEVs, 5% of the replacement vehicles are selected to be retrofitted EVs and 95% are scrapped and replaced by new EVs. Figure 54 contains the results for the Consumer Transformation scenario. Figure 55 utilises the Leading the Way and Figure 56 the Falling Short scenarios.

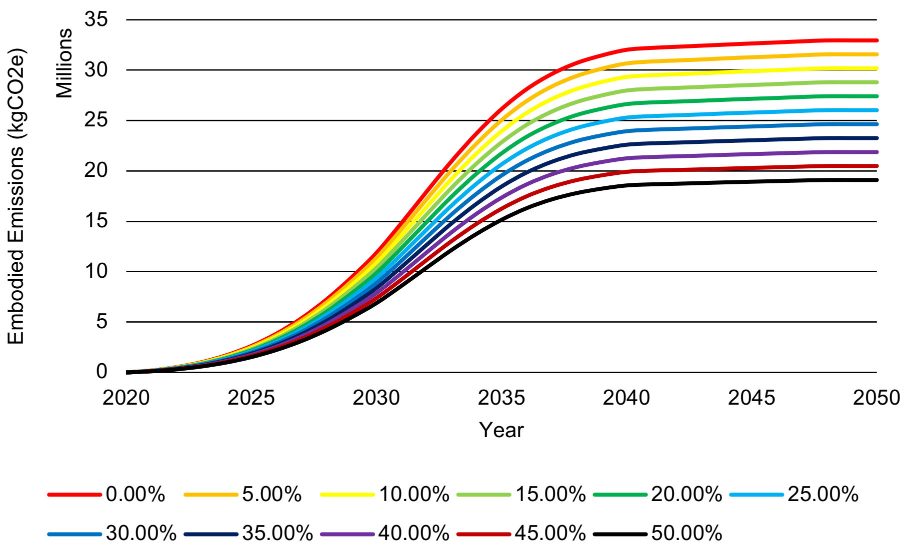


Figure 54: Total landfill embodied emissions for Consumer Transformation scenario.

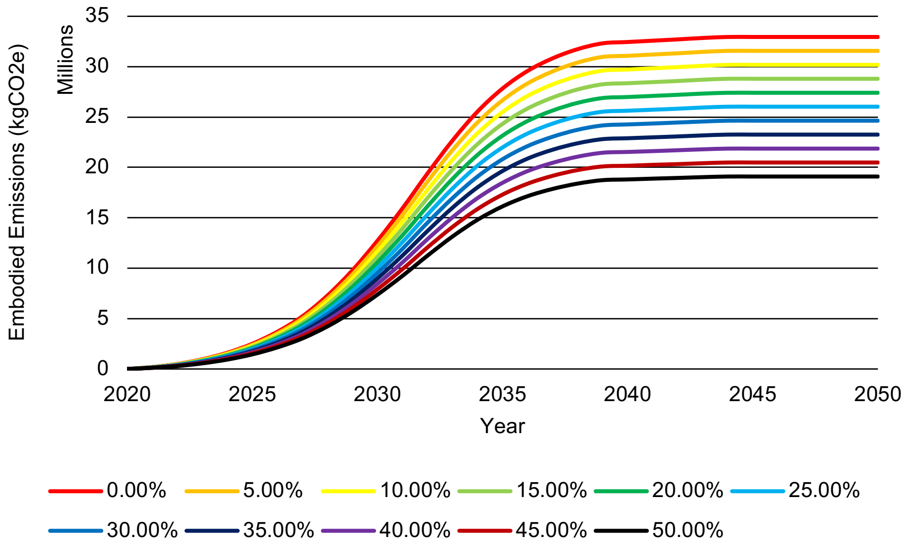


Figure 55: Total landfill embodied emissions for Leading the Way scenario.

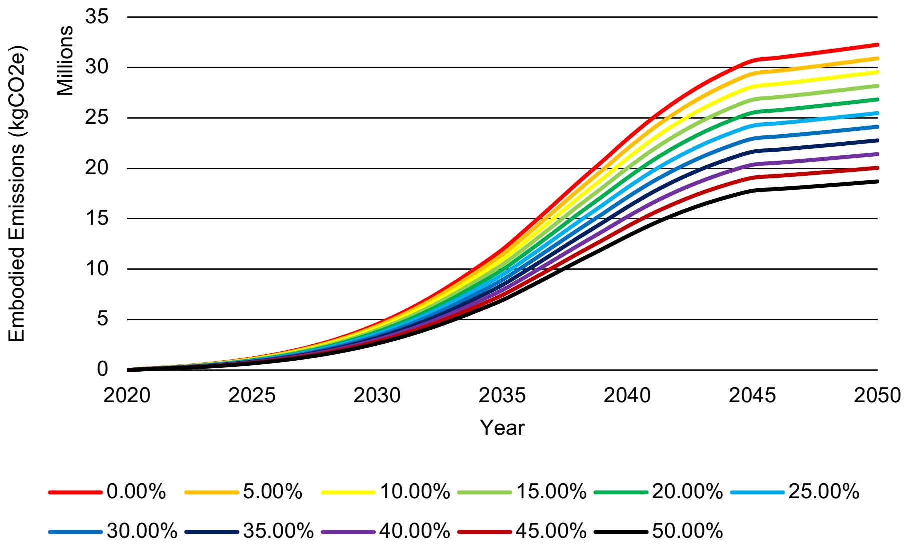


Figure 56: Total landfill embodied emissions for Falling Short scenario.

From the results it is shown that for all scenarios there is a significant reduction in embodied emission to landfill through introduction of the retrofit pathway. The peak reduction in emissions to landfill is more than 42% for the 50% scenario when compared to 0% retrofit. To explore how the emissions progress to landfill over time Figure 57 contains the total embodied emissions to landfill per year for the Falling Short scenario.

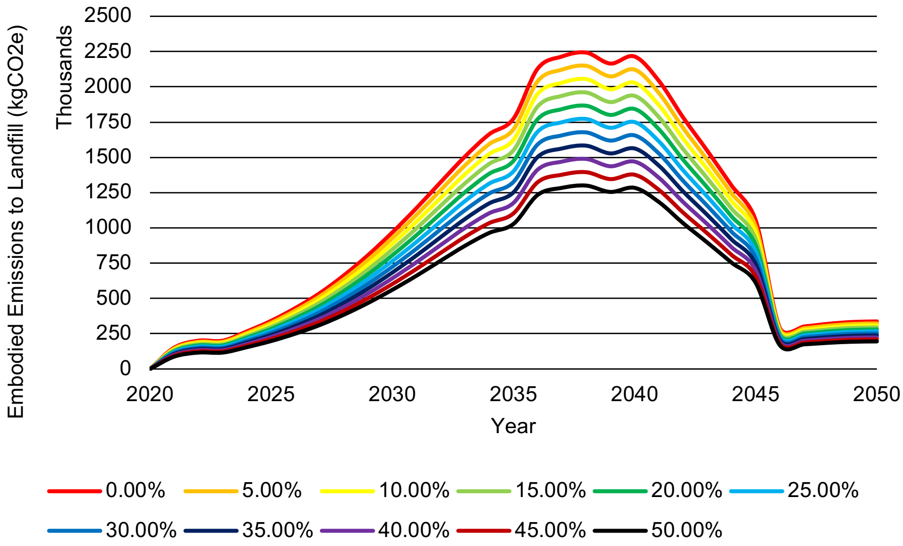


Figure 57: Embodied emissions to landfill per year under Falling Short scenario.

From this figure it is possible to see that the bulk impact of retrofitted EV adoption rates is achieved during the rapid period of transition between 2030 and 2045. This highlights the importance of timely policy design and introduction whilst ensuring policy stability to increase benefit.

To quantify any impacts of policy introduction variations the Falling Short scenario was simulated with a fixed retrofit adoption rate of 25%. However, this policy was delayed in its introduction to the model at increasing 2.5-year increments from 2020 to 2050. With the immediate introduction of a 25% retrofit adoption rate, a maximum 21% saving of embodied emissions to landfill is estimated (0% = 32,260,000kg$CO_2$e, 25% = 25,480,000kg$CO_2$e). After this the percentage loss of this maximum 21% saving is displayed at each 2.5-year incremental delay in policy introduction in Figure 58. The red part of the bar in the figure represents the percentage difference in loss from the previous policy delay increment so that the most influential years can be highlighted.

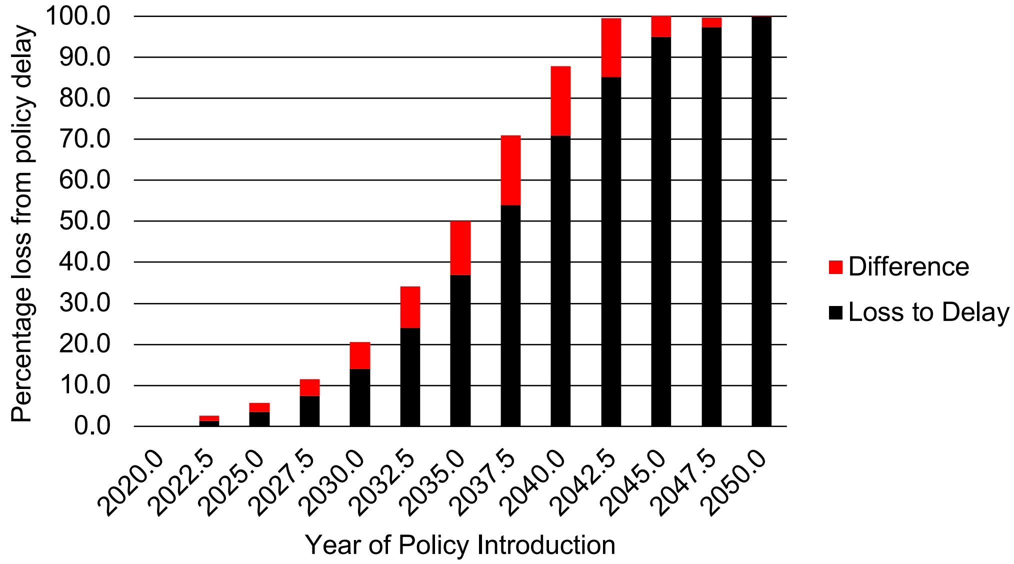


Figure 58: Percentage loss of 21% reduction in emissions to landfill from policy delay.

From the results it is clear to see that as the introduction of a retrofit policy is delayed, the magnitude of embodied emissions sent to landfill increases. More significantly, no introduction in retrofit policy until the years of 2032.5 to 2042.5 is the most significant in terms of removing any savings in this scenario. This is because this is the period of greatest transition speed between ICEV and BEV and thus the loss in the 21% emission saving is greater than 10% per increment. Note that this type of investigation into policy timing could be completed for other policy areas.

Arguably, decisions surrounding retrofit policy introduction need to be made within the next 5 to 7.5 years, and moreover, the feasibility of retrofit in later years will potentially be hindered further from a dwindling supply of donor ICEVs. To view the potential dynamics donor vehicle supply might have on landfill embodied emissions, the ICEV stock was tied to retrofit attractiveness. Retrofit attractiveness will therefore decrease as a percentage of the original ICEV stockpile total i.e., 105220 = 100% retrofit attractiveness. This dynamic is shown in Figure 59. All other model parameters are kept consistent with the previous falling short experiment.

It should be noted that although donor vehicle supply may reduce in future, other developments may increase the attractiveness of retrofit, for example, a larger supply in used battery packs may reduce their costs. This could work to counteract the reduction in retrofit attractiveness from lower donor vehicle supply.

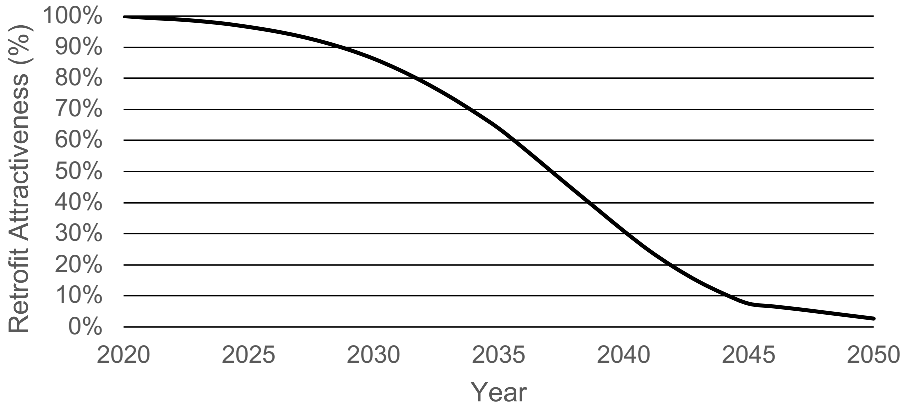


Figure 59: Retrofit attractiveness dynamics due to donor vehicle depletion

Figure 60 contains the per year magnitude of embodied emissions to landfill from the donor vehicle experiment and 30% retrofit attractiveness experiment. This was included as the peaks from both experiments are observed at around 1.6 million kg$CO_2$e per year. The increased attractiveness during the first 15 years when ICEV donor vehicle supply is still strong is seen to significantly reduce the number of emissions contributed to landfill during these years. The lack of donor vehicles after 2040 then has a lag effect, increasing emissions to landfill.

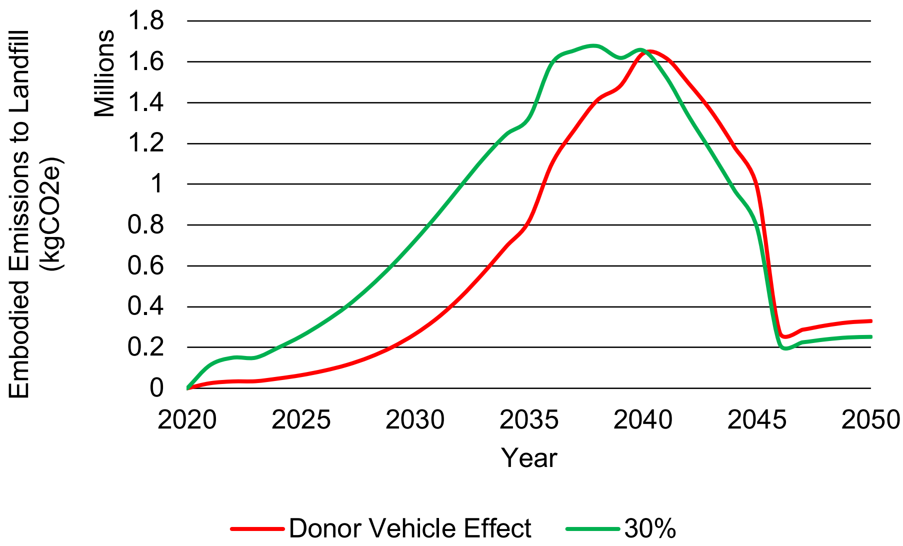


Figure 60: Embodied emissions to landfill per year.

Figure 61 contains the running total of embodied emissions sent to landfill, once again comparing the 30% and donor vehicle supply experiments for completeness.

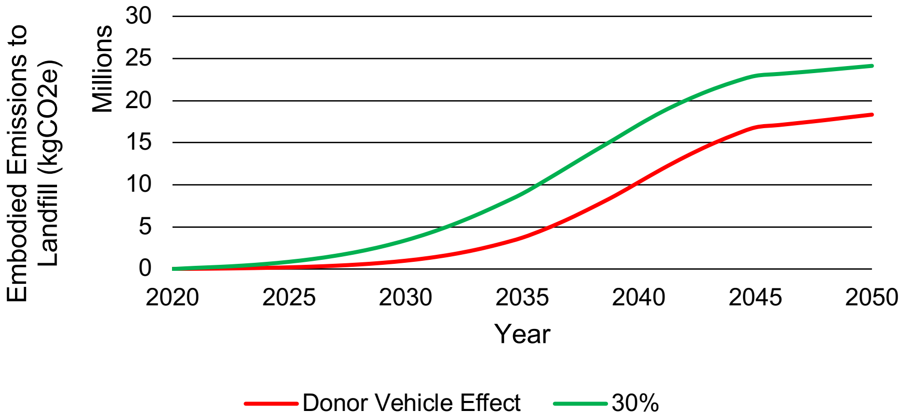


Figure 61: Total embodied emissions to landfill

Due to the aggressiveness of the profile in the early stages where many ICEVs are available the total embodied emissions to landfill are significantly lower during the donor vehicle supply. In reality, this level of retrofit attractiveness may not be possible despite the large supply of ICEVs in the early stages as the growth in attractiveness will likely take many more factors and be achieved over a longer time frame. It is, however, useful to see the significance of this one causality on the success of a retrofit scheme across this vehicle stockpile.

## 6.9 Discussion and Limitations

This chapter has applied a combination of LCA and SD methodologies to:

- Evaluate the life cycle emissions of three possible ICEV replacement scenarios.
- Map the potential causal relationships concerning the embodied emissions dynamics of a stockpile of vehicles without and with a retrofit pathway.
- Map the causalities that could impact retrofit attractiveness.
- Quantify the potential change in the flow of embodied emissions to landfill from a fixed stockpile of vehicles resulting from ICEV replacement during a BEV transition from the adoption of retrofit.

From the LCA of three ICEV replacement scenarios, it was found that the retrofit pathway could reduce life cycle emissions by around 34.4% and 18.6% when compared to direct replacement of an ICEV with an identical ICEV or new EV respectively. Additionally, the SD inspired SFM indicates that as the adoption of retrofit increases the flow of embodied emissions to landfill could slow. Over a fixed time period at a 50% retrofit adoption rate, embodied emissions to landfill from a stockpile of vehicles could be reduced by more than 42% under all FES. Furthermore, the realisation of this reduction could be significantly impacted by the timeline of retrofit policy implementation and/or the selection of other policy measures that may influence the ‘attractiveness’ of retrofit. Specific analysis on retrofit policy delay found that retrofit policy implementation before 2030 is valuable to capitalise upon the window of maximum embodied emissions savings between 2030 and 2042.5.

As previously outlined, the use of 105,220 vehicles in this chapter's agricultural vehicle stockpile is likely to be a significant underestimate given that there are circa. 467,000 employees in the agricultural sector, and it would not be unreasonable to assume that many of these employees has access to a vehicle [100]. For example, Worthy Farm in the case study has more than 20 LRDs.

For the LCA to be improved more work needs to be completed to understand the expected second life cycle period of a vehicle post retrofit as the double 28-year life cycle (56-year total) could be unrealistic for some LRDs and this is considered a current limitation. Furthermore, additional consideration of component replacements and their embodied emission impact to the LCA should also be completed. Significant component's replacements or repair such as suspension components, batteries, chassis dipping should be prioritised. Where possible cost data should also be considered for a potential life cycle cost comparison.

For the outputs of this SFM to be improved, stakeholder input to help further develop and scrutinise each CLD which informed the SFM could be useful. Additional CLD causalities could be explored especially in relation to economic variables such as labour, material, and part costs. Additionally, a higher quantity of accurate, recent data on vehicle stockpiles would be beneficial along with LCI data of used/new vehicle parts to improve estimations of embodied emissions flow during retrofit. The introduction of product passports could be one method of improving understanding of product material content and embodied emissions [344]. Furthermore, additional causalities affecting retrofit attractiveness could be added to the CLDs in future to codify more effects on retrofit attractiveness e.g., right to repair or design for disassembly policies. The option to introduce a used or new part sub-sector within the retrofit sector of the SFM would also be a very interesting experiment.

## 6.10 Conclusion

This chapter has appraised retrofit for transport decarbonisation from a macroscopic (top-down) perspective through assessing its introduction as a broad measure for vehicle stockpile decarbonisation. This has been achieved through the completion of a multi-scenario LCA and SD approach including causal mapping and exploration of embodied emissions dynamics to landfill through the use of a SFM. Overall, the top-down perspective has been useful in providing an overview of what retrofit policy deployment could mean for emissions across a population of vehicles.

From the LCAs conducted (supported through previous LCI data) it is clear that the ICEV retrofit pathway could offer a tangible reduction in life cycle emissions, when compared to ICEV replacement with a new EV or another ICEV. This finding supports objective five of this research to "estimate quantitatively the flow of embodied emissions between vehicles during retrofit and how this compares to new vehicle replacement". The CLD maps constructed clearly codify the causalities of AEE within a vehicle stockpile and how the introduction of retrofit policy can change these links. Additionally, the third CLD successfully displays certain key links between other decarbonisation policy measures and how they could reinforce or counteract the attractiveness of retrofit. This aids the completion of objective four of this research to "consider how potential UK policy may benefit and/or hinder retrofit adoption more broadly as a transport decarbonisation pathway". Finally, from the SFM outputs informed by the LCA scenarios, it is shown that as retrofit adoption is increased, the flow of embodied emissions to landfill from the stockpile of vehicles transitioning from ICEV to BEV is reduced and that early adoption of the pathway increases realisation of this benefit. These dynamics need to be explored in further detail via an extension to sectors in this SFM.

