Towards a framework for the study of ongoing socio-technical transitions: Explored through the UK self-driving car paradigm

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Abstract

The UK government set out to see self-driving cars on roads by 2021. The idea of a self-driving car has been around for almost a century, and more recent technological developments have made self-driving cars a real-life possibility. While a fully self-driving automobility system is some distance away, real-life testing is bringing autonomous driving closer to consumers. Some claim this to be the biggest disruption to mobility systems since the invention of the car. Claims about the potential of self-driving mobility range from economic and social benefits to environmental improvements. A significant ambiguity however remains concerning how they will be deployed and how the technological innovation will affect mobility aims and related transport and infrastructure systems. So far, the vast majority of studies on AVs have focused on the technology aspect of this transition lacking contributions that address this from a broader socio-technical perspective.

With the accelerated adoption of new technologies, Sustainability Transitions has come to prominence as a research area that seeks to understand and guide socio-technical transitions toward sustainable trajectories. Socio-technical transitions theoretical framework has been used to understand historical transitions in the majority of empirical applications. The ability to apply the same framework to ongoing transitions and to guide these towards sustainable outcomes remains unsubstantiated. To address this gap this thesis examines the foundations of multi-level perspective (MLP) – a socio-technical transitions analytical framework – and develops an analytical framework (SRPM – System Rules Pathways Mechanisms) that is appropriate for the study of ongoing transitions. The refocused framework incorporates critical realism to focus analysis on causation and causal mechanisms. It is used to analyse the ongoing socio-technical transition to self-driving cars in the UK through a four-step analytical process. The study is framed as a case-based process mechanism study. The four steps are: i) contextualisation of the ongoing transition to AVs in the UK as a socio-technical transition based on the MLP theoretical framework; ii) identification of internal and external structural relations within the transition through the notion of rules and the morphogenetic cycle; iii) aligning observed processes with transition pathways to theorise about the trajectories of the transition; iv) identification of causal mechanisms in the observed processes through identification of demi-regularities through data analysis of grey literature and theorisation about mechanisms through the development of mechanism sketches and schemata.

The thesis makes two contributions to knowledge: i) methodological and ii) empirical. The methodological contribution is the development of the SRPM analytical framework to study an ongoing socio-technical transition, and the empirical contribution is the application of this framework to the study of the ongoing transition to driverless cars in the UK.

Keywords

Autonomous vehicles; causal mechanisms; future of mobility; socio-technical transitions.

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List of abbreviations

ACES	Automated, Connected, Electric, Shared
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AVs	Autonomous vehicle(s)
BEIS	Department for Business, Energy & Industrial Strategy
BSI	British Standards Institution
CCAV	Centre for Connected and Autonomous Vehicles
CR	Critical realism/critical realist
DfT	Department for Transport
DIT	Department for International Trade
EV	Electric Vehicles
HGV	Heavy Goods Vehicles
IoT	Internet of Things
KTN	Knowledge Transfer Network
MaaS	Mobility-as-a-Service
MLP	Multi-Level Perspective
NTS	National Travel Survey
ONS	Office for National Statistics
SAE	Society of Automotive Engineers
SCOT	Social Construct of Technology
SDGs	Sustainable Development Goals
SMMT	Society of Motor Manufacturers and Traders
SRPM	System-Rules-Pathways-Mechanisms
STS	Science and Technology Studies
STT	Socio Technical Transitions
UK	United Kingdom
UKRI	UK Research and Innovation

1 Introduction

“But with the changes in the car, will the driver too be changed? Will he have lost one bad trait which made him years ago a menace to his own safety and a nuisance to others? Don't count on it. But these cars of 1960 and the highways on which they drive will have in them devices which will correct the faults of human beings as drivers.” (Bel Geddes, 1940)

1.2 Thesis motivation

In the early 20th century cars were introduced to the masses. Ford Model T was the first automobile that was mass-produced and affordable. Model T also became the first car produced and available globally marking a starting point for the car-dominated system of automobility that we know today. In 1939 GM's Futurama - the first concept of a self-driving car was introduced. Eight decades later, in 2017, the UK Government published the Industrial Strategy with the ambition “to see fully self-driving cars on the UK roads by 2021”.

Nowadays driving is seen as part of daily activities for many and the skill of driving is generally regarded as a useful skill to have and is associated with private liberties as well as necessities of life. Whilst very common, the skill of driving is regulated and one must prove their ability and knowledge in order to obtain a license, which in turn provides unspoken trust among drivers about their behaviours on roads with limited means of communication.

Nevertheless, human error is the cause of the vast majority of road traffic accidents. Removal of the human factor from the act of driving promises to remove human error – the major cause of road traffic accidents – but it also requires a lot of trust put into conglomerations of sensors, radars, computers, and algorithms.

While the technology developments are making AVs seem like a near-future reality, many questions remain about the deployment and, more importantly, the impact of such technology on people, cities, and the environment. With urgent environmental pressures, many of which the transportation sector is directly responsible for, the challenge concerning self-driving cars is not only about the potential of technology but its wider role in the future of mobility.

Evidence shows that transport technologies historically have affected the shape of the built environment (James Harris in (Porter et al., 2018)). Innovations in transport have allowed cities and economies to grow, but they have also caused adverse effects in urbanised areas such as reduction in air quality, accidents, congestion, and costly commuting. Furthermore, transformations in transport are directly linked to the transformations in the urban (Alessandrini et al., 2015). In the literature, several changes in the city and urban dynamics that can be triggered by AVs have been identified (Duarte and Ratti, 2018; Fraedrich et al., 2018; Legacy et al., 2018; Lim and Taeihagh, 2018; Porter, 2018). The changes span from more optimised and efficient travel to inclusive travel, to changes in land use requiring less parking spaces and thus providing more space for urban life and also a more radical re-thinking of how we plan and use cities (Duarte and Ratti, 2018). However, currently, there are no frameworks and approaches that would enable a comprehensive assessment of this transition beyond just speculation, which is a knowledge gap that this thesis addresses.

The intended audience for this thesis is researchers in socio-technical transitions and adjacent domains (such as mobilities, innovation studies, and transitions research) and anyone interested in understanding the complex processes of co-evolution of the social and the technical.

1.3 What is autonomous driving?

Autonomous vehicles (AV) are vehicles that are capable of driving without human presence. In literature, multiple terms are used to describe them, such as ‘autonomous car/bus/vehicle’, ‘self-driving car’, ‘driverless car’, ‘connected and autonomous vehicle’, ‘autonomous driving technology’, ‘automated driving’. While most of them imply the fully self-driving capabilities of a vehicle, there is some ambiguity, especially with terms such as ‘automated vehicles’ or ‘highly automated vehicles’, which could refer to vehicles which are capable of some, but not all aspects of independent driving.

The most used standardised classification of driving automation is by SAE International (Society of Automotive Engineers) identifying six different levels of autonomy. Figure 1-1 summarizes the SAE classification. Earlier discourses about the future of autonomous driving saw the adaption of AVs in a phased step-by-step way. However, this approach might be challenging in real-life applications. For example, National Highway Traffic Safety Administration (US) found that it takes up to 17 seconds for the driver to obtain full control of the vehicle and cognition of surroundings due to a lack of attention paid to the road while in autonomous mode

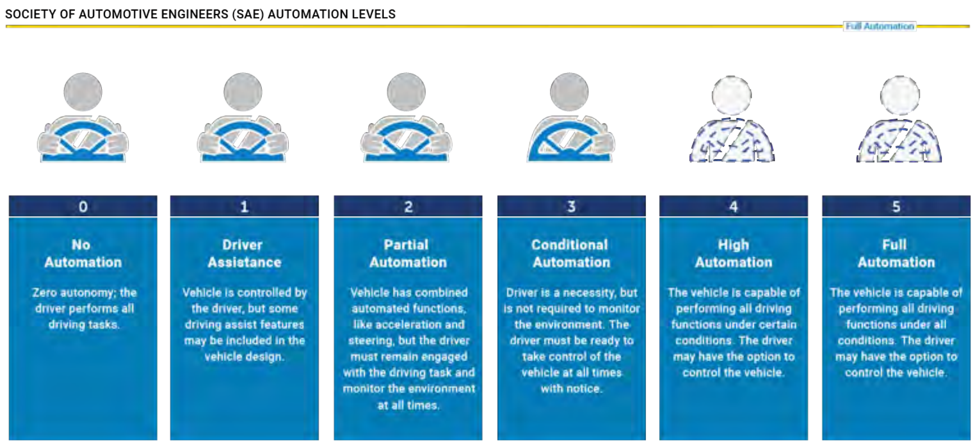

Figure 1-1 SAE levels of autonomy (source: SAE International)

(Blanco et al., 2015). For this reason, it might be that road-ready self-driving vehicles will be level 4 and 5. Even though Level 4 has the option for the driver to take control, the vehicle is capable of performing driving in most situations and does not require human monitoring. For example, such vehicle might not be able to fully perform in an unknown street traffic situation but can operate independently in an airport setting in known surroundings.

Connected and AVs is a specific term commonly used by the UK government which refers to a type of vehicles that are either autonomous (Level 4 or higher) or connected, or both, connected and autonomous (The House of Lords Science and Technology Committee, 2017). Connected refers to a vehicle equipped with communication technology allowing it to communicate to the infrastructure (V2I), to other vehicles (V2V), to the cloud (V2C), to pedestrians (V2P) and other communications. Opposed to the levels of automation, there is no clear international or governmental classification of communication technology embedded in vehicles (or lack of them). Automated driving does not necessarily require communication technology to perform the driving tasks, however, other newly introduced services such as Mobility-as-a-Service (MaaS) as well as other vehicle sharing and ride-hailing operations require vehicles to be connected, and they have often been brought up in discussions about the future of mobility (Jittrapirom et al., 2017; Sprei, 2018) and the future of AVs (Gruel and Stanford, 2016).

1.4 Autonomous Vehicles: premise and current context in the UK

A very significant aspect of self-driving cars in the UK is the proactive role that the governance actors have taken. In Industrial Strategy 2017 the Government set out to “see autonomous cars on roads by 2021”. Since then, the UK government has taken a number of steps to progress the ‘AV on roads’ agenda. It established the Transport Systems Catapult in 2014 with the aim to explore intelligent mobility and it set up the Centre for Connected and Autonomous Vehicles (CCAV) through the Department for Transport (DfT) in the same year to support and accelerate AV. These channels have provided £250m in funding, matched by the industry, to research AVs development and use. The first published regulatory review established that the UK regulatory landscape is friendly to AVs testing, putting the country in an enticing position for domestic and foreign investors (Department of Transport, 2015).