# Chapter 7 Discussion and Conclusion

This chapter provides a closing discussion and conclusion regarding this research into retrofit as a tool to aid transport decarbonisation. Firstly, these remarks are provided generally and in relation to the overarching research methodology, then in relation to the specific content within the literature review and each of the technical chapters. Some recommendations for future work are provided throughout.

## 7.1 Appraisal through Multiple Perspectives

This research has completed a microscopic, mesoscopic, and macroscopic analysis of agricultural retrofit in an attempt to answer the central research question: can electric vehicle retrofit aid the decarbonisation of transport? From the analysis conducted, yes but the context of retrofit implementation is very important. Fossil fuel internal combustion-based powertrains are known entities which are inherently flexible in their usage operationally i.e., fuel tanks store an excess of energy. The retrofitted EVs utilised in this study were designed with specification compromises and tighter operational tolerances including but not limited to reducing installed vehicle battery capacity and increasing the use of solar in conjunction with deployed charging infrastructure to improve techno-economic viability. So, in operational terms, achieving decarbonisation through retrofit can be complex, especially until the practice is better established.

In summary, the bottom-up perspective of this research implemented a techno-economic study of a retrofitted EV for the first time in the agricultural context in the academic literature, to the knowledge of the author. The middle-out perspective then considered how a number of retrofitted EVs could be effectively operated in the context of the case study, and the top-down perspective examined how broad application of retrofit could impact embodied emissions across a population of vehicles. In combination the three analyses provide evidence of how retrofit could potentially alter the production of direct vehicle emissions, and also the dynamics of embodied emissions within vehicle stockpiles in the automotive sector. Furthermore, the perspectives provide additional critiques of the utility of agent-based, causal loop and stock and flow modelling techniques in their applicability to the transport decarbonisation context. Overall, the multiple levels of abstraction considered across the three technical chapters as part of the research methodology were found to be useful in stimulating (in a semi-prescriptive manner) the investigation of:

- The methods of retrofit and key stakeholders within the retrofit market.
- The techno-economic performance of a retrofit.
- The deployment and operational considerations of retrofitted vehicles.
- How retrofit could impact embodied emissions.
- How policy can impact the appeal of retrofit.

This analysis approach was heavily influenced by the consideration of the MLP and in the opinion of the author, a micro, meso, macro approach is also serviceable outside of academia in environments such as policy making. These sectors often undertake wide-ranging appraisals. Policy making environments could also benefit from multi-variate quantitative methods such as SD and LCA [345], [346]. Generally, it was beneficial that the micro, meso and macro approach to this research was adaptable given the impacts of COVID-19 on data provision, access to Worthy Farm, and industrial partner support.

These factors limited the depth to which these perspectives could be investigated using primary data collection and arguably limited the research to the context of one case study i.e., the research focused on the retrofit of LRDs only. Future work should include analysis of the retrofit of other vehicles to further understanding of retrofits decarbonisation potential. For example, the study of heavy-duty vehicle retrofit including tractors. These are particularly problematic for this sector in terms of their emissions. From the available literature, only the Farmtrac FT25G Electric Tractor and Fendt e100 Vario are market ready and the FT25G is only a small tractor [347]. Retrofit of large tractors specifically is very uncommon though one project has been conducted by New Electric [165]. With a battery capacity of 360kWh it is likely to be expensive, so further research is needed to judge its suitability.

The lack of electric tractors could be due to a lack of affordable, reliable, battery technologies that can match the duty cycles of conventional tractors but given that electric refuse vehicles and HGVs are now available, this needs to be better understood. If electrification is a fundamental issue, research into alternative transport fuel retrofit could be conducted. Hydrogen or methane powered tractors could be feasible [348]. Hydrogen combustion conversion is currently under trial by JCB for agricultural equipment [349]. Some literature also suggests using biodiesel as a drop-in fuel [350].

In a similar vein to the study of different types of retrofitted vehicles, the study of transport fuel supply could also be further intertwined into these studies, for example, if a farm holding operates off-grid. Worthy Farm is grid connected, but in the agricultural sector remote farms may not possess strong, or any grid connection. These alternative scenarios would help to appraise retrofits widespread adoption. Furthermore, transport fuel supply will play heavily into the deployment of larger vehicles (e.g., electric tractors) and designing charging/local energy infrastructures etc. Weaker grid connections may result in slower charging and therefore higher battery capacity requirements for long duty cycles or the use of local energy generating assets and a battery buffer.

Finally, from a policy perspective, further research could be conducted into other wider policy contexts or factors that may impact the attractiveness of individual agricultural holding's decarbonisation – potentially through the retrofit decarbonisation pathway. For example, if the emissions content of food and/or the supply chains of food items becomes more important politically/socially for key stakeholders (e.g., supermarkets), this may form an indirect but strong incentive to decarbonise at the level of an individual agricultural holding. This could potentially increase the attractiveness of retrofit.

### 7.2 Literature Review

One of the more significant sections of the literature review was content surrounding the retrofit market. It was found that despite its nicheness, there are a significant number of retrofit practitioners and supporting stakeholders. Any growth in the practice of retrofit will act to increase the size of this post-production economy.  This growth has the potential to benefit the UK economically and socially by providing additional jobs and upskilling in the transport sector and nurturing an industry and skills for the circular economy.

Development of the post-production economy could also help to reduce barriers to entry in the automotive sector. Currently, large amounts of capital, resources and expertise are required to enter a sector on the supply-side of the market [351]. This has arguably led to a number of niche vehicles e.g., agricultural equipment receiving less focus for decarbonisation as there is a smaller market incentive to do so. This could reduce the speed of transition. Retrofit has an opportunity to offer a pathway to decarbonise niche vehicle stockpiles and help ensure vehicles are not ‘left behind’ in a transition to Net Zero.

### 7.3 Bottom-up Perspective

From the bottom-up perspective it has been determined that retrofit is possible and useful for LRD ICEVs in an agricultural setting. Technical analysis of a LRD retrofit clearly demonstrated that it could produce significantly lower direct emissions when compared to its original donor vehicle and in addition, the retrofit vehicles performance was similar to that of a modern EV. This analysis also fulfilled the first objective of this research: to evaluate quantitatively the energy consumption of a retrofit, its donor ICEV and a new EV to determine how they compare technically. Specifically, the LRD retrofit exhibited similar energy consumption to a modern EV at 30.7kWh/100km vs 28.8kWh/100km respectively. The direct emissions of the retrofit were 70% lower when compared to its donor vehicle when utilising UK emission conversion factors.

From an economic analysis, the second objective of this research was satisfied: to evaluate quantitatively the costs of an ICEV retrofit. Overall, the cost of LRD retrofit was found to be lower than LRD replacement with a modern EV (Rivian R1T). It is however noted that the Rivian R1T is not a perfect alternative to the LRD and so if a more analogous new EV was to become available, this should be investigated. The retrofit was also estimated to be 27.5% cheaper than the Rivian R1T and this reduction in cost could be extended to 69.5% if retrofit labour and donor vehicle cost are excluded. The utilisation of retrofit kits could also, through taking advantage of bulk part purchases, further reduce the capital cost of the retrofitted EV. Though, to achieve these positive statistics, the LRD retrofit has sacrificed features including but not limited to comfort, range and peak power when compared to the Rivian. More generally, this bottom-up analysis highlighted that retrofit could offer an alternative decarbonisation pathway for certain ICEVs to replacement with a new EV. One key benefit was the choice to retrofit a vehicle with a more tailored specification for its use case which could, for example, reduce raw material use and cost when compared to more broadly specified mass-produced EVs designed to capture a wider variety of users.

The comparison of ICEV, new EV and retrofitted EV was completed through use of simulated activity models and limited primary data. In future, all vehicles should be investigated using primary data. Furthermore, as mentioned, it will be beneficial to compare the LRD retrofit to a more analogous, fully electric, four-wheel drive, utility focused vehicle when one becomes available on the UK market. The analysis of varying duty cycles under varying conditions (especially temperature) should also be conducted. Weather conditions will play an important role in terms of a retrofitted EVs traction at the wheel (from wet ground), the effects on its battery and subsequent powertrain energy consumption. Analysis should also include the use of trailers and cargo variations. This longer term, more diverse analysis can be facilitated by a more resilient and capable on-board telematics unit for each vehicle type.

### 7.4 Middle-out Perspective

From the middle-out perspective, it was found that the success of a retrofit project (in terms of its decarbonisation potential) depends heavily on operational context. For example, the carbon intensity of the local electricity, potential for utilisation/installation of low/zero carbon energy assets, how the retrofitted EVs will be operated and who will operate them. For the specific agricultural case study considered, the potential of retrofitted vehicles could be improved through the utilisation of operational scenarios that allow the farm to take advantage of lower retrofit battery capacities and increased use of existing solar generation for charging. With this forethought, a retrofitted vehicle can be deployed and tailored to reduce costs/emissions. These findings satisfy the third objective of this research: to consider (qualitatively and quantitatively) the operational changes required to better integrate retrofitted EVs into transport operations.

Naturally, the specific analysis conducted from this perspective is highly dependent on context and to generalise from this case will be difficult as the details, constraints and environment of any future target transport system containing vehicles for retrofit and decarbonisation must be known. Practitioners could however improve a retrofit project greatly if they are informed of useful factors including but not limited to:

- The likely duty cycle of a retrofitted EV e.g., vehicle miles travelled, the terrain it is likely to encounter, typical weather conditions, variability in the duty cycle and cargo requirements etc.
- The limits of potential compromises in a retrofit's specification by its target user/procurer e.g., charge speed though lower power on-board chargers, range through using smaller installed battery capacities and luxuries such as air-conditioning etc. These sacrifices will feedback on interfaces with other transport system actors.
- The fiscal constraints of the client so that calculations of whole life cycle cost can be presented in comparison to other decarbonisation solutions.

If these factors are known, then employing a middle-out perspective could more accurately uncover the applicability of retrofit in a target context such as agriculture. For example, long agricultural asset turnovers and lower available investment capital could restrict the adoption of new EVs in the agricultural sector and therefore the compromises that are required to reduce the cost of a retrofit could be better justified.

The middle-out perspective relied heavily on modelling approaches to conduct its analysis. This was beneficial in allowing the research plan to be conducted under COVID-19 lockdown conditions, however, modelling was hampered by a lack of primary data from the farm owner and industrial partner to inform a longer more realistic simulation. For example, a lack of weather station or site energy consumption data from Worthy Farm meant ground tractive conditions and other electrical loads (anaerobic digestor) were negated from the ABM. It is likely that the inclusion of the anaerobic digestor would significantly impact the middle-out investigation, as it can provide lower carbon electricity overnight to compliment the solar installation in reducing retrofitted EV charging cost and potentially $CO_2$ emissions. This could mean that a different operational scenario is favoured. Furthermore, stochastic elements in this ABM, such as driver behaviour, were simplified. Future work could include more detailed effects from driving style [352] on LRD energy consumption, or poor charging behaviour [353]. In fact, during the deployment of the retrofitted EVs, it was noted by project partners that a key socio-technical issue at Worthy Farm was employees incorrectly scheduling charging of the LRDs or forgetting to plug them in. This type of data collection will need enhanced telematics.

Finally, the ABM could be modified to include bi-directional power flows from the LRD retrofitted EVs to examine them as flexibility service providers. This would require localised grid data to examine the potential for revenue generation via the farm's existing export arrangement with their local distribution network operator or, as mentioned, by acquiring the farm's energy load profile to see if the retrofitted EVs could be utilised to supply the farm's energy needs/to act as energy storage devices. Software to enable these type of flexibility services is already being considered, such as the load shifting of solar energy to power irrigation systems [174].

### 7.5 Top-down Perspective

From the top-down perspective it was found that broad adoption of retrofit is likely to decrease the quantity of embodied emissions of a vehicle stockpile sent to landfill during the evaluated time period as a result of increasing existing vehicle's longevities and delaying end-of-life recovery processes. This act of keeping raw materials in circulation for longer through retrofit improves circularity within transport, and more specifically, the automotive sector [323]. Governments could adopt a broad policy for retrofit in a similar fashion to schemes encouraging retrofit in the housing sector i.e., through subsidy and education of the general public that this pathway exists to aid decarbonisation. This policy is arguably much more environmentally conscious when compared to scrappage schemes as it returns abandoned/obsolete vehicles to the road, saves on raw materials whilst simultaneously removing their direct emissions. Analysis of embodied emissions in this chapter realised the fifth objective of this research: to estimate the flow of embodied emissions between vehicles during a retrofit and compare this to new vehicle replacement.

Many factors could influence the attractiveness and subsequent adoption of retrofit. Contributing to the fourth objective of the research, this chapter outlined some causal relationships between other potential UK policies and retrofit e.g., a scrappage scheme or how if the retrofit pathway becomes more popular, the supply of donor vehicles could decrease over time and impact the popularity of the practice. This should be considered by any long term retrofit policy maker, e.g., if retrofit donor vehicle supply dwindles then these post-production services should complement ongoing repair of EVs more generally.

Although broad retrofit adoption could improve circularity in the automotive sector, it may have some drawbacks. Firstly, it could reinforce existing mass manufacture and consumption systems as even though the process of retrofit can be decentralised the supply of affordable parts for the process is a result of mass-production. Secondly, retrofit acts to encourage the replacement of legacy equipment sustaining the status quo of automobile hegemony in the UK's transport system and does not act to reduce the need for travel. This is not aligned with key sustainable transport frameworks e.g., avoid, shift, improve [354] supporting mostly technological improvement and some modal shift from ICEV to EV. Ultimately, Net Zero 2050 is a transition with a large opportunity to evaluate the value of the contemporary automobile in society e.g., in terms of its effects on land use and equity. Finally, the re-sale market for retrofitted EVs is currently unknown and extensive modifications could deter potential purchasers.

Finally, it would be beneficial in future to take wider stakeholder input to scrutinise and further develop the CLDs presented in the top-down analysis. The SFM analysis could be expanded to cover other contexts/vehicle stockpiles. Work should also be completed on adding more economic factors to the SFM, for example, raw material prices, as they could play a pivotal role in end-of-life recovery and the achievement of circularity [323].

## 7.6 Summary

In summary, the results of the three perspective-based investigations indicate that retrofit offers a viable decarbonisation pathway to new vehicle replacement and can be more cost effective in certain contexts. Retrofit allows for low carbon vehicle solutions to be implemented where there are currently few mass-produced alternatives i.e., in the agricultural sector. A key strength of retrofit is that it can offer bespoke vehicle specification. This can potentially improve resource usage and reduce capital cost. Retrofitted EVs can reduce direct vehicle emissions and increase vehicle efficiency. The practicality of emissions reductions depends on the carbon-intensity of electricity and the effective integration/operation of retrofitted EVs. Finally, broad application of retrofit has potential to slow the movement of embodied emissions to landfill. This potential depends heavily on retrofit policy design and dynamics effecting policy longevity over time.

## References


[1] K. Chatterjee *et al.*, 'Access to Transport and Life Opportunities', NatCen Social Research, Technical Report, Aug. 2019. Accessed: Oct. 25, 2020. [Online]. Available: https://www.gov.uk/government/publications/access-to-transport-and-life-opportunities

[2] P. Campbell and J. Spero, 'Transport sector slow to reach UK emissions targets', *Financial Times*, Apr. 25, 2019. Accessed: Jan. 08, 2020. [Online]. Available: https://www.ft.com/content/61cac1e8-5fa2-11e9-a27a-fdd51850994c

[3] G. Santos, 'Road transport and CO2 emissions: What are the challenges?', *Transp. Policy*, vol. 59, pp. 71–74, Oct. 2017, doi: 10.1016/j.tranpol.2017.06.007.

[4] J. Markard, P. Wells, X.-S. Yap, and H. Van Lente, 'Unsustainabilities: A study on SUVs and Space Tourism and a research agenda for transition studies', *Energy Res. Soc. Sci.*, vol. 106, p. 103302, Dec. 2023, doi: 10.1016/j.erss.2023.103302.

[5] S. H. Appelbaum, 'Socio-technical systems theory: an intervention strategy for organizational development', *Manag. Decis.*, vol. 35, no. 6, pp. 452–463, Jan. 1997, doi: 10.1108/00251749710173823.

[6] Government Office for Science, 'A time of unprecedented change in the transport system', Government Office for Science, UK, Technical Report, Jan. 2019. Accessed: Nov. 15, 2019. [Online]. Available: https://www.gov.uk/government/publications/future-of-mobility

[7] Leeds City Council, 'Connecting Leeds Transport Strategy'. Leeds City Council, 2021. Accessed: Dec. 16, 2021. [Online]. Available: https://www.leeds.gov.uk/parking-roads-and-travel/connecting-leeds-and-transforming-travel/transport-policy

[8] Department for Transport, 'Decarbonising transport: a better, greener Britain'. Department for Transport, Jul. 14, 2021. Accessed: Jul. 14, 2021. [Online]. Available: https://www.gov.uk/government/publications/transport-decarbonisation-plan

[9] Department for Transport, 'Decarbonising Transport: setting the challenge'. Department for Transport, Mar. 26, 2020. Accessed: Mar. 30, 2020. [Online]. Available: https://webarchive.nationalarchives.gov.uk/ukgwa/20210402060829/https://www.gov.uk/government/publications/creating-the-transport-decarbonisation-plan

[10] 'Decarbonisation of transport: options and challenges'. Mar. 2019. Accessed: Dec. 10, 2019. [Online]. Available: https://easac.eu/publications/details/decarbonisation-of-transport-options-and-challenges/

[11] Claire Haigh, 'RISING TO THE CHALLENGE: Achieving net zero will require new thinking, creative solutions and systemic change.', Greener Transport Solutions, Mar. 2021. Accessed: Jun. 30, 2021. [Online]. Available: https://greenertransportsolutions.com/publication/rising-to-the-challenge/

[12] J. Axsen, P. Plötz, and M. Wolinetz, 'Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport', *Nat. Clim. Change*, vol. 10, no. 9, Art. no. 9, Sep. 2020, doi: 10.1038/s41558-020-0877-y.

[13] H. Waisman *et al.*, 'A pathway design framework for national low greenhouse gas emission development strategies', *Nat. Clim. Change*, vol. 9, no. 4, Art. no. 4, Apr. 2019, doi: 10.1038/s41558-019-0442-8.

[14] Energy UK, 'Pathways for the GB Electricity Sector to 2030', Feb. 2016. Accessed: Feb. 16, 2022. [Online]. Available: https://www.docs.energy-uk.org.uk/index.php/publication.html?task=file.download&id=5721

[15] K. H. Tsoi, B. P. Y. Loo, and D. Banister, '"Mind the (Policy-Implementation) Gap": Transport decarbonisation policies and performances of leading global economies (1990–2018)', *Glob. Environ. Change*, vol. 68, p. 102250, May 2021, doi: 10.1016/j.gloenvcha.2021.102250.

[16] J. M. Parker, 'Applying a System of Systems Approach for Improved Transportation', *SAPIENS Surv. Perspect. Integrating Environ. Soc.*, no. 3.2, Art. no. 3.2, Sep. 2010, Accessed: Oct. 12, 2022. [Online]. Available: https://journals.openedition.org/sapiens/1011

[17] Cambridge English Dictionary, 'Retrofit meaning in the Cambridge English Dictionary', Cambridge Dictionary. Accessed: Mar. 31, 2022. [Online]. Available: https://dictionary.cambridge.org/dictionary/english/retrofit

[18] A. Yuksel, 'SCR versus EGR: What's the right choice for the rail industry?', Cummins. Accessed: Apr. 01, 2022. [Online]. Available: https://www.cummins.com/news/2019/08/27/scr-versus-egr-whats-right-choice-rail-industry

[19] Netherlands Maritime Technology Foundation, 'RETROFITing ships with new technology for improved overall environmental footprint', CORDIS. Accessed: Jun. 08, 2022. [Online]. Available: https://cordis.europa.eu/project/id/285420/reporting

[20] Aviation Business News, 'Leading players in the aircraft retrofit industry form alliance', Aviation Business News. Accessed: May 06, 2022. [Online]. Available: https://www.aviationbusinessnews.com/mro/aircraft-retrofit-alliance/

[21] S. Wordsworth, 'Lunaz unveils first-ever upcycled industrial electric vehicle', Industrial Vehicle Technology International. Accessed: May 09, 2022. [Online]. Available: https://www.ivtinternational.com/news/hybrid-electric-vehicles/lunaz-unveils-first-ever-upcycled-industrial-electric-vehicle.html

[22] British Broadcasting Corporation, 'Here are 20 of the best restomods of 2020', Top Gear. Accessed: Apr. 04, 2022. [Online]. Available: https://www.topgear.com/car-news/best-2020/here-are-20-best-restomods-2020

[23] A. G. Mausbach, F. Safa, D. Harrow, and C. Diels, 'Ecofitting Circular Economy: An alternative approach to market, consumption, and design towards zero emissions', in *2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Sep. 2020, pp. 1–9. doi: 10.1109/EVER48776.2020.9242964.