The UK also has a significant automotive industry sector that can play an active role in shaping how future of mobility will look like. The UK has ranked 5th/7th (2018/2019) globally in the AVs readiness index (KPMG International, 2019) and 3rd in total disclosed investment in mobility (specifically in autonomous, smart, and electric mobility) (Holland-Letz et al., 2019). The UK is the fourth biggest car manufacturer in Europe and hence in a strong global position for manufacturing technology and innovation.

The mobility sector in the UK and abroad is facing a number of disruptive and/or progressive innovations including electrification, shared mobility services, and automation. The changes are driven by technological advances but the speed of adoption will be affected by regulatory frameworks and societal practices. Personal cars currently dominate the automobility development landscape, based on historic car ownership practices. New services such as Uber and car sharing, together with increased costs and congested commutes, are challenging the cultural significance of car ownership which has traditionally been associated with freedom and status. People are choosing to lease and upgrade personal vehicles rapidly, contesting the traditional car purchase model. In the context of the number of cars on roads and potential of shared car ownership, the INRIX global scorecard 2018 estimated the congestion cost in the UK at nearly 8bn annually (Reed, 2019). AVs have been assumed to have broad impacts on transport, society, and cities[1]. The findings in that area emphasizing the complexity of evolving dynamics in an uncertain AVs context for policy, society, and technology.

1.5 Current research discourse

[1] for a comprehensive review of potential policy and societal effects of AV see Milakis, Van Arem and Van Wee (2017) and on potential impacts of AV on cities see Duarte and Ratti (2018).

Despite the potential wide-reaching impacts of AV, the vast majority of studies conducted on AVs have focused on individual and predominantly technology aspects of AV. Figure 1-4, Figure 1-3, and Figure 1-2 show search results for ‘autonomous vehicles’, ‘driverless cars’, and ‘self-driving cars’ on the Web of Science database, organised thematically. As seen in the images, the research publications on the topic are overwhelmingly aligning with the engineering side of AVs development.

While research on the technology itself has led to real-life tests and demonstrators of AV, when they reach a road-ready stage, they will need to co-exist with existing infrastructures, other vehicles, users, pedestrians and other systems linked to road transport. They will also need to fit into existing regulatory frameworks, practices and rules. Beyond the technical aspects, there is a need to recognise the place of driverless cars in a socio-technical system (Milakis, 2018). This thesis addresses this gap by addressing the advent of AVs as a socio-technical transition, which enables looking at co-evolving processes beyond just the technology development.

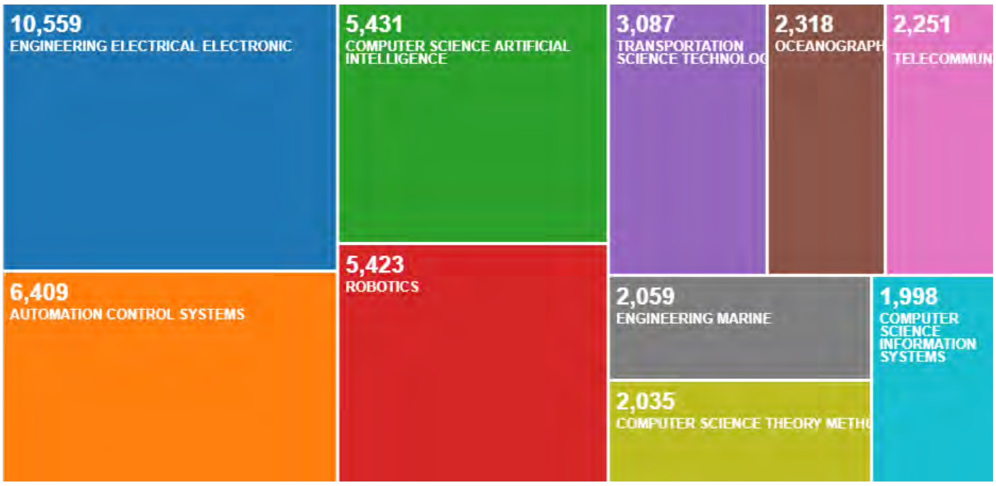

Figure 1-2 Visualisation of Web of Science themes relating to "autonomous vehicles" (by author, source: Web of Science, June 2020)

Figure 1-3 Visualisation of Web of Science themes relating to "driverless cars" (by author, source: Web of Science, June 2020)

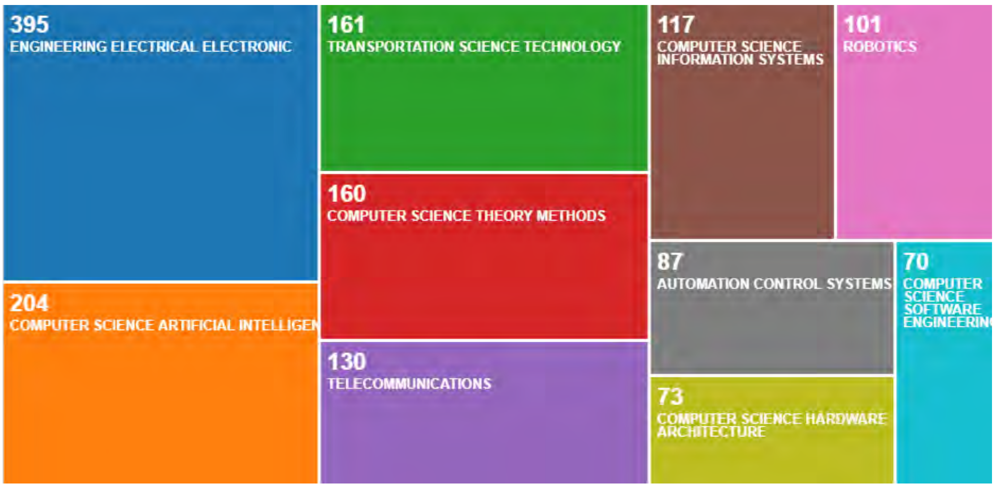

Figure 1-4 Visualisation of Web of Science themes relating to "self-driving cars" (by author, source: Web of Science, June 2020)

1.6 Research question

This thesis seeks to understand and explain the ongoing socio-technical transition to AVs in the UK. The understanding is framed around understanding causation, and causal mechanisms specifically. Because this thesis addresses an ongoing real-world process, it is useful to relate the findings to the current sustainability discourse in mobility. The research questions this thesis seeks to address are:

WHAT ARE THE CAUSAL MECHANISMS SHAPING THE TRANSITION TO AVS IN THE UK? WHAT ARE THE IMPLICATIONS OF THESE FOR FUTURE MOBILITY IN THE CONTEXT OF THE SUSTAINABLE MOBILITY AGENDA?

1.6.1 Contribution to knowledge

This thesis makes two contributions to knowledge: a methodological contribution and an empirical contribution.

Methodological contribution. This thesis engages with the sustainability transitions literature, and the MLP framework specifically. While the framework is widely used in transitions studies, there is still some ambiguity about the core concepts (such as structure, system, regime) and the methodological application. This thesis builds on some recent criticism in this domain and develops an analytical framework that refocuses the MLP framework toward the identification of causal mechanisms. The analytical framework is designed so that it is applicable to other socio-technical transition studies and it is a unique contribution to the transition studies domain, which so far only has a few contributions identifying potential analytical and methodological approaches.

Empirical contribution. This thesis applies the abovementioned new analytical framework to the ongoing transition to driverless vehicles in the UK. Because this is a novel and evolving research and ‘real world’ area, this thesis makes a contribution that sheds some light on the ongoing processes and allows the identification of potential policy and decision-making directions and actions. The socio-technical approach employed in this study offers a different view on the AVs discourse compared to the majority of current studies, which are predominantly focused on the technological aspects of AVs or specific isolated societal and environmental aspects.

1.7 Thesis structure

This thesis consists of 11 chapters. Chapter 2 contextualises the research question within relevant academic disciplines and domains with the aim to establish the most appropriate one for addressing the research question. Multi-Level Perspective (MLP) is identified as a workable framework. Chapter 3 further investigates the MLP to establish its application to an ongoing transition process. Some criticisms are identified, namely issues concerning the notions of structure and system within the MLP that are relevant to the research question. Suggestions from the critical realism (CR) domain are identified as possible directions to address those shortcomings. Chapter 4 aligns the MLP with CR and develops a four-step analytical framework System-Rules-Pathways-Mechanisms (SRPM) that can be applied to the study of ongoing socio-technical transitions. Chapter 5 sets out specific methods for each step of the framework that will be used in the study of the ongoing transition to AVs in the UK. Chapters 6 to 9 present the four-step case study following the SRPM framework. Chapter 10 discusses the significance of the findings and demonstrates how the SRPM framework specifically enabled the discovery of the results. Findings are contextualised in wider academic discourse. Chapter 11 concludes this thesis by outlining contributions to knowledge, recommendations, limitations, and potential areas of future work.

2 Positioning the research question: How should an ongoing socio-technological transition be studied?

2.1 Introduction

This chapter aims to identify and review the appropriate framework to study transitions to AV. Because transitions in mobility are affected by and affect many areas, it is important that it is studied through an appropriate lens for the identified research question. The focus in academic literature is overwhelmingly on the technology of autonomous driving (see Gandia (2018) for a comprehensive scientometric and bibliometric review of AVs research). In terms of societal aspects of AV, the literature predominantly focuses on ethics issues, such as 'the trolley problem' (see, for instance, (Dogan et al., 2016; Sparrow and Howard, 2017; Holstein et al., 2018; Cunneen et al., 2019; Evans et al., 2020; Geisslinger et al., 2021)), which is a philosophical experiment where the participant has a choice to save a number of people from being hit by a trolley by diverging the trolley to instead kill just one person. On the policy and regulatory side, some literature exists that usefully identifies AVs policy challenges and trajectories (Fagnant and Kockelman, 2015; Milakis, Snelder, et al., 2017; Fraedrich et al., 2018; Taeihagh and Lim, 2018; Cohen and Cavoli, 2019). Public attitudes and user adoption has also been a subject of study in the AVs domain with studies exploring user preferences and acceptance regarding AVs (Haboucha et al., 2017; Clayton et al., 2020; Hilgarter and Granig, 2020; Jing et al., 2020), some with specific focus on vulnerable road users (Bennett et al., n.d.; Penmetsa et al., 2019) and also studies looking at user adoption preferences, criteria, and patterns (Földes and Csiszár, 2018; Clayton et al., 2020; Golbabaei et al., 2020; Acheampong et al., 2021). These studies indicate that people may be more likely to use AVs for certain trips, such as long commutes, but less likely to use them for other shorter or more private needs. There is also a preference for a phased approach to the deployment of autonomous vehicles, with people wanting to see them tested and refined in controlled environments before they are widely adopted.

Nevertheless, studies on AVs do not yet offer a comprehensive understanding of what the arrival of the technology actually means for cities, people, the economy and associated practices. This requires a systemic understanding of a transition process to enable informed decision making, which is particularly important in the context of ongoing transitions, where research can be used not only to understand the process but also to provide insights and recommendations for policymakers.