[24] S. Doll, 'Ford is selling Mach-E crate motors to promote custom EV conversions like this F-100 concept', Electrek. Accessed: Apr. 08, 2022. [Online]. Available: https://electrek.co/2021/11/03/ford-is-selling-mach-e-crate-motors-to-promote-custom-ev-conversions-like-this-f-100-concept/

[25] P. Wells and P. Nieuwenhuis, 'Over the hill? Exploring the other side of the Rogers' innovation diffusion model from a consumer and business model

perspective', *J. Clean. Prod.*, vol. 194, pp. 444–451, Sep. 2018, doi: 10.1016/j.jclepro.2018.05.144.

[26] Alicia Tuovila, 'Capital Goods: Types, Examples, vs. Consumer Goods', Investopedia. Accessed: Apr. 06, 2024. [Online]. Available: https://www.investopedia.com/terms/c/capitalgoods.asp

[27] D. Hayes and G. Esposito, 'The Clean Vehicle Retrofit Technology Guide'. Low Carbon Vehicle Partnership, May 2019. Accessed: Jun. 29, 2021. [Online]. Available: https://www.zemo.org.uk/assets/reports/ZEMO_RETROFIT_GUIDE_2021_Final.pdf

[28] Zemo Partnership, 'Clean Vehicle Retrofit Accreditation Scheme', Zemo Partnership. Accessed: Mar. 31, 2022. [Online]. Available: https://www.zemo.org.uk/work-with-us/collaborative-initiatives/projects/clean-vehicle-retrofit-accreditation-scheme.htm

[29] Electric Classic Cars, 'Electric classic cars: top conversions, kits and UK companies', Auto Express. Accessed: Oct. 12, 2023. [Online]. Available: https://www.autoexpress.co.uk/news/356551/electric-classic-cars-top-conversions-kits-and-uk-companies

[30] sellmyclassic, 'Electric classics - Preserving Nostalgia for the Future', Sell My Classic. Accessed: Apr. 06, 2024. [Online]. Available: https://sellmyclassic.co.uk/electric-classics-preserving-nostalgia-for-the-future/

[31] R. Watts, A. Ghosh, and J. Hinshelwood, 'Exploring the Potential for Electric Retrofit Regulations and an Accreditation Scheme for the UK', *Electronics*, vol. 10, no. 24, p. 3110, Dec. 2021, doi: 10.3390/electronics10243110.

[32] Department for Environment, Food & Rural Affairs, 'Written evidence submitted by the Department for Environment, Food and Rural Affairs (AZE0038)'. UK Parliament Committees, Sep. 2019. Accessed: Mar. 03, 2024. [Online]. Available: https://committees.parliament.uk/writtenevidence/105593/pdf/

[33] Land Rover, 'History Of The Defender - Series One To Present Day | One Life | Land Rover UK', landrover. Accessed: Oct. 20, 2022. [Online]. Available: https://www.landrover.co.uk/explore-land-rover/one-life/design/series-one-defender-history.html

[34] *Building the 2,000,000th Defender*, (Jun. 24, 2015). Accessed: Apr. 06, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=h-tNkXo10F8

[35] All About London, 'History - Land Rover', Land Rover. Accessed: Apr. 06, 2024. [Online]. Available: https://www.defender-landrover.co.uk/p/history.html

[36] Solarsense, 'Worthy Farm solar panel installation | Glastonbury Festival | Case Studies - Solarsense'. Accessed: Jun. 09, 2022. [Online]. Available: https://www.solarsense-uk.com/casestudies/worthy-farm-glastonbury/

[37] Michael Eavis, 'Glastonbury Festival - Sustainability', Glastonbury Festival. Accessed: Apr. 07, 2024. [Online]. Available: https://www.glastonburyfestivals.co.uk/information/sustainability/

[38] Electrogenic, 'Electric Land Rover Defender converted by Electrogenic', Electrogenic. Accessed: Mar. 30, 2024. [Online]. Available: https://www.electrogenic.co.uk/bespoke/car-conversions/land-rover-defender-agricultural/

[39] F. W. Geels, ‘The multi-level perspective on sustainability transitions: Responses to seven criticisms’, *Environ. Innov. Soc. Transit.*, vol. 1, no. 1, pp. 24–40, Jun. 2011, doi: 10.1016/j.eist.2011.02.002.

[40] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, ‘Energy white paper: Powering our net zero future’, GOV.UK. Accessed: Oct. 12, 2022. [Online]. Available: https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

[41] D. Nicolaides, ‘Power Infrastructure Requirements for Road Transport Electrification’, Mar. 2018, doi: 10.17863/CAM.28055.

[42] D. McCollum, V. Krey, P. Kolp, Y. Nagai, and K. Riahi, ‘Transport electrification: A key element for energy system transformation and climate stabilization’, *Clim. Change*, vol. 123, no. 3–4, pp. 651–664, Apr. 2014, doi: 10.1007/s10584-013-0969-z.

[43] UK Research and Innovation, ‘Driving the electric revolution in the agri-food sector’, Nov. 2021. Accessed: Oct. 12, 2022. [Online]. Available: https://www.ukri.org/publications/driving-the-electric-revolution-in-the-agrifood-sector/

[44] D. Nicolaides, D. Cebon, and J. Miles, ‘Prospects for Electrification of Road Freight’, *IEEE Syst. J.*, vol. 12, no. 2, pp. 1838–1849, Jun. 2018, doi: 10.1109/JSYST.2017.2691408.

[45] J. Dixon, ‘Keeping the car clean, on the electrification of private transport’, University of Strathclyde, 2020. doi: 10.48730/V9BA-7E07.

[46] I. Philips, J. Anable, and T. Chatterton, ‘E-bikes and their capability to reduce car CO2 emissions’, *Transp. Policy*, vol. 116, pp. 11–23, Feb. 2022, doi: 10.1016/j.tranpol.2021.11.019.

[47] L. Stilo, D. Segura-Velandia, H. Lugo, P. P. Conway, and A. A. West, ‘Electric bicycles, next generation low carbon transport systems: A survey’, *Transp. Res. Interdiscip. Perspect.*, vol. 10, p. 100347, Jun. 2021, doi: 10.1016/j.trip.2021.100347.

[48] European Commission, ‘Electrification of the Transport System’, European Commission, Belgium, 2017. Accessed: Dec. 15, 2021. [Online]. Available: https://ec.europa.eu/newsroom/horizon2020/document.cfm?doc_id=46372

[49] A. Stips, D. Macias, C. Coughlan, E. Garcia-Gorriz, and X. S. Liang, ‘On the causal structure between CO2 and global temperature’, *Sci. Rep.*, vol. 6, no. 1, p. 21691, Apr. 2016, doi: 10.1038/srep21691.

[50] Y. Yan *et al.*, ‘Two-million-year-old snapshots of atmospheric gases from Antarctic ice’, *Nature*, vol. 574, no. 7780, pp. 663–666, Oct. 2019, doi: 10.1038/s41586-019-1692-3.

[51] D. Lüthi *et al.*, ‘High-resolution carbon dioxide concentration record 650,000–800,000 years before present’, *Nature*, vol. 453, no. 7193, pp. 379–382, May 2008, doi: 10.1038/nature06949.

[52] Department for Business, Energy & Industrial Strategy, ‘Final UK greenhouse gas emissions national statistics: 1990 to 2018’, GOV.UK. Accessed: Mar. 10, 2020. [Online]. Available: https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2018

[53] NOAA Global Monitoring Laboratory, ‘Annual Greenhouse Gas Index (AGGI)’, National Oceanic and Atmospheric Administration. Accessed: Mar. 22, 2022. [Online]. Available: https://gml.noaa.gov/aggi/aggi.html

[54] W. J. Ripple, C. Wolf, T. M. Newsome, P. Barnard, and W. R. Moomaw, ‘World Scientists’ Warning of a Climate Emergency’, *BioScience*, p. biz088, Nov. 2019, doi: 10.1093/biosci/biz088.

[55] Jacob Teter and Fabian Voswinkel, ‘Transport - Energy System’, IEA. Accessed: Apr. 06, 2024. [Online]. Available: https://www.iea.org/energy-system/transport

[56] International Energy Agency, ‘Transport’, IEA. Accessed: Jun. 20, 2022. [Online]. Available: https://www.iea.org/topics/transport

[57] Department for Transport, ‘Transport and environment statistics: Autumn 2021’, GOV.UK. Accessed: Feb. 22, 2022. [Online]. Available: https://www.gov.uk/government/statistics/transport-and-environment-statistics-autumn-2021/transport-and-environment-statistics-autumn-2021

[58] Department for Transport, ‘Transport Statistics Great Britain: 2019 summary’. Department for Transport, Dec. 17, 2019. Accessed: Dec. 30, 2019. [Online]. Available: https://www.gov.uk/government/statistics/transport-statistics-great-britain-2019

[59] Climate Change Committee, ‘Sixth Carbon Budget’, Climate Change Committee. Accessed: Jul. 15, 2021. [Online]. Available: https://www.theccc.org.uk/publication/sixth-carbon-budget/

[60] UK Government, *Climate Change Act 2008*, vol. 2008 c 27. 2008, p. 108. Accessed: Nov. 19, 2019. [Online]. Available: https://www.legislation.gov.uk/ukpga/2008/27/contents

[61] S. Priestley, ‘UK Carbon Budgets’, House of Commons, London, CBP7555, Jul. 2019. Accessed: Oct. 30, 2019. [Online]. Available: https://commonslibrary.parliament.uk/research-briefings/cbp-7555/

[62] Department for Transport, ‘Consultation on when to phase out the sale of new, non-zero emission heavy good vehicles’, GOV.UK. Accessed: Jul. 14, 2021. [Online]. Available: https://www.gov.uk/government/consultations/heavy-goods-vehicles-ending-the-sale-of-new-non-zero-emission-models

[63] Department for Transport and Office for Zero Emission Vehicles, ‘Consulting on ending the sale of new petrol, diesel and hybrid cars and vans’, GOV.UK. Accessed: Apr. 16, 2020. [Online]. Available: https://www.gov.uk/government/consultations/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans

[64] Department for Transport, ‘The Road to Zero - Next steps towards cleaner road transport and delivering our Industrial Strategy’. Department for Transport, Jul. 2018. Accessed: Feb. 16, 2022. [Online]. Available: https://www.gov.uk/government/publications/reducing-emissions-from-road-transport-road-to-zero-strategy

[65] Florent Grelier, ‘CO2 emissions from cars: The facts - Transport & Environment’, Transport & Environment, Belgium, Technical Report, Apr. 2018. Accessed: Mar. 07, 2022. [Online]. Available: https://www.transportenvironment.org/discover/co2-emissions-cars-facts/

[66] World Economic Forum, ‘The Future of the Last-Mile Ecosystem’, World Economic Forum, Switzerland, Technical Report, Jan. 2020. Accessed: Mar. 07, 2022. [Online]. Available: https://www.weforum.org/reports/the-future-of-the-last-mile-ecosystem/

[67] J. Woodcock, D. Banister, P. Edwards, A. M. Prentice, and I. Roberts, ‘Energy and transport’, *The Lancet*, vol. 370, no. 9592, pp. 1078–1088, Sep. 2007, doi: 10.1016/S0140-6736(07)61254-9.

[68] Air Quality Expert Group, ‘Non-Exhaust Emissions from Road Traffic’, Air Quality Expert Group, Research PB14581, 2019. Accessed: Feb. 16, 2022. [Online]. Available: https://uk-air.defra.gov.uk/library/reports.php?report_id=992

[69] Department for Environment, Food & Rural Affairs, ‘Causes of air pollution- Defra, UK’. GOV.UK, 2019. Accessed: May 06, 2022. [Online]. Available: https://uk-air.defra.gov.uk/air-pollution/causes

[70] C. Kouridis and C. Vlachokostas, ‘Towards decarbonizing road transport: Environmental and social benefit of vehicle fleet electrification in urban areas of Greece’, *Renew. Sustain. Energy Rev.*, vol. 153, p. 111775, Jan. 2022, doi: 10.1016/j.rser.2021.111775.

[71] J. Vidal, ‘WHO: air pollution “is single biggest environmental health risk”’, *The Guardian*, Mar. 25, 2014. Accessed: Mar. 03, 2022. [Online]. Available: https://www.theguardian.com/environment/2014/mar/25/air-pollution-single-biggest-environmental-health-risk-who

[72] European Environment Agency, ‘Air pollution: how it affects our health’, Air pollution: how it affects our health. Accessed: Mar. 03, 2022. [Online]. Available: https://www.eea.europa.eu/themes/air/health-impacts-of-air-pollution

[73] Environmental Protection Agency, ‘History of Reducing Air Pollution from Transportation in the United States’, United States Environmental Protection Agency. Accessed: Mar. 04, 2022. [Online]. Available: https://www.epa.gov/transportation-air-pollution-and-climate-change/accomplishments-and-success-air-pollution-transportation

[74] T. Grigoratos and G. Martini, ‘Non-exhaust traffic related emissions - Brake and tyre wear PM: literature review.’, European Commission, LU, Policy Report JRC89231, 2014. Accessed: Mar. 04, 2022. [Online]. Available: https://data.europa.eu/doi/10.2790/21481

[75] D. Mehlig, H. Woodward, T. Oxley, M. Holland, and H. ApSimon, ‘Electrification of Road Transport and the Impacts on Air Quality and Health in the UK’, *Atmosphere*, vol. 12, no. 11, p. 1491, Nov. 2021, doi: 10.3390/atmos12111491.

[76] O. Edenhofer *et al.*, ‘Climate Change 2014: Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change’, Cambridge University Press, Technical Report AR5, 2014. [Online]. Available: https://www.ipcc.ch/report/ar5/wg3/

[77] World Business Council for Sustainable Development and World Resources Institute, *Greenhouse Gas Protocol*. 2004. Accessed: Mar. 23, 2022. [Online]. Available: https://ghgprotocol.org/

[78] Network for Transport Measures, ‘Scope and system boundaries’. Accessed: Feb. 21, 2022. [Online]. Available: https://www.transportmeasures.org/en/wiki/manuals/system-boundaries/

[79] A.-M. Tillman, T. Ekvall, H. Baumann, and T. Rydberg, ‘Choice of system boundaries in life cycle assessment’, *J. Clean. Prod.*, vol. 2, no. 1, pp. 21–29, Jan. 1994, doi: 10.1016/0959-6526(94)90021-3.

[80] A. Pathak, G. Sethuraman, A. Ongel, and M. Lienkamp, ‘Impacts of electrification & automation of public bus transportation on sustainability—A case study in Singapore’, *Forsch. Im Ingenieurwesen*, vol. 85, no. 2, pp. 431–442, Jun. 2021, doi: 10.1007/s10010-020-00408-z.

[81] Tesla, ‘Tesla 2020 Impact Report’, 2020. Accessed: Dec. 02, 2021. [Online]. Available: https://www.tesla.com/impact-report/2020

[82] International Organisation for Standardization, ‘Environmental management — Life cycle assessment — Principles and framework’. Jul. 2006. [Online]. Available: https://www.iso.org/standard/37456.html

[83] E. Nieuwlaar, ‘Life Cycle Assessment and Energy Systems’, in *Encyclopedia of Energy*, C. J. Cleveland, Ed., New York: Elsevier, 2004, pp. 647–654. doi: 10.1016/B0-12-176480-X/00233-3.

[84] International Organisation for Standardization, ‘Greenhouse gases - Quantification and reporting of greenhouse gas emissions arising from transport chain operations’. BSI British Standards, Mar. 2023. Accessed: Feb. 11, 2024. [Online]. Available: https://www.iso.org/standard/78864.html

[85] H.O. Portner *et al.*, ‘Climate Change 2022: Impacts, Adaption, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change’, Cambridge University Press, Technical Report AR6, 2022. Accessed: Mar. 23, 2022. [Online]. Available: https://www.ipcc.ch/report/ar6/wg2/

[86] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, ‘Greenhouse gas reporting: conversion factors 2021’, GOV.UK. Accessed: Mar. 09, 2022. [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

[87] Department for Transport, ‘TAG data book’, GOV.UK. Accessed: Mar. 10, 2022. [Online]. Available: https://www.gov.uk/government/publications/tag-data-book

[88] K. Lokesh, D. Densley-Tingley, and G. Marsden, ‘Measuring Road Infrastructure Carbon: A “critical” in transport’s journey to net-zero’, DecarboN8, Leeds, Technical Report, Feb. 2022. Accessed: Mar. 23, 2022. [Online]. Available: https://decarbon8.org.uk/embodiedemissions-road/

[89] K. Lokesh, D. Densley-Tingley, and G. Marsden, ‘Measuring Railway Infrastructure Carbon: A “critical” in transport’s journey to net-zero’, DecarboN8, Leeds, Technical Report, Feb. 2022. Accessed: Mar. 23, 2022. [Online]. Available: https://decarbon8.org.uk/embodiedemissions-rail/

[90] Department for Transport, ‘Transport and environment statistics: 2023’. [Online]. Available: https://www.gov.uk/government/statistics/transport-and-environment-statistics-2023/transport-and-environment-statistics-2023

[91] G. Marsden, K. Lokesh, and D. Densley-Tingley, ‘Policy Briefing: Everything Counts: Why transport infrastructure emissions matter for decision makers’. DecarboN8, Feb. 24, 2022. Accessed: Mar. 23, 2022. [Online]. Available: https://decarbon8.org.uk/embodiedemissions-policy/

[92] V. Reis, J. Fabian Meier, G. Pace, and R. Palacin, ‘Rail and multi-modal transport’, *Res. Transp. Econ.*, vol. 41, no. 1, pp. 17–30, May 2013, doi: 10.1016/j.retrec.2012.10.005.

[93] Department for Environment, Food & Rural Affairs and Department for Business, Energy & Industrial Strategy, ‘Environmental reporting guidelines: including Streamlined Energy and Carbon Reporting requirements’, GOV.UK. Accessed: Jul. 05, 2022. [Online]. Available: https://www.gov.uk/government/publications/environmental-reporting-guidelines-including-mandatory-greenhouse-gas-emissions-reporting-guidance

[94] Carbon Footprint Ltd, ‘carbonfootprint.com - SECR’. Accessed: Oct. 08, 2022. [Online]. Available: https://www.carbonfootprint.com/secr.html

[95] Government Commercial Function, ‘Procurement Policy Note 06/21: Taking account of Carbon Reduction Plans in the procurement of major government contracts’, GOV.UK. Accessed: Oct. 08, 2022. [Online]. Available: https://www.gov.uk/government/publications/procurement-policy-note-0621-taking-account-of-carbon-reduction-plans-in-the-procurement-of-major-government-contracts

[96] Deloitte, ‘What are scope 1, 2 and 3 emissions?’, Deloitte United Kingdom. Accessed: Dec. 02, 2022. [Online]. Available: https://www2.deloitte.com/uk/en/focus/climate-change/zero-in-on-scope-1-2-and-3-emissions.html

[97] CEMA, ‘The role of agricultural machinery in decarbonising agriculture’, Apr. 2022. Accessed: May 24, 2023. [Online]. Available: https://www.cema-agri.org/images/publications/position-papers/CEMA_decarbonising_agriculture_27-04-22.pdf

[98] PBL Netherlands Environmental Assessment Agency and Utrecht University, ‘Mitigating Greenhouse Gas Emissions in Hard-To-Abate Sectors’, The Hague, 4901, Jul. 2022. Accessed: Apr. 07, 2024. [Online]. Available: https://www.pbl.nl/sites/default/files/downloads/pbl-2022-mitigating-greenhouse-gas-emissions-in-hard-to-abate-sectors-4901.pdf

[99] Royal Agricultural Society of England, ‘Farm of the Future: Journey to Net Zero’. Royal Agricultural Society of England, Mar. 08, 2022. [Online]. Available: https://www.rase.org.uk/v_uploads/documents/website-report/FARM%20OF%20THE%20FUTURE-%20JOURNEY%20TO%20NET%20ZERO.pdf

[100] Department for Environment, Food & Rural Affairs and Government Statistical Service, ‘Agriculture in the UK Evidence Pack’, Sep. 2022. Accessed: Apr. 07, 2024. [Online]. Available: https://assets.publishing.service.gov.uk/media/6331b071e90e0711d5d595df/AUK_Evidence_Pack_2021_Sept22.pdf

[101] Department for Environment, Food & Rural Affairs, ‘Machinery investment on farms in England: 2009/10 to 2017/18 Results from the Farm Business Survey’. Department for Environment Food and Rural Affairs, Dec. 20, 2018. Accessed: Apr. 12, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/790710/fbs_machinery_investment_29mar19.pdf

[102] Nimblefins, ‘Average Cost of an Electric Car UK 2022’. Accessed: Jul. 07, 2022. [Online]. Available: https://www.nimblefins.co.uk/average-cost-electric-car-uk

[103] Y. Ai *et al.*, 'Quantifying Air Pollutant Emission from Agricultural Machinery Using Surveys—A Case Study in Anhui, China', *Atmosphere*, vol. 12, no. 4, p. 440, Mar. 2021, doi: 10.3390/atmos12040440.