Understandably, because the topic of AVs crosses over with other systems, sub-systems, innovations and actors, it is challenging to distil the topic and focus on AVs alone. Just as AVs are seen as the next leap in automobility by many, so is, for example, the transition to electric vehicles (EV) and products and services enabled by technology development, such as sharing schemes and Mobility-as-a-Service (MaaS). A key aspect in this process is the change – the transformation, the transition – from a known configuration to a new set of technologies, rules, and practices. Therefore, a method of abstracting, conceptualising, and describing a system is needed.

This chapter reviews relevant literature in transportation AND mobilities studies in order to contextualise the research question within academic domains and to identify the most appropriate framework for the research question. The chapter covers:

- Relation of transportation studies to wider sustainability agenda
- Addressing transition in transportation through a socio-technical system perspective
- Identification of frameworks to study transition in automobility
- Identifying sustainability transitions research domain as the most appropriate framework to address the research question
- identifying MLP (multi-level perspective) as a particular methodological framework for the research question
- demonstrating its use in other case studies

The chapter finishes by identifying the need to further explore foundational theoretical arguments of MLP in order to establish a clear framework that would be suitable for a study of an ongoing socio-technical transition.

2.2 Transportation and sustainability

The transportation sector is one of the main contributors to greenhouse gas emissions in the UK (BEIS (2021)) and globally. Transport produced 27% of the UK's total emissions in 2019 (Figure 2-3). Of this, the majority (91%) came from road transport vehicles (111 MtCO2e). The biggest contributors to this were road transport (Figure 2-1). In this category cars and taxis made up 62% of the emissions from road transport (68 MtCO2e), followed by Heavy Goods Vehicles (HGVs) (18% of road transport emissions, 19.5 MtCO2e) and vans (17% of emissions, 19 MtCO2e) Figure 2-2.

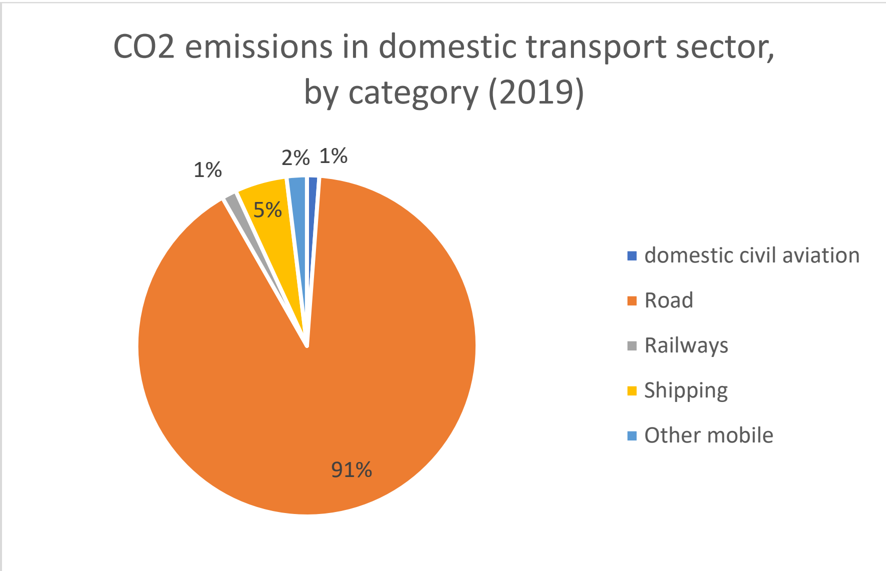

Figure 2-1 CO2 emissions in domestic transport sector, by category (2019) (source: BEIS, 2021)

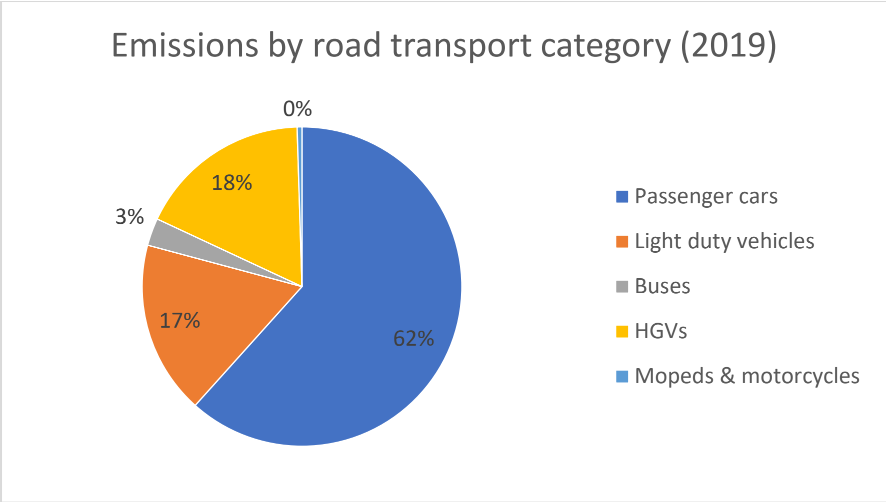

Figure 2-2 Emissions by road transport category (2019) (source: BEIS:2021)