[104] F. Un-Noor *et al.*, 'Off-Road Construction and Agricultural Equipment Electrification: Review, Challenges, and Opportunities', *Vehicles*, vol. 4, no. 3, pp. 780–807, Aug. 2022, doi: 10.3390/vehicles4030044.

[105] Driver and Vehicle Licensing Agency, 'Driving licence categories', GOV.UK. Accessed: Jul. 18, 2022. [Online]. Available: https://www.gov.uk/driving-licence-categories

[106] Driver and Vehicle Licensing Agency, 'Agricultural vehicle licences, tax information and fuel', GOV.UK. Accessed: Apr. 12, 2022. [Online]. Available: https://www.gov.uk/guidance/agricultural-vehicle-licences-and-fuel

[107] Department for Environment, Food & Rural Affairs, 'Non-road mobile machinery and red diesel', GOV.UK. Accessed: Oct. 08, 2022. [Online]. Available: https://consult.defra.gov.uk/airquality/non-road-mobile-machinery-and-red-diesel/supporting_documents/reddieselnrmmcallforevidence.pdf

[108] HM Revenue & Customs, 'Non-agricultural use of red diesel for non-road mobile machinery', HM Revenue and Customs, London, Research 534, Feb. 2019. Accessed: May 09, 2022. [Online]. Available: https://www.gov.uk/government/publications/non-agricultural-use-of-red-diesel-for-non-road-mobile-machinery

[109] J. McGinlay, 'Non-Road Mobile Machinery Usage, Life and Correction Factors', Netcen, Didcot, Research AEAT/ENV/R/1895, Nov. 2004. Accessed: May 09, 2022. [Online]. Available: https://uk-air.defra.gov.uk/library/reports?report_id=304

[110] M. P. Aragonès, I. Vafiadis, and D. D. Lorenzo, 'All that the NRMM regulation isn't and what it could be'. Bellona Europa, Jul. 06, 2020. Accessed: Apr. 15, 2022. [Online]. Available: https://bellona.org/publication/position-paper-all-that-the-nrmm-regulation-isnt

[111] Department for Transport, 'Improving air quality: reducing emissions from machinery, government response'. Department for Transport, Mar. 20, 2018. Accessed: Apr. 15, 2022. [Online]. Available: https://www.gov.uk/government/consultations/improving-air-quality-reducing-emissions-from-machinery

[112] Department for Transport, Department for Environment, Food & Rural Affairs, and Department for Energy Security and Net Zero, 'Non-road mobile machinery: decarbonisation options - open call for evidence', GOV.UK. Accessed: Mar. 24, 2024. [Online]. Available: https://www.gov.uk/government/calls-for-evidence/non-road-mobile-machinery-decarbonisation-options

[113] HM Revenue & Customs, 'Reform of red diesel and other rebated fuels entitlement', GOV.UK. Accessed: Apr. 08, 2024. [Online]. Available: https://www.gov.uk/government/publications/reform-of-red-diesel-entitlements/reform-of-red-diesel-and-other-rebated-fuels-entitlement

[114] Department for Transport, 'Renewable fuel statistics: Notes and definitions', GOV.UK. Accessed: Apr. 15, 2022. [Online]. Available: https://www.gov.uk/government/publications/renewable-fuel-statistics-information/renewable-fuel-statistics-notes-and-definitions

[115] Greater London Authority, ‘Non-Road Mobile Machinery (NRMM)’, Mayor of London. Accessed: Apr. 08, 2022. [Online]. Available: https://www.london.gov.uk//what-we-do/environment/pollution-and-air-quality/nrmm

[116] Department for Energy Security and Net Zero, Department for Environment, Food & Rural Affairs, and Department for Transport, ‘Non-Road Mobile Machinery Decarbonisation Options: call for evidence’. Mar. 2024. [Online]. Available: https://assets.publishing.service.gov.uk/media/658454dd23b70a0013234dec/nrmm-decarbonisation-options-call-for-evidence.pdf

[117] C. D. Desouza, D. J. Marsh, S. D. Beevers, N. Molden, and D. C. Green, ‘A spatial and fleet disaggregated approach to calculating the NOX emissions inventory for non-road mobile machinery in London’, *Atmospheric Environ. X*, vol. 12, p. 100125, Dec. 2021, doi: 10.1016/j.aeaoa.2021.100125.

[118] B. Conlan, ‘Research to inform policy development to address emissions from Non-Road Mobile Machinery (NRMM) – UK’, Sep. 2020. [Online]. Available: https://fairmode.jrc.ec.europa.eu/document/fairmode/event/presentation/Oslo2020/20201002CT7_Conlan.pdf

[119] Ricardo Energy & Environment, ‘Research to inform policy development to address emissions from Non-Road Mobile Machinery (NRMM)’, Interim Report (Task 1) ED13076, Sep. 2020. [Online]. Available: https://www.whatdotheyknow.com/request/768655/response/1841673/attach/3/Annex%20C%20NRMM%20Interim%20Report%20Final%20Redacted.pdf?cookie_passthrough=1

[120] P. Lijewski and J. Merkisz, ‘Exhaust emissions from farm tractors operating in urban areas’, presented at the URBAN TRANSPORT 2013, Kos, Greece, May 2013, pp. 447–453. doi: 10.2495/UT130351.

[121] Department for Transport and Driver and Vehicle Licensing Agency, ‘Statutory Off Road Notification vehicles (SORN) - VEH0121’, GOV.UK. Accessed: May 10, 2022. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/all-vehicles-veh01

[122] Department for Transport, ‘Greenhouse gas emissions from transport by local authority’. Accessed: Apr. 08, 2024. [Online]. Available: https://maps.dft.gov.uk/ghg-emissions-by-local-authority/index.html

[123] UK Civil Aviation Authority, ‘Supplemental type certificates - List of UK Supplemental Type Certificates’. [Online]. Available: https://www.caa.co.uk/Commercial-industry/Aircraft/Airworthiness/Type-certificate-and-type-approval-data-sheets/Part-21/Supplemental-Type-Certificates/

[124] Y. Y. Lai *et al.*, ‘Analysing the opportunities and challenges for mitigating the climate impact of aviation: A narrative review’, *Renew. Sustain. Energy Rev.*, vol. 156, p. 111972, Mar. 2022, doi: 10.1016/j.rser.2021.111972.

[125] N. Gray, S. McDonagh, R. O’Shea, B. Smyth, and J. D. Murphy, ‘Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors’, *Adv. Appl. Energy*, vol. 1, p. 100008, Feb. 2021, doi: 10.1016/j.adapen.2021.100008.

[126] M. Mandorino, P. D. Vecchia, F. Nicolosi, and G. Cerino, ‘Regional jet retrofitting through multidisciplinary aircraft design’, *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1226, no. 1, p. 012047, Feb. 2022, doi: 10.1088/1757-899X/1226/1/012047.

[127] Airbus, ‘Airbus performs first five-bladed H145 retrofit of DRF Luftrettung helicopter’, Airbus. Accessed: Apr. 06, 2022. [Online]. Available: https://www.airbus.com/en/newsroom/press-releases/2021-05-airbus-performs-first-five-bladed-h145-retrofit-of-drf-luftrettung

[128] Cruise118, ‘What happens during a dry dock?’ Accessed: Jun. 08, 2022. [Online]. Available: https://www.cruise118.com/advice/what-happens-during-dry-dock/

[129] Splash, ‘A midlife crisis? Ships above 15 years may miss the cut for ballast water system installation’, Splash247. Accessed: Jun. 08, 2022. [Online]. Available: https://splash247.com/a-midlife-crisis-ships-above-15-years-may-miss-the-cut-for-ballast-water-system-installation/

[130] S. Bourboulis, R. Krantz, and L. Mouftier, ‘Alternative fuels: Retrofitting ship engines’, Global Maritime Forum. Accessed: Jun. 08, 2022. [Online]. Available: https://www.globalmaritimeforum.org/news/alternative-fuels-retrofitting-ship-engines

[131] K. Q. Bui, L. P. Perera, and J. Emblemsvåg, ‘Development of a Life-cycle Cost Framework for Retrofitting Marine Engines towards Emission Reduction in Shipping’, *IFAC-Pap.*, vol. 54, no. 16, pp. 181–187, Jan. 2021, doi: 10.1016/j.ifacol.2021.10.091.

[132] H. Schwartz, M. Gustafsson, and J. Spohr, ‘Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably?’, *J. Clean. Prod.*, vol. 254, p. 120069, May 2020, doi: 10.1016/j.jclepro.2020.120069.

[133] J. Yu, S. Voß, and G. Tang, ‘Strategy development for retrofitting ships for implementing shore side electricity’, *Transp. Res. Part Transp. Environ.*, vol. 74, pp. 201–213, Sep. 2019, doi: 10.1016/j.trd.2019.08.004.

[134] ShipFC Project, ‘ShipFC’, ShipFC. Accessed: Apr. 04, 2022. [Online]. Available: https://shipfc.eu

[135] Tersus DEF, ‘Selective Catalytic Reduction | How it works’, Tersus Diesel Exhaust Fluid. Accessed: Mar. 18, 2022. [Online]. Available: https://www.tersusdef.com/about/how-selective-catalytic-reduction-scr-works/

[136] DNV, ‘Challenging road ahead for retrofitting to dual-fuel engines’, dnv.com. Accessed: Apr. 01, 2022. [Online]. Available: https://www.dnv.com/expert-story/maritime-impact/challenging-road-ahead-for-retrofitting-to-dual-fuel-engine.html

[137] A. S. Santos, L. Gilio, V. Halmenschlager, T. B. Diniz, and A. N. Almeida, ‘Flexible-fuel automobiles and CO2 emissions in Brazil: Parametric and semiparametric analysis using panel data’, *Habitat Int.*, vol. 71, pp. 147–155, Jan. 2018, doi: 10.1016/j.habitatint.2017.11.014.

[138] M. A. Seitz, ‘A critical assessment of motives for product recovery: the case of engine remanufacturing’, *J. Clean. Prod.*, vol. 15, no. 11–12, pp. 1147–1157, Jan. 2007, doi: 10.1016/j.jclepro.2006.05.029.

[139] M. A. Seitz and P. E. Wells, ‘Challenging the implementation of corporate sustainability: The case of automotive engine remanufacturing’, *Bus. Process Manag. J.*, vol. 12, no. 6, pp. 822–836, Nov. 2006, doi: 10.1108/14637150610710954.

[140] Essential Fleet Operator, ‘Hydrogen fuel cell conversion from Caigan Vehicle Technologies’. Accessed: Dec. 05, 2022. [Online]. Available:

https://myessentialfleet.co.uk/hydrogen-fuel-cell-conversion-from-caigan-vehicle-technologies/

[141] ULEMCo Limited, ‘ULEMCo Completes First Hydrogen / HVO Dual-Fuel Conversion’, Hydrogen Solutions for Transport | ULEMCo Ltd. Accessed: Dec. 05, 2022. [Online]. Available: https://ulemco.com/ulemco-completes-first-hydrogen-hvo-dual-fuel-conversion/

[142] S. Ramachandran and U. Stimming, ‘Well to wheel analysis of low carbon alternatives for road traffic’, *Energy Environ. Sci.*, vol. 8, no. 11, pp. 3313–3324, Oct. 2015, doi: 10.1039/C5EE01512J.

[143] A. Reddaway and D. Moyse, ‘Hydrogen: help or hype?’ Renew, Jun. 17, 2019. Accessed: Oct. 12, 2022. [Online]. Available: https://renew.org.au/research/hydrogen-help-or-hype/

[144] International Energy Agency, ‘Trends and developments in electric vehicle markets’. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets

[145] B. C. Keoun, ‘Designing an electric vehicle conversion’, in *Proceedings of Southcon ’95*, Mar. 1995, pp. 303–308. doi: 10.1109/SOUTHC.1995.516121.

[146] M. Gordic, D. Stamenkovic, V. Popovic, M. Slavko, and M. Aleksandar, ‘Electric vehicle conversion: optimisation of parameters in the design process’, *Teh. Vjesn. - Tech. Gaz.*, vol. 24, no. 4, Aug. 2017, doi: 10.17559/TV-20160613131757.

[147] National Aeronautics and Space Administration, ‘State-of-the-art-assessment of electric and hybrid vehicles’, Technical Report NASA TM-73756, Sep. 1977. [Online]. Available: https://ntrs.nasa.gov/api/citations/19780011045/downloads/19780011045.pdf#page=254

[148] D. Sherman, ‘Athols’s Answer to the Energy Crisis’, *Car and Driver*, pp. 72–75, Oct. 1973.

[149] Shandoka Electric Motorcycles, ‘Shandoka Electric Motorcycles’, shandokacycles.com. [Online]. Available: https://shandokacycles.com/

[150] GCK Mobility, ‘GCK Mobility Truck Retrofit’. Accessed: Oct. 12, 2023. [Online]. Available: https://www.gck-mobility.com/en/applications/heavy-goods-vehicles/

[151] D. Pedrosa, V. Monteiro, H. Goncalves, J. S. Martins, and J. L. Afonso, ‘A Case Study on the Conversion of an Internal Combustion Engine Vehicle into an Electric Vehicle’, in *2014 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Oct. 2014, pp. 1–5. doi: 10.1109/VPPC.2014.7006994.

[152] S. Kaleg, A. Hapid, and M. R. Kurnia, ‘Electric Vehicle Conversion Based on Distance, Speed and Cost Requirements’, *Energy Procedia*, vol. 68, pp. 446–454, Apr. 2015, doi: 10.1016/j.egypro.2015.03.276.

[153] F. Hoeft, ‘Internal combustion engine to electric vehicle retrofitting: Potential customer’s needs, public perception and business model implications’, *Transp. Res. Interdiscip. Perspect.*, vol. 9, p. 100330, Mar. 2021, doi: 10.1016/j.trip.2021.100330.

[154] D. M. Kuchta, ‘Best EV Conversion Companies of 2023’, Treehugger. Accessed: Oct. 12, 2023. [Online]. Available: https://www.treehugger.com/electric-vehicle-ev-conversion-companies-85249

[155] Driver and Vehicle Licensing Agency, ‘Vehicle registration’, GOV.UK. Accessed: Oct. 08, 2022. [Online]. Available: https://www.gov.uk/vehicle-registration/radically-altered-vehicles

[156] HM Revenue & Customs, ‘Introduction of Vehicle Excise Duty for zero emission cars, vans and motorcycles from 2025’. [Online]. Available: https://www.gov.uk/government/publications/introduction-of-vehicle-excise-duty-for-zero-emission-cars-vans-and-motorcycles-from-2025/introduction-of-vehicle-excise-duty-for-zero-emission-cars-vans-and-motorcycles-from-2025

[157] Flash Drive Motors, ‘Flash Drive Motors - EVolve Your Ride’, flashdrivemotors.com. Accessed: Jun. 13, 2022. [Online]. Available: https://flashdrivemotors.com/

[158] Zero Labs, ‘Zero Labs Automotive’, Zero Labs Automotive - Premium Classic Electric Vehicles. Accessed: Jun. 13, 2022. [Online]. Available: https://www.zerolabs.com

[159] Zelectric, ‘Zelectric Motors’. Accessed: Jun. 13, 2022. [Online]. Available: https://www.zelectricmotors.com/

[160] Electric GT, ‘Electric GT - Electric Vehicle Systems and Components’. Accessed: Jun. 13, 2022. [Online]. Available: https://electricgt.com/

[161] EV West, ‘EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits’. Accessed: Jun. 13, 2022. [Online]. Available: https://www.evwest.com/catalog/index.php

[162] Electrogenic, ‘Electrogenic’, electrogenic.co.uk. Accessed: Jun. 13, 2022. [Online]. Available: https://www.electrogenic.co.uk/

[163] Lunaz, ‘Lunaz - UEV Upcycled Electric Vehicle’, Lunaz Tech. Accessed: Jun. 13, 2022. [Online]. Available: https://lunaz.tech/

[164] Lunaz, ‘Discovery - Lunaz Design - Classic Electric Cars’. Accessed: Jun. 08, 2022. [Online]. Available: https://lunaz.design/

[165] New Electric, ‘High Performance Electric Vehicle Drivetrains | New Electric | Amsterdam’, New Electric. Accessed: Jun. 13, 2022. [Online]. Available: https://www.newelectric.nl

[166] Everrati, ‘Everrati’. Accessed: Jun. 13, 2022. [Online]. Available: https://everrati.com/

[167] Zero EV, ‘Zero EV - Electric Vehicle Conversions’, Zero EV. Accessed: Jun. 13, 2022. [Online]. Available: https://zero-ev.co.uk/

[168] Electric Classic Cars, ‘Electric Classic Cars’. Accessed: Jun. 13, 2022. [Online]. Available: https://www.electricclassiccars.co.uk/

[169] EV Europe, ‘EV Europe’. Accessed: Jun. 13, 2022. [Online]. Available: https://eveurope.eu/en/

[170] Electron Garage, 'Electron Garage', Electric Vehicle Conversions | Electron Garage. Accessed: Jun. 13, 2022. [Online]. Available: https://www.electrongarage.co.uk/

[171] London Electric Cars, 'London Electric Cars'. Accessed: Jun. 13, 2022. [Online]. Available: https://www.londonelectriccars.com/

[172] NetGain, 'NetGain Motors'. Accessed: May 10, 2022. [Online]. Available: https://www.go-ev.com/

[173] Danfoss, 'Danfoss - Engineering Tomorrow'. Accessed: Jun. 13, 2022. [Online]. Available: https://www.danfoss.com/en/about-danfoss/our-businesses/power-solutions/danfoss-editron/

[174] S. Doll, 'GridTractor Archives', Electrek. Accessed: Jun. 13, 2022. [Online]. Available: https://electrek.co/guides/gridtractor/

[175] Renault Group, 'Re-Factory: The Flins Site Enters the Circle of the Circular Economy', renaultgroup.com. Accessed: Apr. 08, 2022. [Online]. Available: https://www.renaultgroup.com/en/news-on-air/news/re-factory-the-flins-site-enters-the-circle-of-the-circular-economy/

[176] Aston Martin Lagonda, 'Aston Martin Works create first reversible EV powertrain concept', media.astonmartin.com. Accessed: Apr. 08, 2022. [Online]. Available: https://media.astonmartin.com/aston-martin-works-create-first-reversible-ev-powertrain-conceptnbsp/

[177] Renault Group, 'Going from combustion to electric through retrofitting - Renault Group'. Accessed: Mar. 30, 2024. [Online]. Available: https://www.renaultgroup.com/en/news-on-air/news/retrofit-transform-a-combustion-motor-car-into-a-full-electric-car/

[178] C. Bjelkengren, 'The impact of mass decompounding on assessing the value of vehicle lightweighting', Masters Thesis, Massachusetts Institute of Technology, Massachusetts Institute of Technology, 2008. Accessed: Jun. 16, 2021. [Online]. Available: https://dspace.mit.edu/handle/1721.1/44384

[179] A. Sardar and S. Babu Muttana, 'EV Lightweighting: Impact of Mass Decompounding, Optimum Drivetrain Sizing', *Auto Tech Rev.*, vol. 2, no. 1, pp. 18–23, Jan. 2013, doi: 10.1365/s40112-013-0206-1.

[180] F. W. Geels, 'The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930)', *Technol. Anal. Strateg. Manag.*, vol. 17, no. 4, pp. 445–476, Dec. 2005, doi: 10.1080/09537320500357319.

[181] Directorate-General for Research and Innovation, 'Final report of the High-Level Panel of the European Decarbonisation Pathways Initiative.', European Commission, Nov. 2018. Accessed: Jun. 11, 2021. [Online]. Available: https://research-and-innovation.ec.europa.eu/document/download/a1032193-f110-4b58-a3ff-661e7388de4c_en

[182] Claire Haigh, 'Delivering Net Zero in a changing world'. Zemo Partnership, Feb. 01, 2024. [Online]. Available: https://www.zemo.org.uk/assets/reports/DELIVERING_NET_ZERO_REPORT_FEB2024_SINGLE_PAGES.pdf

[183] A. S. Penn *et al.*, 'Adopting a Whole Systems Approach to Transport Decarbonisation, Air Quality and Health: An Online Participatory Systems

Mapping Case Study in the UK', *Atmosphere*, vol. 13, no. 3, Art. no. 3, Mar. 2022, doi: 10.3390/atmos13030492.

[184] Infrastructure and Cities for Economic Development, 'A Whole System Approach in Energy'. Jul. 2019. Accessed: Feb. 16, 2022. [Online]. Available: http://icedfacility.org/a-whole-system-approach-in-energy/

[185] UK Research and Innovation, 'A whole systems approach to decarbonisation'. Accessed: Oct. 14, 2023. [Online]. Available: https://www.ukri.org/blog/a-whole-systems-approach-to-decarbonisation/

[186] Prime Minister's Council for Science and Technology, 'A Systems Approach to Delivering Net Zero: Recommendations from the Prime Minister's Council for Science and Technology'. Jan. 30, 2020. Accessed: Oct. 14, 2023. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910446/cst-net-zero-report-30-january-2020.pdf

[187] H. Baumann, F. Boons, and A. Bragd, 'Mapping the green product development field: engineering, policy and business perspectives', *J. Clean. Prod.*, vol. 10, no. 5, pp. 409–425, Oct. 2002, doi: 10.1016/S0959-6526(02)00015-X.

[188] G. Ropohl and Society for Philosophy and Technology, 'Philosophy of Socio-Technical Systems', *Soc. Philos. Technol. Q. Electron. J.*, vol. 4, no. 3, pp. 186–194, 1999, doi: 10.5840/techne19994311.

[189] P. Stansinoupolos, M. H. Smith, K. Hargroves, and C. Desha, *Whole System Design: an Integrated Approach to Sustainable Engineering*, 1st ed. Routledge, 2008. Accessed: Oct. 10, 2023. [Online]. Available: https://www.routledge.com/Whole-System-Design-An-Integrated-Approach-to-Sustainable-Engineering/Stansinoupolos-Smith-Hargroves-Desha/p/book/9781844076437

[190] F. Charnley, M. Lemon, and S. Evans, 'Exploring the process of whole system design', *Des. Stud.*, vol. 32, no. 2, pp. 156–179, Mar. 2011, doi: 10.1016/j.destud.2010.08.002.

[191] E. L. Trist and K. W. Bamforth, 'Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System', *Hum. Relat.*, vol. 4, no. 1, pp. 3–38, Feb. 1951, doi: 10.1177/001872675100400101.

[192] R. Cooper and M. Foster, 'Sociotechnical systems', *Am. Psychol.*, vol. 26, no. 5, pp. 467–474, 1971, doi: 10.1037/h0031539.

[193] W. Pasmore, C. Francis, J. Haldeman, and A. Shani, 'Sociotechnical Systems: A North American Reflection on Empirical Studies of the Seventies', *Hum. Relat.*, vol. 35, no. 12, pp. 1179–1204, Dec. 1982, doi: 10.1177/001872678203501207.

[194] R. Abbas and K. Michael, *Socio-Technical Theory: A review*. 2023. Accessed: Mar. 23, 2024. [Online]. Available: https://open.ncl.ac.uk/theories/9/socio-technical-theory/

[195] F. W. Geels, Ed., *Automobility in transition? a socio-technical analysis of sustainable transport*, 1st ed. in Routledge studies in sustainability transitions, no. 2. New York: Routledge, 2012. Accessed: Feb. 10, 2022. [Online]. Available: https://www.routledge.com/Automobility-in-Transition-A-Socio-Technical-

Analysis-of-Sustainable-Transport/Geels-Kemp-Dudley-Lyons/p/book/9780415885058

[196] M. Niblett and K. Beuret, ‘Why Travel? Understanding our Need to Move and How it Shapes our Lives’, Bristol University Press. Accessed: Feb. 16, 2022. [Online]. Available: https://bristoluniversitypress.co.uk/why-travel

[197] J. Allen, J. C. Muñoz, and J. de D. Ortúzar, ‘Understanding public transport satisfaction: Using Maslow’s hierarchy of (transit) needs’, *Transp. Policy*, vol. 81, pp. 75–94, Sep. 2019, doi: 10.1016/j.tranpol.2019.06.005.

[198] T. Jackson, ‘Motivating Sustainable Consumption: A Review of Evidence on Consumer Behaviour and Behavioural Change’, University of Surrey, Surrey, Jan. 2005. Accessed: Feb. 18, 2022. [Online]. Available: https://timjackson.org.uk/wp-content/uploads/2018/04/Jackson.-2005.-Motivating-Sustainable-Consumption.pdf

[199] F. W. Geels, ‘A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies’, *J. Transp. Geogr.*, vol. 24, pp. 471–482, Sep. 2012, doi: 10.1016/j.jtrangeo.2012.01.021.

[200] M. J. Figueroa and O. Lah, ‘What do we know about the role the human dimension plays in shaping a sustainable low-carbon transport transition?’, in *Energy and Behaviour*, Elsevier, 2020, pp. 177–208. doi: 10.1016/B978-0-12-818567-4.00008-9.

[201] Department for Transport and Britainthinks, ‘Decarbonising transport: deliberative research’, Government, Dec. 2020. Accessed: Dec. 16, 2021. [Online]. Available: https://www.gov.uk/government/publications/decarbonising-transport-deliberative-research

[202] M. Puhe and J. Schippl, ‘User Perceptions and Attitudes on Sustainable Urban Transport among Young Adults: Findings from Copenhagen, Budapest and Karlsruhe’, *J Env. Policy Plann*, vol. 16, no. 3, pp. 337–357, Jul. 2014.

[203] F. W. Geels, ‘Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study’, *Res. Policy*, vol. 31, no. 8–9, pp. 1257–1274, Dec. 2002, doi: 10.1016/S0048-7333(02)00062-8.

[204] F. G. N. Li and N. Strachan, ‘Modelling energy transitions for climate targets under landscape and actor inertia’, *Environ. Innov. Soc. Transit.*, vol. 24, pp. 106–129, Sep. 2017, doi: 10.1016/j.eist.2016.08.002.

[205] S. Steinhilber, P. Wells, and S. Thankappan, ‘Socio-technical inertia: Understanding the barriers to electric vehicles’, *Energy Policy*, vol. 60, pp. 531–539, Sep. 2013, doi: 10.1016/j.enpol.2013.04.076.

[206] T. Steward, ‘A Brief Introduction to the Multi-Level Perspective (MLP)’, Nov. 2012. Accessed: Feb. 16, 2022. [Online]. Available: https://projects.exeter.ac.uk/igov/presentation-a-brief-introduction-to-the-multi-level-perspective-mlp/

[207] F. W. Geels and J. Schot, ‘Typology of sociotechnical transition pathways’, *Res. Policy*, vol. 36, no. 3, pp. 399–417, Apr. 2007, doi: 10.1016/j.respol.2007.01.003.

[208] M. Prantner, ‘Driving forces and barriers of electricity production from solid biomass in Hungary : an empirical example for a multi-level constellation analysis’, in *Proceedings of the 3rd International Conference on Sustainability*

*Transitions, August 29th-31st 2012, Lyngby, Denmark ; Track E*, Lyngby: Technical Univ. of Denmark, 2012, pp. 308–335.

[209] X. Wu, S. Zhao, Y. Shen, H. Madani, and Y. Chen, ‘A Combined Multi-Level Perspective and Agent-Based Modeling in Low-Carbon Transition Analysis’, *Energies*, vol. 13, no. 19, p. 5050, Sep. 2020, doi: 10.3390/en13195050.

[210] D. Guzzo, D. C. A. Pigosso, N. Videira, and J. Mascarenhas, ‘A system dynamics-based framework for examining Circular Economy transitions’, *J. Clean. Prod.*, vol. 333, p. 129933, Jan. 2022, doi: 10.1016/j.jclepro.2021.129933.

[211] A. McMeekin, F. W. Geels, and M. Hodson, ‘Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016)’, *Res. Policy*, vol. 48, no. 5, pp. 1216–1231, Jun. 2019, doi: 10.1016/j.respol.2018.12.007.

[212] L. Shiu and C. Sin, ‘Top-down, Middle-out, and Bottom-up Processes: A Cognitive Perspective of Teaching and Learning Economics’, *Int. Rev. Econ. Educ.*, vol. 5, no. 1, pp. 60–72, 2006, doi: 10.1016/S1477-3880(15)30124-9.

[213] K. B. Janda and Y. Parag, ‘A middle-out approach for improving energy performance in buildings’, *Build. Res. Inf.*, vol. 41, no. 1, pp. 39–50, Feb. 2013, doi: 10.1080/09613218.2013.743396.

[214] P. A. Sabatier, ‘Top-Down and Bottom-Up Approaches to Implementation Research: a Critical Analysis and Suggested Synthesis’, *J. Public Policy*, vol. 6, no. 1, pp. 21–48, Jan. 1986, doi: 10.1017/S0143814X00003846.

[215] E. Nisbet and R. Weiss, ‘Top-Down Versus Bottom-Up’, *Science*, vol. 328, no. 5983, pp. 1241–1243, Jun. 2010, doi: 10.1126/science.1189936.

[216] P. H. Lindsay and D. A. Norman, *Human Information Processing - An Introduction to Psychology*, 2nd ed. Elsevier Science, 2013. Accessed: Mar. 17, 2022. [Online]. Available: https://www.elsevier.com/books/human-information-processing/lindsay/978-0-12-450960-3

[217] B. Stich, J. H. Holland, R. A. A. Nobrega, and C. G. O’Hara, ‘Using multi-criteria decision making to highlight stakeholders’ values in the corridor planning process’, *J. Transp. Land Use*, vol. 4, no. 3, pp. 105–118, Dec. 2011, doi: 10.5198/jtlu.v4i3.171.

[218] National Renewable Energy Laboratory, ‘FASTSim: Future Automotive Systems Technology Simulator’, NREL. Accessed: Jul. 08, 2022. [Online]. Available: https://www.nrel.gov/transportation/fastsim.html

[219] C. Baker, M. Moniot, A. Brooker, L. Wang, E. Wood, and J. Gonder, ‘Future Automotive Systems Technology Simulator (FASTSim) Validation Report - 2021’, National Renewable Energy Lab. (NREL), Golden, CO (United States), NREL/TP-5400-81097, Oct. 2021. doi: 10.2172/1828851.

[220] R. A. Kinchla and J. M. Wolfe, ‘The order of visual processing: “Top-down,” “bottom-up,” or “middle-out”’, *Percept. Psychophys.*, vol. 25, no. 3, pp. 225–231, May 1979, doi: 10.3758/BF03202991.

[221] T. Zohar, Y. Parag, and O. Ayalon, ‘Of agency, action, and influence: The middle-out mechanism for promoting a low-carbon energy transition’, *Energy Res. Soc. Sci.*, vol. 72, p. 101900, Feb. 2021, doi: 10.1016/j.erss.2020.101900.

[222] T. Zohar, Y. Parag, and O. Ayalon, ‘Strategizing demand management from the middle out: Harnessing middle actors to reduce peak electricity consumption’, *Energy Res. Soc. Sci.*, vol. 61, p. 101360, Mar. 2020, doi: 10.1016/j.erss.2019.101360.

[223] J. Hamilton, R. Mayne, Y. Parag, and N. Bergman, ‘Scaling up local carbon action: the role of partnerships, networks and policy’, *Carbon Manag.*, vol. 5, no. 4, pp. 463–476, Jul. 2014, doi: 10.1080/17583004.2015.1035515.

[224] E. Bonabeau, ‘Agent-based modeling: Methods and techniques for simulating human systems’, *Proc. Natl. Acad. Sci.*, vol. 99, no. suppl_3, pp. 7280–7287, May 2002, doi: 10.1073/pnas.082080899.

[225] S. Abar, G. K. Theodoropoulos, P. Lemarinier, and G. M. P. O’Hare, ‘Agent Based Modelling and Simulation tools: A review of the state-of-art software’, *Comput. Sci. Rev.*, vol. 24, pp. 13–33, May 2017, doi: 10.1016/j.cosrev.2017.03.001.

[226] L. Tesfatsion and K. L. Judd, *Handbook of Computational Economics: Agent-Based Computational Economics*. Elsevier, 2006. [Online]. Available: https://philarchive.org/rec/TESHOC

[227] J. D. Farmer and D. Foley, ‘The economy needs agent-based modelling’, *Nature*, vol. 460, no. 7256, pp. 685–686, Aug. 2009, doi: 10.1038/460685a.

[228] J. Holmgren, P. Davidsson, J. A. Persson, and L. Ramstedt, ‘TAPAS: A multi-agent-based model for simulation of transport chains’, *Simul. Model. Pract. Theory*, vol. 23, pp. 1–18, Apr. 2012, doi: 10.1016/j.simpat.2011.12.011.

[229] S. Torres, O. Barambones, J. M. Gonzalez de Durana, F. Marzabal, E. Kremers, and J. Wirges, ‘Agent-based modelling of electric vehicle driving and charging behavior’, in *2015 23rd Mediterranean Conference on Control and Automation (MED)*, Torremolinos: IEEE, Jun. 2015, pp. 459–464. doi: 10.1109/MED.2015.7158791.

[230] R. Yao and D. Y. Hu, ‘Agent-based energy flow simulation of integrated energy systems’, 2021. Accessed: Oct. 13, 2022. [Online]. Available: https://www.anylogic.com/upload/pdf/alc-2021/ucl-Agent-based-energy-flow-simulation-of-integrated-energy-systems.pdf

[231] Y. Li, ‘Agent-Based Modeling of Chronic Diseases: A Narrative Review and Future Research Directions’, *Prev. Chronic. Dis.*, vol. 13, 2016, doi: 10.5888/pcd13.150561.

[232] G. Casey, F. Shone, F. Karim-Khaku, and C. Bruce, ‘An Agent Based Model for London: Exploratory Case Study’, presented at the European Transport Conference 2019Association for European Transport (AET), 2019. Accessed: Apr. 28, 2024. [Online]. Available: https://trid.trb.org/View/1728830

[233] J. D. Sterman, ‘All models are wrong: reflections on becoming a systems scientist’, *Syst. Dyn. Rev.*, vol. 18, no. 4, pp. 501–531, 2002, doi: 10.1002/sdr.261.

[234] B. Edmonds and L. ní Aodha, ‘Using Agent-Based Modelling to Inform Policy – What Could Possibly Go Wrong?’, in *Multi-Agent-Based Simulation XIX*, P. Davidsson and H. Verhagen, Eds., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 1–16. doi: 10.1007/978-3-030-22270-3_1.

[235] G. O. Kagho, M. Balac, and K. W. Axhausen, ‘Agent-Based Models in Transport Planning: Current State, Issues, and Expectations’, *Procedia Comput. Sci.*, vol. 170, pp. 726–732, 2020, doi: 10.1016/j.procs.2020.03.164.

[236] R. Evans, ‘Economic Models and Policy Advice: Theory Choice or Moral Choice?’, *Sci. Context*, vol. 12, no. 2, pp. 351–376, 1999, doi: 10.1017/s026988970000346x.

[237] D. Muravev, H. Hu, A. Rakhmangulov, and P. Mishkurov, ‘Multi-agent optimization of the intermodal terminal main parameters by using AnyLogic simulation platform: Case study on the Ningbo-Zhoushan Port’, *Int. J. Inf. Manag.*, vol. 57, p. 102133, Apr. 2021, doi: 10.1016/j.ijinfomgt.2020.102133.

[238] D. A. Robertson, ‘Agent-Based Modeling Toolkits NetLogo, RePast, and Swarm’, *Acad. Manag. Learn. Educ.*, vol. 4, no. 4, pp. 525–527, Dec. 2005.

[239] V. Mikhailov, N. Churkov, and A. Borshchev, ‘AnyLogic 8 new features. Python in AnyLogic (R&D)’, presented at the AnyLogic Conference 2021, 2021, p. 25. [Online]. Available: https://www.anylogic.com/upload/pdf/alc-2021/anylogic-8-new-features-python-in-anylogic-rnd.pdf

[240] C. Linton, S. Grant-Muller, and W. F. Gale, ‘Approaches and Techniques for Modelling CO2 Emissions from Road Transport’, *Transp. Rev.*, vol. 35, no. 4, pp. 533–553, Jul. 2015, doi: 10.1080/01441647.2015.1030004.

[241] A. Borshchev, *The Big Book of Simulation Modeling: Multimethod Modeling with Anylogic 6*. S.l.: Anylogic North America, 2014. [Online]. Available: https://www.anylogic.com/resources/books/big-book-of-simulation-modeling/

[242] HM Treasury, *Green Book: Central Government Guidance on Appraisal and Evaluation*. 2020. Accessed: Feb. 17, 2022. [Online]. Available: https://www.webarchive.org.uk/access/resolve/20201125231833/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938046/The_Green_Book_2020.pdf

[243] Welsh Government, ‘Welsh transport appraisal guidance (WelTAG)’, GOV.WALES. Accessed: Feb. 16, 2022. [Online]. Available: https://gov.wales/welsh-transport-appraisal-guidance-weltag

[244] Department for Transport, ‘TAG overview’, GOV.UK. Accessed: Feb. 16, 2022. [Online]. Available: https://www.gov.uk/government/publications/webtag-tag-overview

[245] Land Rover, ‘Defender Technical Detail’, Auto Catalog Archive. [Online]. Available: https://autocatalogarchive.com/wp-content/uploads/2017/05/Land-Rover-Defender-2003-INT.pdf

[246] Automobile Catalog, ‘Detailed specs review of 1995 Land-Rover Defender 110 County 300tdi model for Europe’, www.automobile-catalog.com. Accessed: Apr. 21, 2022. [Online]. Available: https://www.automobile-catalog.com/car/1995/1395815/land-rover_defender_110_county_300tdi.html

[247] Land Rover, ‘Land Rover Workshop Manuals > 300Tdi Defender > COOLING SYSTEM > ENGINE COOLING SYSTEM’. Accessed: Oct. 20, 2022. [Online]. Available: https://workshop-manuals.com/landrover/defender300tdi/cooling_system/engine_cooling_system/

[248] A. Brooker, J. Gonder, L. Wang, E. Wood, S. Lopp, and L. Ramroth, 'FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance', *SAE Tech. Pap.*, 2015, doi: 10.4271/2015-01-0973.