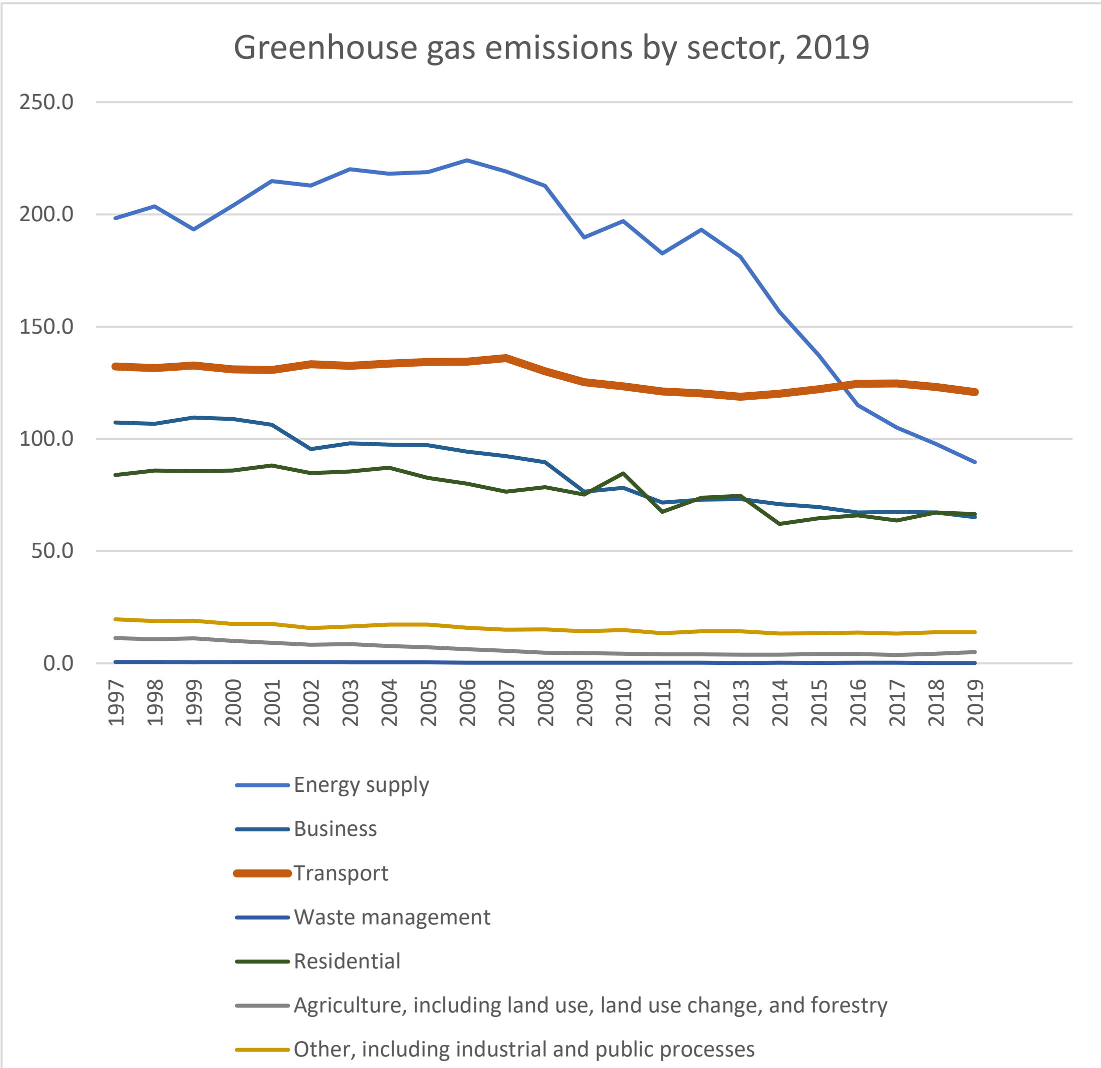

Figure 2-3 Greenhouse gas emissions by sector, 2019 (source: BEIS, 2021)

Because of the transport sector’s role in carbon emissions, pollution and other related issues, transport policy and legislation seek to reduce the detrimental impacts that transport has on the environment. In the UK, the transport decarbonisation plan (Department for Transport, 2021) sets out the pathway to net zero transportation as well as identifies the associated benefits of transport decarbonisation in the economy, skills, innovation, and jobs. This is part of the wider ambition that the Government has called a “Green Industrial Revolution” (HM Government, 2020) and the transportation decarbonisation strategy also aligns with the wider Industrial Decarbonisation Strategy (HM Government, 2021).

Because the transport sector is one of the major contributors to carbon emissions and greenhouse gas, a significant underlying discourse in automobility studies is sustainability. Sustainability is often seen as a goal and main driver for change in academic literature (for example, the sustainable mobility paradigm (Banister, 2008) and in policymaking (for example, Greater Manchester Transport Strategy 2040). There is however no unified definition of sustainability (in the context of transport) in literature. The broadest description of sustainability in the transportation sector comes from Richardson's (2005) paper, where he defines it as “the ability to meet today’s transportation needs without compromising the ability of future generations to meet their transportation needs”. A similar definition is also offered by Nunen et al. (2011a). Banister described sustainable mobility as requiring actions to reduce the need to travel, encourage modal shifts, reduce trip lengths, and “to encourage greater efficiency in the transport system” (Banister, 2008). In order to understand, analyse and assess specific aspects of mobility systems in relation to sustainability, the United Nations Sustainable Development Goals (SDGs) can be used as a goal-specific guide because it sets out specific qualifiable targets. Table 2-1 summarises the relevant SDGs to transportation and mobility (*THE 17 GOALS | Sustainable Development*, n.d.).