[249] National Renewable Energy Laboratory, 'FASTSim Overview Fact Sheet'. NREL, Apr. 2018. [Online]. Available: https://www.nrel.gov/docs/fy18osti/71126.pdf

[250] Land Rover, 'Land Rover Defender Catalog'. 1990. [Online]. Available: https://autocatalogarchive.com/wp-content/uploads/2017/05/Land-Rover-Defender-1990-UK.pdf

[251] Department for Energy Security and Net Zero, 'Digest of UK Energy Statistics (DUKES): calorific values and density of fuels', GOV.UK. Accessed: May 09, 2022. [Online]. Available: https://www.gov.uk/government/statistics/dukes-calorific-values

[252] Fuelly, '1995 Land Rover Defender 110 L/100km - Actual L/100km from 16 1995 Land Rover Defender 110 owners'. Accessed: Apr. 14, 2024. [Online]. Available: https://www.fuelly.com/car/land_rover/defender_110/1995

[253] European Union, *Council Directive on the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles*. 1970. Accessed: Apr. 14, 2024. [Online]. Available: http://data.europa.eu/eli/dir/1970/220/oj/eng

[254] Jaguar Land Rover, 'Landrover Defender', landrover.co.uk. Accessed: Feb. 20, 2024. [Online]. Available: https://www.landrover.co.uk/defender/index.html

[255] EVSpecifications, '2022 Rivian R1T Explore - Specifications and price', evspecifications.com. Accessed: Apr. 26, 2022. [Online]. Available: https://www.evspecifications.com/en/model/58f1107

[256] Motor Matchup, '2022 Rivian R1T (Launch Edition (135 kWh)) Specs'. Accessed: May 10, 2022. [Online]. Available: https://www.motormatchup.com/catalog/Rivian/R1T/2022/Launch-Edition-(135-kWh)

[257] Stealth EV, 'Tesla 5.3 kWh Module (85 kWh Pack) | Batteries', stealthev.com. Accessed: May 10, 2022. [Online]. Available: https://stealthev.com/product/tesla-module/

[258] S. Corrigan, 'Introduction to the Controller Area Network (CAN)', Texas Instruments, Application Report SLOA101B, Aug. 2002. Accessed: May 09, 2022. [Online]. Available: https://www.ti.com/lit/pdf/sloa101

[259] AHK Group, 'Calorific Value, what's the difference between Gross and Net CV?', What is Calorific Value? Accessed: Apr. 25, 2022. [Online]. Available: https://www.ahkgroup.com/difference-between-gross-calorific-value-and-net-calorific-value/

[260] IEA, 'Comparative life-cycle greenhouse gas emissions of a mid-size BEV and ICE vehicle – Charts – Data & Statistics', IEA. Accessed: Mar. 31, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/charts/comparative-life-cycle-greenhouse-gas-emissions-of-a-mid-size-bev-and-ice-vehicle

[261] Green NCAP, 'European Life Cycle Assessment Results & Fact Sheets', greenncap.com. Accessed: Mar. 31, 2024. [Online]. Available: https://www.greenncap.com/european-lca-results/

[262] Transport & Environment, ‘How much CO2 can electric cars really save?’, transportenvironment.org. Accessed: Mar. 31, 2024. [Online]. Available: https://www.transportenvironment.org/discover/how-clean-are-electric-cars/

[263] Second Life EV Batteries Ltd, ‘Tesla 5.3 kWh Modules | 22.8V | 232Ah - Tested Used EV Modules’, Second Life EV Batteries Ltd. Accessed: Jun. 13, 2022. [Online]. Available: https://www.secondlife-evbatteries.com/products/tesla-5-3-kwh-22-8v-232ah-3

[264] ampREVOLT, ‘Modular Battery Box for Tesla Battery Modules [pat. pending]’, amprevolt.com. Accessed: Jun. 13, 2022. [Online]. Available: https://amprevolt.com/products/battery-boxes-2-pack-for-tesla-model-s-battery-modules

[265] EV Components, ‘Elcon TC HK-J 6600W Charger’. Accessed: Jul. 10, 2022. [Online]. Available: https://www.evcomponents.com/customized-chargers/elcon-tc-hk-j-6600w-charger.html

[266] Evolve Electrics, ‘Evolve Electrics’, evolveelectrics.com. Accessed: Jun. 13, 2022. [Online]. Available: https://evolveelectrics.com/products/andromeda-display

[267] Checkatrade, ‘Average Mechanic Hourly Rate In The UK In 2022’, checkatrade.com. Accessed: Jun. 13, 2022. [Online]. Available: https://www.checkatrade.com/blog/cost-guides/mechanic-hourly-rate-uk/

[268] Falcon Electric, ‘Electric Vehicle (EV) Conversions’, falconelectric.co.uk. Accessed: Aug. 24, 2022. [Online]. Available: https://falconelectric.co.uk/ev-conversions/

[269] Hagerty, ‘1990 Land Rover Defender 110 Base | Hagerty Valuation Tools’. Accessed: Jun. 13, 2022. [Online]. Available: https://www.hagerty.com/valuation-tools/land_rover/defender_110/1990/1990-land_rover-defender_110

[270] Bank of England, ‘Inflation calculator 1949-2021’. Accessed: May 10, 2022. [Online]. Available: https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

[271] H. Whately, ‘Electric Vehicles: Excise Duties’, TheyWorkForYou. Accessed: Aug. 24, 2022. [Online]. Available: https://www.theyworkforyou.com/wrans/?id=2022-06-27.25907.h

[272] AnyLogic, ‘Probability distributions | anyLogistix Help’. Accessed: Sep. 13, 2022. [Online]. Available: https://anylogistix.help/ui/probability-distributions.html

[273] AnyLogic, ‘uniform_discr | AnyLogic Help’. Accessed: Sep. 13, 2022. [Online]. Available: https://anylogic.help/advanced/functions/uniform-discr.html

[274] Triodos, ‘Glastonbury Festival’s Worthy Farm | Triodos Bank’. Accessed: Jun. 09, 2022. [Online]. Available: https://www.triodos.co.uk/projects/glastonbury-festivals-worthy-farm

[275] Met Office, ‘MIDAS Open: UK hourly solar radiation data, v202107’. NERC EDS Centre for Environmental Data Analysis, 2021. doi: 10.5285/625F5EA4DDAC4578A2AACF47BCF39657.

[276] S. I. Staff, ‘Watts Matter: Maintaining The Performance Ratio of PV Systems’, Solar Industry. Accessed: Jun. 10, 2022. [Online]. Available: https://solarindustrymag.com/watts-matter-maintaining-the-performance-ratio-of-pv-systems

[277] National Grid ESO, 'ESO Data Portal: Historic Generation Mix & Carbon Intensity - Dataset| National Grid Electricity System Operator'. Accessed: Jun. 13, 2022. [Online]. Available: https://data.nationalgrideso.com/carbon-intensity1/historic-generation-mix

[278] S. Byrom, 'Compare Gas & Electricity Prices per kWh Across the UK | The Energy Shop', TheEnergyShop.com. Accessed: Jun. 14, 2022. [Online]. Available: https://www.theenergyshop.com/guides/compare-gas-electricity-prices-per-kwh

[279] Y. Al-Wreikat, C. Serrano, and J. R. Sodré, 'Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle', *Energy*, vol. 238, p. 122028, Jan. 2022, doi: 10.1016/j.energy.2021.122028.

[280] J. Y. Wong, *Terramechanics and Off-Road Vehicle Engineering: Terrain Behaviour, Off-Road Vehicle Performance and Design*. Butterworth-Heinemann, 2009. [Online]. Available: https://www.sciencedirect.com/book/9780750685610/terramechanics-and-off-road-vehicle-engineering

[281] T. R. Hawkins, B. Singh, G. Majeau-Bettez, and A. H. Strømman, 'Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles', *J. Ind. Ecol.*, vol. 17, no. 1, pp. 53–64, 2013, doi: 10.1111/j.1530-9290.2012.00532.x.

[282] S. McAvoy, T. Grant, C. Smith, and P. Bontinck, 'Combining Life Cycle Assessment and System Dynamics to improve impact assessment: A systematic review', *J. Clean. Prod.*, vol. 315, p. 128060, Sep. 2021, doi: 10.1016/j.jclepro.2021.128060.

[283] Urban Transport Group, 'UK Transport Governance - an introduction'. Aug. 07, 2022. [Online]. Available: https://www.urbantransportgroup.org/resources/types/briefings/uk-transport-governance-introduction

[284] Welsh Government, 'Llwybr Newydd – a new Wales transport strategy'. Welsh Government, Nov. 17, 2020. Accessed: Mar. 30, 2022. [Online]. Available: https://gov.wales/llwybr-newydd-wales-transport-strategy-2021

[285] S. P. Shepherd, 'A review of system dynamics models applied in transportation', *Transp. B Transp. Dyn.*, vol. 2, no. 2, pp. 83–105, May 2014, doi: 10.1080/21680566.2014.916236.

[286] P. Pfaffenbichler, G. Emberger, and S. Shepherd, 'A system dynamics approach to land use transport interaction modelling: the strategic model MARS and its application', *Syst. Dyn. Rev.*, vol. 26, no. 3, pp. 262–282, Jul. 2010, doi: 10.1002/sdr.451.

[287] X. Liu, S. Ma, J. Tian, N. Jia, and G. Li, 'A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO 2 emissions: A case study of Beijing', *Energy Policy*, vol. 85, pp. 253–270, Oct. 2015, doi: 10.1016/j.enpol.2015.06.007.

[288] S. Armenia, F. Baldoni, D. Falsini, and E. Taibi, 'A System Dynamics Energy Model for a Sustainable Transportation System', in *ISDC 2010*, Seoul South Korea, Jul. 2010, p. 26.

[289] J. Struben and J. D. Sterman, ‘Transition Challenges for Alternative Fuel Vehicle and Transportation Systems’, *Environ. Plan. B Plan. Des.*, vol. 35, no. 6, pp. 1070–1097, Dec. 2008, doi: 10.1068/b33022t.

[290] Jay Wright Forrester, ‘Industrial Dynamics’, *Harv. Bus. Rev.*, vol. 36, no. 12, 1958, Accessed: Aug. 02, 2022. [Online]. Available: https://books.google.co.uk/books/about/Industrial_Dynamics_a_Major_Breakthrough.html?id=dcfzvgEACAAJ&redir_esc=y

[291] Jay Wright Forrester, *Industrial Dynamics*, 6th ed. M.I.T. Press, 1961. [Online]. Available: https://books.google.co.uk/books/about/Industrial_Dynamics.html?id=4CgzAAAAMAAJ&redir_esc=y

[292] J. Sterman, *Business dynamics: systems thinking and modeling for a complex world*. Boston: Irwin/McGraw-Hill, 2000. [Online]. Available: https://archive.org/details/businessdynamics0000ster

[293] J. Sterman, ‘In a Complex World’, 2002, Accessed: Aug. 04, 2022. [Online]. Available: https://www.semanticscholar.org/paper/In-a-Complex-World-Sterman/a338f39a1eadc5dcae99776af6e2f6f821387536

[294] J. Busch, J. K. Steinberger, D. A. Dawson, P. Purnell, and K. Roelich, ‘Managing Critical Materials with a Technology-Specific Stocks and Flows Model’, *Environ. Sci. Technol.*, vol. 48, no. 2, pp. 1298–1305, Jan. 2014, doi: 10.1021/es404877u.

[295] D. H. Meadows and Club of Rome, Eds., *The Limits to growth: a report for the Club of Rome’s project on the predicament of mankind*. New York: Universe Books, 1972.

[296] T. Rebs, M. Brandenburg, and S. Seuring, ‘System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach’, *J. Clean. Prod.*, vol. 208, pp. 1265–1280, Jan. 2019, doi: 10.1016/j.jclepro.2018.10.100.

[297] J. W. Forrester, ‘Information Sources for Modeling the National Economy’, *J. Am. Stat. Assoc.*, vol. 75, no. 371, pp. 555–566, Sep. 1980, doi: 10.1080/01621459.1980.10477508.

[298] J. M. Lyneis, ‘System dynamics for market forecasting and structural analysis’, *Syst. Dyn. Rev.*, vol. 16, no. 1, pp. 3–25, 2000, doi: 10.1002/(SICI)1099-1727(200021)16:1<3::AID-SDR183>3.0.CO;2-5.

[299] J. W. Forrester, ‘System dynamics, systems thinking, and soft OR’, *Syst. Dyn. Rev.*, vol. 10, no. 2–3, pp. 245–256, 1994, doi: 10.1002/sdr.4260100211.

[300] Centre for the Evaluation of Complexity Across the Nexus, ‘CECAN Webinar: Participatory Systems Mapping for Policy Evaluation’, CECAN. Accessed: Feb. 16, 2022. [Online]. Available: https://www.cecan.ac.uk/news/cecan-webinar-participatory-systems-mapping-for-policy-evaluation-2/

[301] P. Barbrook-Johnson and A. Penn, ‘Participatory systems mapping for complex energy policy evaluation’, *Evaluation*, vol. 27, no. 1, pp. 57–79, Jan. 2021, doi: 10.1177/1356389020976153.

[302] A. Jones *et al.*, ‘En-ROADS Guide Documentation’. Sep. 01, 2021. Accessed: Jan. 05, 2021. [Online]. Available: https://www.climateinteractive.org/en-roads/

[303] N. Papakatsikas, M. Eriksson, M. Berglund, C. Malmström, and K. Ounsi, ‘Supporting decision-makers with a web-based system dynamics tool’, presented at the 27th ITS World Congress, Hamburg, Oct. 2021. [Online]. Available: https://www.wsp.com/en-gb/insights/supporting-decision-makers-with-a-web-based-system-dynamics-tool

[304] E. Czaika, ‘Using System Dynamics Models to Make Better Decisions’, presented at the SDM Webinar, Feb. 13, 2018. [Online]. Available: https://sdm.mit.edu/using-systems-dynamics-models-to-make-better-decisions/

[305] Department of Energy and Climate Change (DECC), ‘DECC 2050 energy calculator’, Nesta. Accessed: Aug. 09, 2022. [Online]. Available: https://www.nesta.org.uk/feature/smarter-policy-through-simulation/decc-2050-energy-calculator/

[306] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, ‘Carbon calculator’, GOV.UK. Accessed: Aug. 09, 2022. [Online]. Available: https://www.gov.uk/guidance/carbon-calculator

[307] S. Agnew, C. Smith, and P. Dargusch, ‘Causal loop modelling of residential solar and battery adoption dynamics: A case study of Queensland, Australia’, *J. Clean. Prod.*, vol. 172, pp. 2363–2373, Jan. 2018, doi: 10.1016/j.jclepro.2017.11.174.

[308] Y. Mamatok, Y. Huang, C. Jin, and X. Cheng, ‘A System Dynamics Model for CO2 Mitigation Strategies at a Container Seaport’, *Sustainability*, vol. 11, no. 10, p. 2806, May 2019, doi: 10.3390/su11102806.

[309] N. Shamsapour, A. Hajinezhad, and Y. Noorollahi, ‘Developing a system dynamics approach for CNG vehicles for low-carbon urban transport: a case study’, *Int. J. Low-Carbon Technol.*, vol. 16, no. 2, pp. 577–591, May 2021, doi: 10.1093/ijlct/ctaa085.

[310] F. Boons, B. Doherty, J. Köhler, G. Papachristos, and P. Wells, ‘Disrupting transitions: Qualitatively modelling the impact of Covid-19 on UK food and mobility provision’, *Environ. Innov. Soc. Transit.*, vol. 40, pp. 1–19, Sep. 2021, doi: 10.1016/j.eist.2021.04.003.

[311] V. Ghisolfi, L. A. Tavasszy, G. H. de A. Correia, G. de L. D. Chaves, and G. M. Ribeiro, ‘Freight Transport Decarbonization: A Systematic Literature Review of System Dynamics Models’, *Sustainability*, vol. 14, no. 6, Art. no. 6, Jan. 2022, doi: 10.3390/su14063625.

[312] Y. A. Alamerew and D. Brissaud, ‘Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries’, *J. Clean. Prod.*, vol. 254, p. 120025, May 2020, doi: 10.1016/j.jclepro.2020.120025.

[313] World Economic Forum, ‘Towards the circular economy: Accelerating the scale-up across global supply chains’, Towards the circular economy. Accessed: Feb. 16, 2022. [Online]. Available: http://wef.ch/1rvDRDL

[314] B. P. Federation, ‘Life Cycle Analysis (LCA) - A Complete Guide to LCAs’, British Plastics Federation. Accessed: Sep. 21, 2022. [Online]. Available: https://www.bpf.co.uk/sustainable_manufacturing/life-cycle-analysis-lca.aspx

[315] Evolve Electrics, ‘Tesla Model S Lithium Ion Battery 18650 - 22.8 Volt, 5.3 kWh**’. Accessed: Sep. 21, 2022. [Online]. Available: https://evolveelectrics.com/products/tesla-model-s-lithium-ion-battery

[316] Voltaplex, ‘Panasonic B 18650 Battery, 3350mAh, 4.875A, 3.6V, Grade A Lithium-ion (NCR18650B)’, voltaplex.com. Accessed: Sep. 21, 2022. [Online]. Available: https://voltaplex.com/panasonic-b-18650-battery-ncr18650b

[317] ICAX Limited, ‘Grid Carbon Factors Decarbonising Heating and Cooling’, ICAX. Accessed: Sep. 15, 2022. [Online]. Available: https://icax.co.uk/Grid_Carbon_Factors.html

[318] ecoinvent, ‘ecoinvent version 2’, ecoinvent.org. Accessed: Jul. 20, 2022. [Online]. Available: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-version-2/

[319] M. Zolfagharian, B. Walrave, A. G. L. Romme, and R. Raven, ‘Toward the Dynamic Modeling of Transition Problems: The Case of Electric Mobility’, *Sustainability*, vol. 13, no. 1, p. 38, Dec. 2020, doi: 10.3390/su13010038.

[320] T. Kwon, ‘Strategic niche management of alternative fuel vehicles: A system dynamics model of the policy effect’, *Technol. Forecast. Soc. Change*, vol. 79, no. 9, pp. 1672–1680, Nov. 2012, doi: 10.1016/j.techfore.2012.05.015.

[321] B. Walrave and R. Raven, ‘Modelling the dynamics of technological innovation systems’, *Res. Policy*, vol. 45, no. 9, pp. 1833–1844, Nov. 2016, doi: 10.1016/j.respol.2016.05.011.

[322] J. Busch, D. Dawson, and K. Roelich, ‘Closing the low-carbon material loop using a dynamic whole system approach’, *J. Clean. Prod.*, vol. 149, pp. 751–761, Apr. 2017, doi: 10.1016/j.jclepro.2017.02.166.

[323] P. Rosa and S. Terzi, ‘Improving end of life vehicle’s management practices: An economic assessment through system dynamics’, *J. Clean. Prod.*, vol. 184, pp. 520–536, May 2018, doi: 10.1016/j.jclepro.2018.02.264.

[324] P. Zamudio-Ramírez, ‘Economics of automobile recycling’, Thesis, Massachusetts Institute of Technology, 1996. Accessed: Jul. 20, 2022. [Online]. Available: https://dspace.mit.edu/handle/1721.1/10976

[325] Department for Environment, Food & Rural Affairs and Department for Transport, ‘Air quality: clean air zone framework for England’, GOV.UK. Accessed: Feb. 16, 2022. [Online]. Available: https://www.gov.uk/government/publications/air-quality-clean-air-zone-framework-for-england

[326] C. Reiner, G. Beard, N. Kinnear, and T. Park, ‘Driving and accelerating the adoption of electric vehicles in the UK’, The Behavioural Insights Team and TRL, Jul. 2020. Accessed: Jun. 10, 2021. [Online]. Available: https://trl.co.uk/publications/driving-and-accelerating-the-adoption-of-electric-vehicles-in-the--uk

[327] D. Turner, ‘Independent review of road user charging in Wales’, Welsh Government, Nov. 2020. [Online]. Available: https://gov.wales/independent-review-road-user-charging-wales

[328] Y. A. Alamerew and D. Brissaud, ‘Circular economy assessment tool for end of life product recovery strategies’, *J. Remanufacturing*, vol. 9, no. 3, pp. 169–185, Oct. 2019, doi: 10.1007/s13243-018-0064-8.

[329] Climate Change Committee, ‘Policies for the Sixth Carbon Budget and Net Zero’, Climate Change Committee, 2020. [Online]. Available: https://www.theccc.org.uk/publication/sixth-carbon-budget/

[330] Department for Transport, ‘Green Paper on a New Road Vehicle CO2 Emissions Regulatory Framework for the United Kingdom’. UK Government, Jul. 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1007466/green-paper-on-a-new-road-vehicle-CO2-emissions-regulatory-framework-for-the-United-Kingdom-web-version.pdf

[331] House of Commons Transport Committee, ‘Road Pricing’, House of Commons, HC789, Feb. 2022. Accessed: Sep. 23, 2022. [Online]. Available: https://publications.parliament.uk/pa/cm5802/cmselect/cmtrans/789/report.html

[332] Y. Wang *et al.*, ‘Study on International Practices for Low Emission Zone and Congestion Charging’. World Resources Institute, Jan. 2017. Accessed: Oct. 10, 2022. [Online]. Available: https://www.wri.org/research/study-international-practices-low-emission-zone-and-congestion-charging

[333] G. Santos, ‘Urban Congestion Charging: A Comparison between London and Singapore’, *Transp. Rev.*, vol. 25, no. 5, pp. 511–534, Sep. 2005, doi: 10.1080/01441640500064439.

[334] HM Revenue & Customs, ‘Vehicle Excise Duty’, GOV.UK. Accessed: Sep. 23, 2022. [Online]. Available: https://www.gov.uk/government/publications/vehicle-excise-duty/vehicle-excise-duty

[335] HM Revenue & Customs, ‘Fuel Duty rates 2022-23’, GOV.UK. Accessed: Sep. 23, 2022. [Online]. Available: https://www.gov.uk/government/publications/changes-to-fuel-duty-rates/fuel-duty-rates-2022-23

[336] HM Revenue & Customs, ‘Carbon Emissions Tax’, GOV.UK. Accessed: Sep. 23, 2022. [Online]. Available: https://www.gov.uk/government/publications/carbon-emmisions-tax/carbon-emmisions-tax

[337] Department for Transport, ‘Low-emission vehicles eligible for a plug-in grant’, GOV.UK. Accessed: Sep. 23, 2022. [Online]. Available: https://www.gov.uk/plug-in-vehicle-grants

[338] Transport for London, ‘Scrappage schemes’, Transport for London. Accessed: Sep. 23, 2022. [Online]. Available: https://www.tfl.gov.uk/modes/driving/scrappage-schemes

[339] Birmingham City Council, ‘Applications to the Clean Air Zone Vehicle Scrappage and Travel Credit Scheme are now open’. Accessed: Sep. 23, 2022. [Online]. Available: https://www.birmingham.gov.uk/news/article/871/applications_to_the_clean_air_zone_vehicle_scrappage_and_travel_credit_scheme_are_now_open

[340] National Grid ESO, ‘Future Energy Scenarios 2022 | National Grid ESO’. Accessed: Aug. 10, 2022. [Online]. Available: https://www.nationalgrideso.com/future-energy/future-energy-scenarios

[341] Europa, ‘End-of-life vehicle statistics’. Accessed: Aug. 10, 2022. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics

[342] UK Government, ‘EU legislation and UK law’, legistlation.gov.uk. Accessed: Sep. 15, 2022. [Online]. Available: https://www.legislation.gov.uk/eu-legislation-and-uk-law

[343] Institute for European Environmental Policy (IEEP), ‘Managing waste batteries from electric vehicles in the EU and the Republic of Korea’. Accessed: Oct. 31, 2022. [Online]. Available: https://ieep.eu/publications/managing-waste-batteries-from-electric-vehicles-in-the-eu-and-the-republic-of-korea

[344] Department for Environment, Food & Rural Affairs, ‘Waste Prevention Programme for England: Towards a Resource-Efficient Economy - Consultation version’, Mar. 2021. Accessed: Dec. 02, 2021. [Online]. Available: https://consult.defra.gov.uk/waste-and-recycling/waste-prevention-programme-for-england-2021/

[345] M. Goulden, T. Ryley, and R. Dingwall, ‘Beyond “predict and provide”: UK transport, the growth paradigm and climate change’, *Transp. Policy*, vol. 32, pp. 139–147, Mar. 2014, doi: 10.1016/j.tranpol.2014.01.006.

[346] I. Baker, A. Peterson, G. Brown, and C. McAlpine, ‘Local government response to the impacts of climate change: An evaluation of local climate adaptation plans’, *Landsc. Urban Plan.*, vol. 107, no. 2, pp. 127–136, Aug. 2012, doi: 10.1016/j.landurbplan.2012.05.009.

[347] Tharran Gaines, ‘An electric tractor may be in your future’, agriculture.com. Accessed: Jul. 09, 2022. [Online]. Available: https://www.agriculture.com/machinery/tractors/an-electric-tractor-may-be-in-your-future

[348] FuelCellsWorks, ‘The First Hydrogen Tractor In The Netherlands’, FuelCellsWorks. Accessed: May 09, 2022. [Online]. Available: https://fuelcellsworks.com/news/the-first-hydrogen-tractor-in-the-netherlands/

[349] O. Mark, ‘JCB’s hydrogen-fuelled combustion engine examined’, Farmers Weekly. Accessed: Apr. 08, 2022. [Online]. Available: https://www.fwi.co.uk/machinery/technology/jcbs-hydrogen-fuelled-combustion-engine-examined

[350] D. S. Powlson, A. B. Riche, and I. Shield, ‘Biofuels and other approaches for decreasing fossil fuel emissions from agriculture’, *Ann. Appl. Biol.*, vol. 146, no. 2, pp. 193–201, 2005, doi: 10.1111/j.1744-7348.2005.040056.x.

[351] P. Wells, ‘Sustainability and diversity in the global automotive industry’, *Int. J. Automot. Technol. Manag.*, vol. 10, no. 2–3, pp. 305–320, Jan. 2010, doi: 10.1504/IJATM.2010.03263.

[352] I. Michelle, ‘The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles’, Sep. 2010.

[353] Element Energy, ‘Electric Vehicle Charging Behaviour Study’, Element Energy, Cambridge, Final Report, Mar. 2019. Accessed: Oct. 25, 2021. [Online]. Available: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/04/20190329-NG-EV-CHARGING-BEHAVIOUR-STUDY-FINAL-REPORT-V1-EXTERNAL.pdf

[354] F. Creutzig *et al.*, ‘Towards demand-side solutions for mitigating climate change’, *Nat. Clim. Change*, vol. 8, no. 4, pp. 260–263, Apr. 2018, doi: 10.1038/s41558-018-0121-1.

[355] ‘Environmental labels, and declarations — Self-declared environmental claims (Type II environmental labelling)’, ISO 14021:2016, 2016

[356] ‘Environmental labels and declarations — Type III environmental declarations — Principles and procedures’, ISO 14025:2006, 2006

[357] ‘Environmental management — Life cycle assessment — Requirements and guidelines’, ISO 14044:2006, 2006

[358] ‘Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals’, ISO 14064-1:2018, 2018

[359] ‘Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements’, ISO 14064-2:2019, 2019

[360] ‘Greenhouse gases — Part 3: Specification with guidance for the verification and validation of greenhouse gas statements’, ISO 14064-3:2019, 2019

[361] ‘General principles and requirements for bodies validating and verifying environmental information’, ISO 14065:2020, 2020

[362] ‘Greenhouse gases — Competence requirements for greenhouse gas validation teams and verification teams’, ISO 14066:2011, 2011

[363] ‘Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification’, ISO 14067:2018, 2018

[364] ‘Greenhouse gases — Quantification and reporting of greenhouse gas emissions for organizations — Guidance for the application of ISO 14064-1’, ISO 14069:2013, 2013

[365] ‘Greenhouse gas management and related activities — Framework and principles for methodologies on climate actions’, ISO 14080:2018, 2018

[366] ‘Greenhouse gas management and related activities - Carbon neutrality’, ISO/AWI 14068, Under development

[367] ‘Specification for the assessment of the life cycle greenhouse gas emissions of goods and services’, PAS 2050:2011, 2011

[368] ‘Specification for the demonstration of carbon neutrality’, PAS 2060:2014, 2014

[369] ‘Specification for the assessment of greenhouse gas emissions of a city. Direct plus supply chain and consumption-based methodologies’, PAS 2070:2013, 2013

[370] ‘Carbon management in infrastructure’, PAS 2080:2016, 2016

[371] International Organisation for Standardization, ‘Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations’. Under development. [Online]. Available: https://www.iso.org/standard/78864.html

[372] ‘Intelligent transport systems — Extracting trip data via nomadic device for estimating CO2 emissions — Part 1: Fuel consumption determination for fleet management’, ISO/FDIS 23795-1, Under development

[373] ‘Intelligent transport systems (ITS) — Extracting trip data via nomadic device for estimating CO2 emissions — Part 2: Information provision for eco-friendly driving behaviour’, ISO/CD 23795-2, Under development

[374] ‘Intelligent transport systems – Framework for green ITS (G-ITS) standards – Part 1: General information and use case definitions’, ISO 20529-1:2017, 2017

[375] ‘Intelligent transport systems – Framework for green ITS (G-ITS) standards – Part 2: Integrated mobile service applications’, ISO 20529-2:2021, 2021

[376] ‘Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)’, CSN EN 16258, 2012

[377] ‘International harmonized method(s) for a coherent quantification of CO2e emissions of freight transport.’, IWA 16:2015, 2015

[378] HP Wizard, ‘Tire friction and rolling coefficients’, HP Wizard. Accessed: Apr. 21, 2022. [Online]. Available: http://hpwizard.com/tire-friction-coefficient.html

[379] S. Mason, ‘Rotational Inertia Calculator’, BND Techsource. Accessed: Apr. 21, 2022. [Online]. Available: https://bndtechsource.wixsite.com/home/rotational-inertia-calculator

[380] Wheel-Size.com, ‘Land Rover Defender 1995 - Wheel & Tire Sizes, PCD, Offset and Rims specs’, Wheel-Size.com. Accessed: May 09, 2022. [Online]. Available: www.wheel-size.com/size/land-rover/defender/1995/

[381] Goodyear, ‘Goodyear Endurance 235/80R16’. Accessed: May 09, 2022. [Online]. Available: https://tiresize.com/tires/Goodyear/Endurance-235-80R16.htm

[382] Bearmach, ‘Homepage - Bearmach’. Accessed: May 09, 2022. [Online]. Available: https://bearmach.com/

[383] Pirelli, ‘Pirelli tires tailor made for Rivian’. Accessed: May 09, 2022. [Online]. Available: https://www.pirelli.com/global/en-ww/road/pirelli-tires-tailor-made-for-rivian

[384] Tyre Reviews, ‘Pirelli Scorpion Zero’, Tyre Reviews. Accessed: May 09, 2022. [Online]. Available: https://www.TyreReviews.com/Tyre/Pirelli/Scorpion-Zero.htm

[385] Department for Environment, Food & Rural Affairs, ‘Agriculture in the United Kingdom data sets’, GOV.UK. Accessed: Jul. 18, 2022. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom

[386] Department for Environment, Food & Rural Affairs, ‘Structure of the agricultural industry’, GOV.UK. Accessed: Jul. 18, 2022. [Online]. Available: https://www.gov.uk/government/collections/structure-of-the-agricultural-industry

## Appendix A – Tables of Standards

Table 24: ISO standards associated with GHG emissions.

| International Organisation for Standardisation (ISO) | | |
|---|---|---|
| ISO 14021:2016 | Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling) | [355] |
| ISO 14025:2010 | Environmental labels and declarations – Type III environmental declarations – Principles and procedures | [356] |
| ISO 14040:2006 | Environmental management – Life cycle assessment – Principles and framework | [82] |
| ISO 14044:2006 | Environmental management – Life cycle assessment – Requirements and guidelines | [357] |
| ISO 14064-1:2018 | Greenhouse gases Part 1: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals | [358] |
| ISO 14064-2:2019 | Greenhouse gases Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements | [359] |
| ISO 14064-3:2019 | Greenhouse gases Part 3: Specification with guidance for the verification and validation of greenhouse gas statements | [360] |
| ISO 14065:2020 | General principles and requirements for bodies validating and verifying environmental information | [361] |
| ISO 14066:2011 | Greenhouse gases – Competence requirements for greenhouse gas validation teams and verification teams | [362] |
| ISO 14067:2018 | Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification | [363] |
| ISO 14069:2013 | Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organisations – Guidance for application of ISO 14064-1 | [364] |
| ISO 14080:2018 | Greenhouse gas management and related activities. Framework and principles for methodologies on climate actions | [365] |
| ISO 14068 | Greenhouse gas management and related activities – Carbon neutrality | [366] |

Table 25: PAS associated with GHG emissions.

| Publicly Available Standards (PAS) | | |
|---|---|---|
| PAS 2050:2011 | Specification for the assessment of the life cycle greenhouse gas emissions of goods and services | [367] |
| PAS 2060:2014 | Specification for the demonstration of carbon neutrality | [368] |
| PAS 2070:2013 | Specification for the assessment of greenhouse gas emissions of a city. Direct plus supply chain and consumption-based methodologies | [369] |
| PAS 2080:2016 | Carbon management in infrastructure | [370] |

Table 26: Transport Emission Standards.

| Transport Emission Standards | | |
|---|---|---|
| ISO 14083 | Greenhouse gases – Quantification and reporting of greenhouse gas emissions arising from transport chain operations (under development). | [371] |
| ISO 23795-1 | Intelligent transport systems – Extracting trip data via nomadic device for estimating $CO_2$ emissions – Part 1: Fuel consumption determination for fleet management (under development). | [372] |
| ISO 23795-2: | Intelligent transport systems – Extracting trip data via nomadic device for estimating $CO_2$ emissions – Part 2: Information provision for eco-friendly driving behaviour (under development). | [373] |
| ISO 20529-1:2017 | Intelligent transport systems – Framework for green ITS (G-ITS) standards – Part 1: General information and use case definitions. | [374] |
| ISO 20529-2:2021 | Intelligent transport systems – Framework for green ITS (G-ITS) standards – Part 2: Integrated mobile service applications | [375] |
| CSN EN 16258 | Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers). | [376] |
| IWA 16:2015 | International harmonized method(s) for a coherent quantification of $CO_2e$ emissions of freight transport (not published). | [377] |

## Appendix B – FASTSim Information and Tabulated Inputs

Table 27: FASTSim inputs for 1995 LRD 110 300Tdi completing a WFDC.

| **Vehicle** | | |
|---|---|---|
| Fuel economy test procedure | Conv | Default |
| Drag coefficient | 0.65 | [246] |
| Frontal area ($m^2$) | 2.97 | [246] |
| Vehicle glider mass (kg) | 1979 | Mass overridden |
| Vehicle centre of gravity height (m) | 0.743 | Estimated as half-track width |
| Drive axle weight fraction | 0.53 | Average of LRD 110s in 2003 [245] |
| Wheelbase (m) | 2.794 | [246] |
| Cargo mass (kg) | 160 | Two passengers (80kg each) |
| Vehicle override test mass (kg) | 2139 | Curb weight plus two passengers |

| Fuel storage | | |
|---|---|---|
| Fuel storage power (kW) | 2000 | Default – no limit |
| Fuel storage time to full power (sec) | 1 | Default – no limit |
| Fuel storage energy (kWh) | 800 | 10kWh/L of Diesel |
| Fuel and fuel storage mass (kWh/kg) | 12.02 | 1L Diesel = 832g |

| Fuel Converter | | |
|---|---|---|
| Fuel converter power (kW) | 83 | [246] |
| Fuel converter efficiency type | Diesel | Supplementary info in Appendix C |
| Efficiency improvement (%) | 0 | Default – no improvement |
| Fuel converter time to full power (sec) | 6 | Default – captures transient limits |
| Fuel converter base mass (kg) | 200 | Approx. Mass of 300Tdi ICE |
| Fuel converter specific power (kW/kg) | 0.42 | 83/200 = 0.42 |
| Minimum engine-on time (sec) | 30 | Default |

| Wheel | | |
|---|---|---|
| Wheel inertia – one wheel ($kgm^2$) | 2.706 | See Appendix D |
| Number of wheels | 4 | Default |
| Rolling resistance coefficient | 0.02 | Off-road tyre on gravel, see [378] |
| Tire radius (m) | 0.391 | 235 80 R16 |
| Wheel coefficient of friction | 0.6 | Off-road tyre on gravel, see [378] |

Table 28: FASTSim inputs for 2022 Rivian R1T 135kWh completing a WFDC.

| | | |
|---|---|---|
| **Vehicle** | | |
| Fuel economy test procedure | EV | Default |
| Drag coefficient | 0.3 | [255], [256] |
| Frontal area ($m^2$) | 3.094 | FASTSim Calculator SAEJ1263 |
| Vehicle glider mass (kg) | 2670 | Mass overridden |
| Vehicle centre of gravity height (m)[25] | 0.441 | [255], [256] |
| Drive axle weight fraction | 0.51 | [255], [256] |
| Wheelbase (m) | 3.429 | [255], [256] |
| Cargo mass (kg) | 160 | Two passengers (80kg each) |
| Vehicle override test mass (kg) | 2830 | Curb weight plus two passengers |

| | | |
|---|---|---|
| **Motor** | | |
| Motor power (kW) | 562 | [255], [256] |
| Motor peak efficiency (%) | 95 | Default |
| Motor time to full power (s) | 4 | Default |
| Motor controller mass (kg/kW) | 0.833 | Default |
| Motor controller base mass (kg) | 21.6 | Default |

| | | |
|---|---|---|
| **Traction Battery** | | |
| Battery power (kW) | 2000 | No limit |
| Battery energy (kWh) | 135 | [255], [256] |
| Battery mass (kg/kWh) | 8 | Default |
| Battery base mass (kg) | 75 | Default |
| Battery round trip efficiency | 97% | Default |
| Battery life coefficient A/B | 110/-0.681 | Default |

| | | |
|---|---|---|
| **Wheel** | | |
| Wheel inertia – one wheel ($kgm^2$) | 3.576 | See Appendix D |
| Number of wheels | 4 | Default |
| Rolling resistance coefficient | 0.02 | Off-road tyre on gravel, see [378] |
| Tire radius (m) | 0.418 | 275 55 R21 |
| Wheel coefficient of friction | 0.6 | Off-road tyre on gravel, see [378] |

[25] Based on the maximum ground clearance of 366mm plus estimated battery pack height of (75mm)

Table 29: FASTSim inputs for 1995 LRD 110 retrofitted EV completing a WFDC.

| **Vehicle** | | |
|---|---|---|
| Fuel economy test procedure | EV | Default |
| Drag coefficient | 0.65 | [246] |
| Frontal area ($m^2$) | 2.97 | [246] |
| Vehicle glider mass (kg) | 1979 | Mass overridden |
| Vehicle centre of gravity height (m) | 0.743 | Estimated as half-track width |
| Drive axle weight fraction | 0.53 | Average of LRD 110s in 2003 [245] |
| Wheelbase (m) | 2.794 | [246] |
| Cargo mass (kg) | 160 | Two passengers (80kg each) |
| Vehicle override test mass (kg) | 2700 | Assumed mass plus 2x passengers |

| **Motor** | | |
|---|---|---|
| Motor power (kW) | 41.5 | Hyper 9 108V continuous use [172] |
| Motor peak efficiency (%) | 95 | Default |
| Motor time to full power (s) | 4 | Default |
| Motor controller mass (kg/kW) | 0.833 | Default |
| Motor controller base mass (kg) | 21.6 | Default |

| **Traction Battery** | | |
|---|---|---|
| Battery power (kW) | 2000 | No limit |
| Battery energy (kWh) | 52 | Electrogenic |
| Battery mass (kg/kWh) | 8 | Default |
| Battery base mass (kg) | 75 | Default |
| Battery round trip efficiency | 97% | Default |
| Battery life coefficient A/B | 110/-0.681 | Default |
| Minimum engine-on time (sec) | 30 | Default |

| Wheel | | |
|---|---|---|
| Wheel inertia – one wheel ($kgm^2$) | 2.706 | See Appendix D |
| Number of wheels | 4 | Default |
| Rolling resistance coefficient | 0.02 | Off-road tyre on gravel, see [378] |
| Tire radius (m) | 0.391 | 235 80 R16 |
| Wheel coefficient of friction | 0.6 | Off-road tyre on gravel, see [378] |

## Appendix C – 1995 LRD 110 300Tdi FASTSim Detailed Data

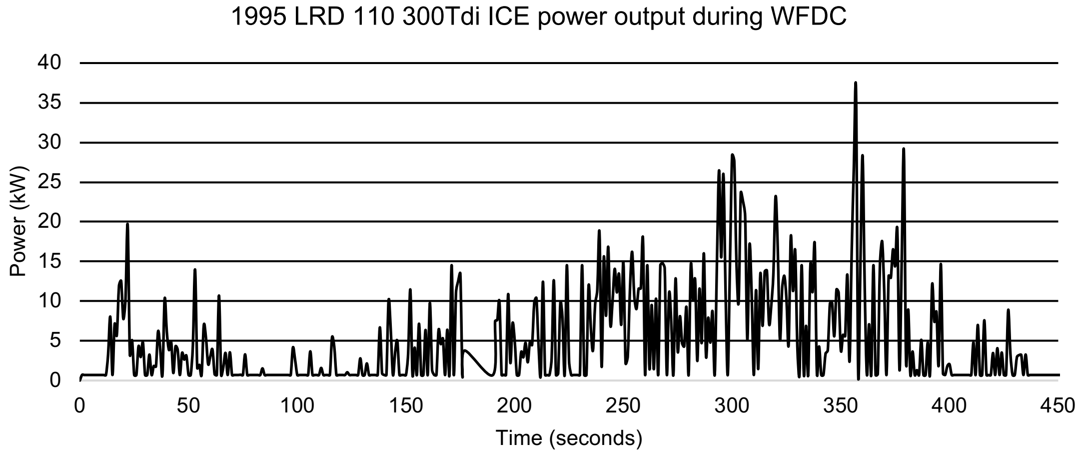


Figure 62: FASTSim of 1995 LRD 110 300Tdi ICE power output during WFDC.