Table 2-1 SDGs by target and indicator specific and relevant to transportation (THE 17 GOALS | Sustainable Development, n.d.).

Target	indicator
SUSTAINABLE DEVELOPMENT GOAL 3 Ensure healthy lives and promote well-being for all at all ages	
3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents	3.6.1 Death rate due to road traffic injuries
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	3.9.1 Mortality rate attributed to household and ambient air pollution 3.9.3 Mortality rate attributed to unintentional poisoning
SUSTAINABLE DEVELOPMENT GOAL 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	
9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for al	9.1.2 Passenger and freight volumes, by mode of transport
9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	9.4.1 CO_2 emission per unit of value added
SUSTAINABLE DEVELOPMENT GOAL 11 Make cities and human settlements inclusive, safe, resilient and sustainable	
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding	11.2.1 Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities

public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
SUSTAINABLE DEVELOPMENT GOAL 13 Take urgent action to combat climate change and its impacts	
13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other)
SUSTAINABLE DEVELOPMENT GOAL 7 Ensure access to affordable, reliable, sustainable and modern energy for all	
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.2 Proportion of population with primary reliance on clean fuels and technology
SUSTAINABLE DEVELOPMENT GOAL 17 Strengthen the means of implementation and revitalize the global partnership for sustainable development	
17.14 Enhance policy coherence for sustainable development	17.14.1 Number of countries with mechanisms in place to enhance policy coherence of sustainable development

2.3

2.4 The socio-technical system of automobility

Because the car is deeply embodied within the everyday lives of the majority of people, a disruptive deep structural change will cover not only the artefact (the vehicle) itself, but all of its subsystems and practices associated with travel, driving, ownership, manufacturing, and regulating the industry. Transport systems are complex multi-layer systems. For an understanding of the scale of impact and for analysis, it is useful to describe the system of automobility[2] as constituting of series of social and technical systems. Geels (2002)portrays the modern socio-technical configuration for land-based personal transportation as a heterogeneous set of elements (Figure 2-4(a))(Geels, 2002) that fulfil the transportation function. Urry (2004a), instead of breaking it down into components, constructs automobility as a set of characteristics that enable and empower automobility, emphasizing that the key to the system of automobility is not the car itself, but the system of other fluid interactions (Urry, 2004a) (Figure 2-4(b)). In return, the car-centred socio-technical configuration has major impacts on public policy, land use, cultural patterns, social relations, community, natural resources, environmental quality, and options for the spatial mobility of individuals (Freund and Martin, 1993).

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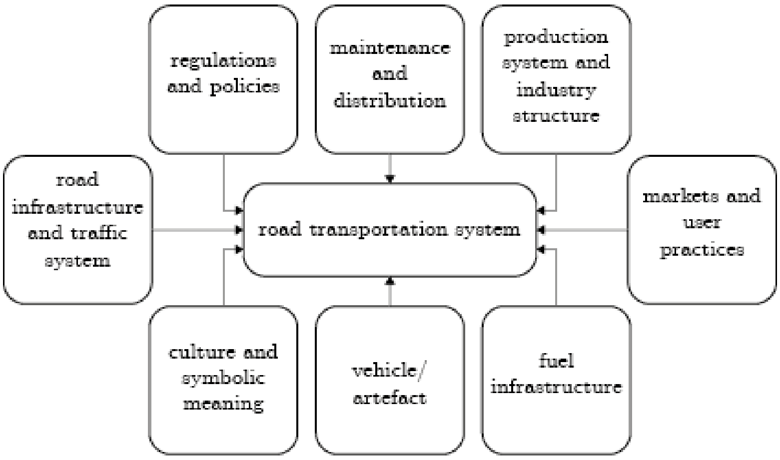
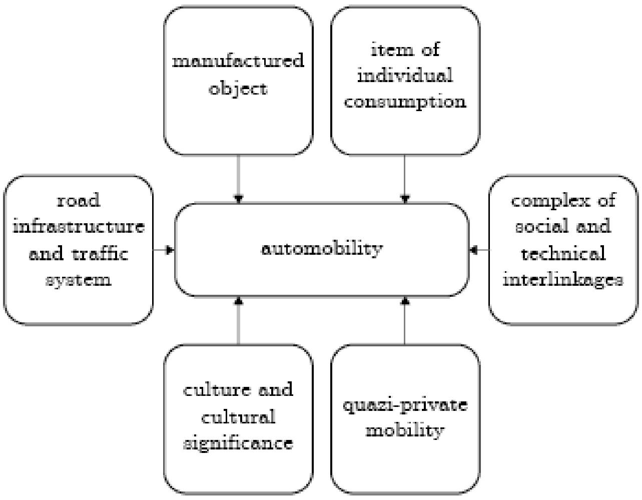
[2] Automobility here refers to the use of automobiles as the major means of transportation. “automobility.”Merriam-Webster.com 2018. https://www.merriam-webster.com/dictionary/automobility (24 September 2018)



(a)



(b)

Figure 2-4 (a) Road transportation system (Geels, 2002) (b) the system of automobility (Urry, 2004)

The multi-dimensional nature of the transportation system can be approached as a socio-technical system, and the transitions of such a system is studied within the field of socio-technical transitions studies (Geels, 2002, 2005b; Whitmarsh, 2012; Ernst et al., 2016; Loorbach et al., 2017). *Socio-technical* refers to the co-evolution of social and technological relationships, while *transitions* refer to the dynamics of such change. It focuses on technological, social and economic change that entails profound alterations in structures, institutions and social relations. As a result, a subsystem or the entire system starts operating according to new assumptions, rules and practices (Fischer-Kowalski et al., 2012).