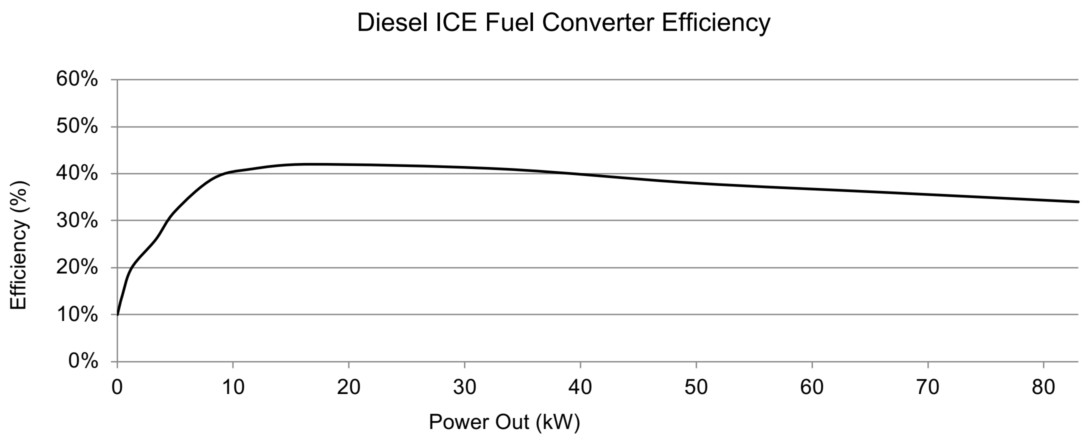


Figure 63: FASTSim diesel ICE efficiency curve applied to model.

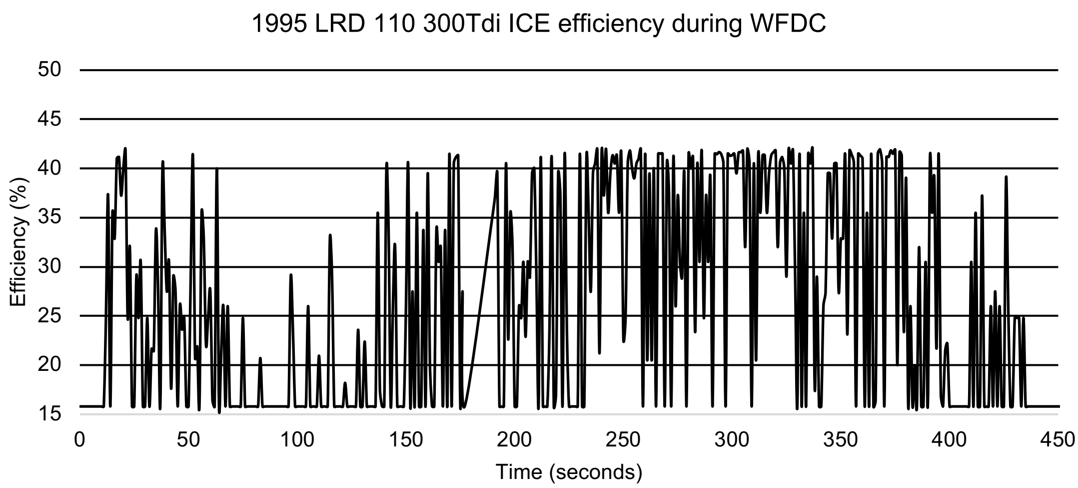


Figure 64: FASTSim of 1995 LRD 110 300Tdi ICE efficiency during WFDC.

## Appendix D – Rotational Inertia Calculations

Wheel Inertia Calculator used from [379]. Calculator outputs then used for two FASTSim models. Note that disc brake inertia is ignored on the fact that detailed enough dimension data could not be found. Similarly, Lugnut inertia is also ignored as it is so small it is essentially negligible.

### 1995 LRD 110 300Tdi ICE

Table 30: Tyre rotational inertia of 1995 LRD 110 300Tdi ICE.

| Specification | Value | Source |
|---|---|---|
| Tire Size | 235 80 R16 | [380] |
| Tire Mass | 18.14kg | [381] |
| Tread to sidewall thickness ratio | 2 | Online tool default value |
| Rotational Inertia = 2.39kgm$^2$ | | |

Table 31: Wheel rotational inertia of 1995 LRD 110 300Tdi ICE

| Specification | Value | Source |
|---|---|---|
| Rim Diameter | 16in | 235 80 R16 |
| Rim Mass | 12.62kg | [239] |
| Rim Mass % | 41% | 12.62/(18.14+12.62) x 100 = 41% |
| Rolling radius | 0.391m | 235 80 R16 |
| Rotational Inertia = 0.316kgm$^2$ | | |
| Total Rotational Inertia (One Wheel) = 2.39 + 0.316 = 2.706 kgm$^2$ | | |

### Rivian R1T 135kWh EV

Table 32: Tyre rotational inertia of Rivian R1T 135kWh EV.

| Specification | Value | Source |
|---|---|---|
| Tire Size | 275 55 R21 | [214] |
| Tire Mass | 18kg | [384] |
| Tread to sidewall thickness ratio | 2 | Online tool default value |
| Rotational Inertia = 2.86kgm$^2$ | | |

Table 33: Wheel rotational inertia of Rivian R1T 135kWh EV.

| Specification | Value | Source |
|---|---|---|
| Rim Diameter | 21in | 275 55 R21 |
| Rim Mass | 15.65kg | Estimate based on Audi 21in rims |
| Rim Mass % | 46.5% | 15.65/(18+15.65) x 100 = 46.5% |
| Rolling radius | 0.418m | 275 55 R21 |
| Rotational Inertia = 0.716kgm$^2$ | | |
| Total Rotational Inertia (One Wheel) = 2.86 + 0.716 = 3.576 kgm$^2$ | | |

## Appendix E – Vehicle Depreciation Estimation

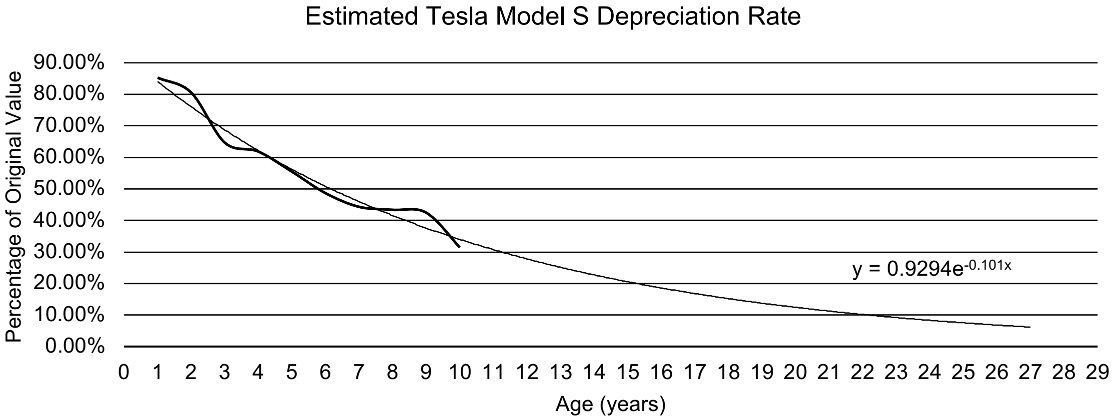


Figure 65: Tesla Model S depreciation data taken from [68] and extrapolated[26].

From extrapolation:

$$y = 0.9294e^{-0.101(x)}$$

Where y is the percentage of the vehicles original value and x is number of years of depreciation.

[26] Extrapolated to estimate yearly depreciation rate up to age of 1995 LRD for direct comparison. Depreciation data was extrapolated exponentially, logarithmically and a linearly. Linear extrapolation resulted in zero and negative residual values with is not representative. Furthermore, logarithmic extrapolation did not fit the initial data. Exponential fit was the final choice.

**Appendix F – Agricultural Sector Data**

Table 34: Number of farm holdings 2021 [385].

| Farm Holding Size | 2021 Quantity |
|---|---|
| <20 hectares | 105,000 |
| 20<50 hectares | 41,000 |
| 50<100 hectares | 30,000 |
| >=100 hectares | 41,000 |
| **Total** | 216,000 |

Table 35: Number of commercial farm holdings 2021 [386].

| Commercial Farm Holding Size | 2021 Quantity |
|---|---|
| <5 hectares | 15,941 |
| 5<20 hectares | 27,112 |
| 20<50 hectares | 20,494 |
| 50<100 hectares | 16,791 |
| >=100 hectares | 24,882 |
| **Total** | 105,220 |

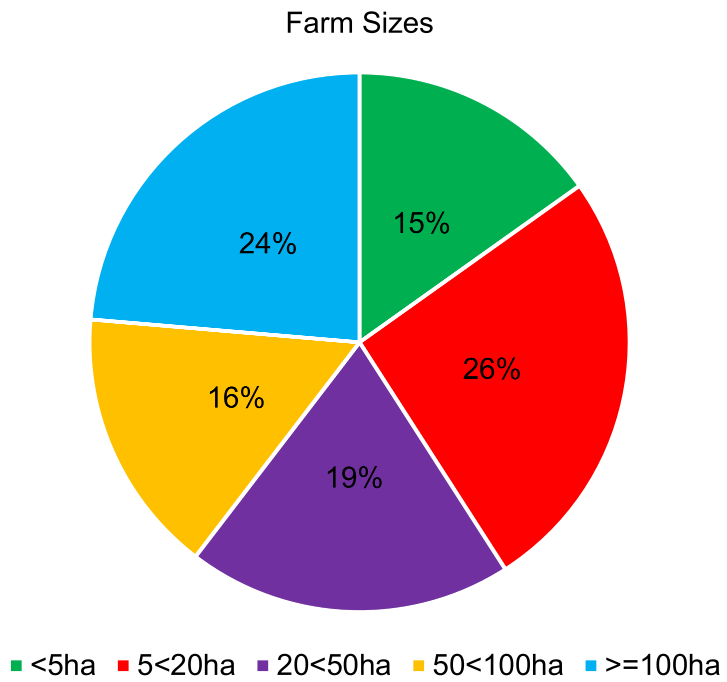


Figure 66: Breakdown of farm sizes by hectare area in 2021 produced from [386].

Table 36: Number of commercial farm employees in 2021 [385].

| Commercial Farm Total Employees | 2021 Quantity |
|---|---|
| Total labour force (incl. farmers and spouses) | 467,000 |
| Farmers, business partners, directors, and spouses | 301,000 |
| Regular employees, salaried managers and | 167,000 |

Table 37: Definition of a commercial farm holding from [386].

| Commercial Holdings | | |
|---|---|---|
| Commercial holdings are those with significant levels of farming activity. Commercial holdings are defined as those that exceed at least one of the thresholds detailed below. | | |
| **Characteristics** | | Threshold |
| Utilised agricultural area | Arable land, kitchen gardens, permanent grassland, permanent crops | >5 ha |
| Permanent outdoor crops | Fruit, berry, citrus and olive plantations, vineyards, and nurseries | >1 ha |
| | Hops | >0.5 ha |
| | Tobacco | >0.5 ha |
| | Cotton | >0.5 ha |
| Outdoor intensive production | Fresh vegetables, melons, and strawberries, which are outdoors or under low (not accessible) protective cover | >0.5 ha |
| Crops under glass or other (accessible) protective cover | Fresh vegetables, melons, and strawberries | >0.1 ha |
| | Flowers and ornamental plants (excluding nurseries) | >0.1 ha |
| Bovine animals | All | >10 Head |
| Pigs | All | >50 Head |
| | Breeding sows | >10 Head |
| Sheep | All | >20 Head |
| Goats | All | >20 Head |
| Poultry | All | >1,000 Head |
| Hardy nursery stock | | >1 ha |
| Mushrooms | All mushroom holdings to be included | >0 |

## Appendix G – Vehicle Embodied Carbon Inventory

Table 38: Component embodied emissions (kg$CO_2$e) from LCI conducted in [281].

| **Component**[27] | **kg$CO_2$e** | **Comment** |
|---|---|---|
| Body & Doors | 2090 | Kept for LRD retrofit |
| Brakes | 104 | Kept for LRD retrofit |
| Chassis | 589 | Kept for LRD retrofit |
| Electric motor | 1070 | Installed in retrofit |
| EV controller | 7.18 | Installed in retrofit |
| EV invertor | 641 | Installed in retrofit |
| EV cooling system & other hardware | 930 | Installed in retrofit |
| Engine | 593 | Based on VW Golf A4 |
| Fluids ICEV and EV | 18.9 | Kept for LRD retrofit |
| Fluids ICEV only | 14.8 | Drained during retrofit |
| Interior and exterior | 1820 | Kept for LRD retrofit |
| Other powertrain ICEV | 417 | Auxiliary systems removed |
| Tires and wheels | 323 | Kept for LRD retrofit |
| Transmission EV | 68.4 | Other conversion may require |
| Transmission ICEV | 372 | Kept for LRD retrofit |
| PbA batteries | 87.4 | Kept for 12V system |
| Battery Li-NCM | 4620 | Based on 214kg 24kWh pack[28] |

Table 39: ICEV component embodied emissions (kg$CO_2$e) based on [281].

| **Component** | **kg$CO_2$e** |
|---|---|
| Body & Doors | 2090 |
| Brakes | 104 |
| Chassis | 589 |
| Engine | 593 |
| Fluids ICEV and EV | 18.9 |
| Fluids ICEV only | 14.8 |
| Interior and exterior | 1820 |
| Other powertrain ICEV | 417 |
| Tires and wheels | 323 |
| Transmission ICEV | 372 |
| PbA batteries | 87.4 |
| **Total** | **6429.1** |

Table 40: Embodied emissions removed for retrofit (kg$CO_2$e) based on [281].

| **Component** | **kg$CO_2$e** |
|---|---|
| Engine | 593 |
| Fluids ICEV only | 14.8 |
| Other powertrain ICEV | 417 |
| **Total** | **1024.8** |

[27] Black text represents components retained after retrofitting, green represents components added and red represents components removed. Orange represents components that could be added depending on the conversion.
[28] To be scaled for the 26.5kWh pack LRD i.e., 10.42% larger than 24kWh.

Table 41: Embodied emissions retained during retrofit ($kgCO_2e$) based on [281].

| **Component** | **$kgCO_2e$** |
|---|---|
| Body & Doors | 2090 |
| Brakes | 104 |
| Chassis | 589 |
| Fluids ICEV and EV | 18.9 |
| Interior and exterior | 1820 |
| Tires and wheels | 323 |
| Transmission ICEV | 372 |
| PbA batteries | 87.4 |
| **Total** | **5404.3** |

Table 42: Embodied emissions added during retrofit ($kgCO_2e$) based on [281].

| **Component** | **$kgCO_2e$** |
|---|---|
| Electric motor | 1070 |
| EV controller | 7.18 |
| EV invertor | 641 |
| EV cooling system & other hardware | 930 |
| Battery Li-NCM 52kWh[29] | 10011.54 |
| Battery Li-NCM 26.5kWh | 5101.4 |
| Battery Li-NCM 21.2kWh | 4079.46 |
| Battery Li-NCM 15.9kWh | 3063.06 |
| **Total 52kWh** | **12659.72** |
| **Total 26.5kWh** | **7749.58** |
| **Total 21.2kWh** | **6727.64** |
| **Total 15.9kWh** | **5711.24** |

Table 43: Retrofitted EV embodied emissions ($kgCO_2e$) based on [281].

| **Component** | **$kgCO_2e$** |
|---|---|
| Body & Doors | 2090 |
| Brakes | 104 |
| Chassis | 589 |
| Electric motor | 1070 |
| EV controller | 7.18 |
| EV invertor | 641 |
| EV cooling system & other hardware | 930 |
| Fluids ICEV and EV | 18.9 |
| Interior and exterior | 1820 |
| Tires and wheels | 323 |
| Transmission ICEV | 372 |
| PbA batteries | 87.4 |
| Battery Li-NCM 52kWh | 10011.54 |
| Battery Li-NCM 26.5kWh | 5101.4 |
| Battery Li-NCM 21.2kWh | 4079.46 |
| Battery Li-NCM 15.9kWh | 3063.06 |
| **Total 52kWh** | **18064.02** |
| **Total 26.5kWh** | **13153.88** |
| **Total 21.2kWh** | **12131.94** |
| **Total 15.9kWh** | **11115.54** |

[29] Assuming linear variation in $kgCO_2e$ as a function of capacity. In reality, other changes e.g., bolstered battery supporting systems may impact this assumption.

Table 44: New EV embodied emissions ($kgCO_2e$) based on [281].

| **Component** | **$kgCO_2e$** |
|---|---|
| Body & Doors | 2090 |
| Brakes | 104 |
| Chassis | 589 |
| Electric motor | 1070 |
| EV controller | 7.18 |
| EV invertor | 641 |
| EV cooling system & other hardware | 930 |
| Fluids ICEV and EV | 18.9 |
| Interior and exterior | 1820 |
| Tires and wheels | 323 |
| Transmission EV | 68.4 |
| PbA batteries | 87.4 |
| Battery Li-NCM 135kWh[30] | 25987.5 |
| **Total** | **33736.38** |

30 Based on the Rivian R1T battery capacity of 135kWh scaled linearly for Li-NCM data with capacity. The flexibility provided by a big battery pack leads to high embodied emissions, even the Range Rover P440e hybrid has a 31.8kWh battery pack to offer efficiency with range and still requires all the additional ICEV componentry.

## Appendix H – Stock and Flow Model Inputs

Table 45: Variable inputs for the BEV Adoption Sector of the SFM model in AnyLogic.

| Variable | Type | Value |
|---|---|---|
| consumerTransformation | Table Function | National Grid FES Data |
| leadingTheWay | Table Function | National Grid FES Data |
| fallingShort | Table Function | National Grid FES Data |
| population | Dynamic Variable | 105220 |
| perYearBEV | Dynamic Variable | (scenario(getYear())*population)-(scenario(getYear()-1)*population) |
| adoptionRate | Flow | perYearBEV |

Table 46: Variable inputs for the SFM Retrofit vs Replacement Sector in AnyLogic.

| Variable | Type | Value |
|---|---|---|
| delayTime | Event | Delay of policy in years |
| replaceRate | Flow | adoptionRate*(1-adoptionFraction) |
| retrofitAttractiveness | Parameter | % in decimal |
| policyDelay | Parameter | 0 (changes at event delay in years) |
| adoptionFraction | Dynamic Variable | retrofitAttractiveness*policyDelay |
| retrofitRate | Flow | adoptionRate*(adoptionFraction) |

Table 47: Variable inputs for the Embodied Emission Sector of the SFM in AnyLogic.

| Variable | Type | Value |
|---|---|---|
| eePerNEV | Dynamic Variable | 33736.38 |
| eeRateNEV | Flow | eePerNEV*replaceRate |
| eePerICEV | Dynamic Variable | 6429.1 |
| eeSavedPerREV | Dynamic Variable | 5404.3 |
| eeAddedPerREV | Dynamic Variable | 7749.58 |
| eeRemovedPerREV | Dynamic Variable | 1024.8 |
| scrapRate | Flow | replaceRate*eePerICEV |
| removeRate | Flow | eeRemovedPerREV*retrofitRate |
| saveRate | Flow | eeSavedPerREV*retrofitRate |
| addRate | Flow | eeAddedPerREV*retrofitRate |

Table 48: Variable inputs for the End-of-Life Sector of the SFM in AnyLogic.

| Variable | Type | Value |
|---|---|---|
| recoveryPercent | Dynamic Variable | 0.055 |
| recoveredRate | Flow | (scrapRate+removeRate)*recoveryPercent |
| recyclePercent | Dynamic Variable | 0.896 |
| recycleRate | Flow | (scrapRate+removeRate)*recyclePercent |
| landfillPercent | Dynamic Variable | 0.049 |
| landfillRate | Flow | (scrapRate+removeRate)*landfillPercent |