2.4.1 Socio-Technical Transitions (STT) within wider academic context

Socio-technical as a term to describe systems developed in the 1930s as part of the Human Relations Movement in the context of industrial democracy (Klein, 2014). The movement examined the effects of social relations, motivation and employee satisfaction on factory productivity. At the time, engineering and production engineering were criticised for being self-contained. Socio-technical approach, in contrast, explicitly implies that the technology and the people in a work system are interdependent (Klein, 2014). The socio-technical theory states that technology only fulfils functions in association with human agency, social structures and organisations (Geels, 2002), implying that social and technological systems are always interlinked; they are both socially constructed and society shaping (Hughes, 1987).

Technological transitions (and later socio-technical transitions following a highly influential paper on ‘Technological transitions as evolutionary reconfiguration processes’ by Geels (2002)) is distinct from a general systems theory approach in socio-technical systems, because they deal particularly and specifically with ***transitions*** of socio-technical systems, while socio-technical systems generally refers to social and technical aspects of organisations (see, for instance, Emery (2016) and Emery and Marek (1962). Socio-technical transitions framework is based on theoretical foundations from science and technology studies and evolutionary economics (Figure 2-5). Drawing upon Rip and Kemp's (1998) work on technological change, Geels (2002) emphasised the significance of their description of technology as ‘configurations that work’. It suggests a certain alignment of artefacts (objects) or practices that fulfil a function (work). The other theoretical basis for Geels’s work on socio-technical transitions comes from

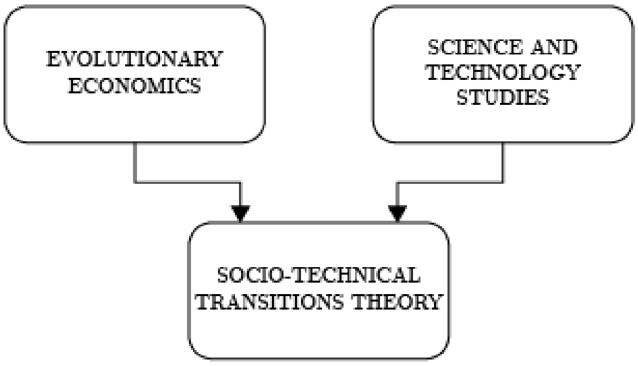


Figure 2-5 Socio-Technical transitions Theory theoretical foundations (by author)

evolutionary economics. Evolutionary economics provides two views on evolution that have been applied to socio-technical transitions by Geels in order to build toward a socio-technical transitions theory framework. Firstly, evolution as 'variation and selection', which Nelson and Winter (1982) used to understand inertia and regimes of established technologies. Secondly, evolution as a process of unfolding that creates new combinations (based on Schumpeter, 1934).

Socio-technical transitions studies (STTS) is a framework that allows understanding and analysing transitions within such systems. Scholars have developed multiple methodological approaches to understand and analyse socio-technical transitions (see section 2.6). The best-known method is the multi-level perspective by Geels (2002), which is also addressed in detail later in this thesis.

2.4.1.1 Is the transition to AVs a socio-technical transition?

The sections above have introduced the concepts of socio-technical system and socio-technical transitions and they demonstrate how the system of automobility can be conceptualised as a socio-technical system.

A socio-technical transition refers to a process of change in which new technologies and practices are adopted and integrate into a society, replacing existing technologies and practices. Transitions literature identifies multiple characteristics of transitions (Köhler et al., 2019). They are identified and aligned with the AVs discourse below:

- ***Multi-dimensionality and co-evolution***: The transition to AVs is a multi-dimensional process that involves the co-evolution of different technological, institutional, and societal factors. For example, the development of AVs requires advancements in AI and sensor technologies, changes to legal and regulatory frameworks, and societal acceptance of the technology, which requires significant changes in the current system of automobility.
- ***Multi-actor process***: The transition to AVs involves a multitude of actors, including policymakers, industry stakeholders, technology developers, and users. These actors have different interests, goals, and perspectives on the technology, which can lead to conflicting agendas and power struggles (Geels, 2010b).
- ***Stability and change***: The transition to AVs involves a tension between stability and change. On the one hand, existing socio-technical systems and practices (e.g., car ownership, driving habits) provide stability and inertia that can slow down the adoption of new technologies. On the other hand, the emergence of new technologies and applications of the technology together with other pressing challenges (such as the climate concerns, congestion, cost, modal shift) can disrupt existing systems and practices and create the conditions for change.
- ***Long-term process***: The transition to AVs is a long-term process that is likely to take decades to fully unfold. This is because it involves significant technological, institutional, and societal changes that require time to develop and diffuse, and because the system of automobility has strong path dependency characteristics (embedded infrastructure, deep cultural connections, complex legal and regulatory framework that requires cross-border agreements for change).
- ***Open-endedness and uncertainty***: The transition to AVs is an open-ended and uncertain process that is subject to a range of unknowns and contingencies. For example, the speed and direction of technological development, the pace of regulatory change, and the extent of societal acceptance are all uncertain and subject to change.
- ***Values, contestation, and disagreement***: The transition to AVs involves values, contestation, and disagreement. Different actors have different values and priorities that shape their attitudes and

behaviours towards the technology. For example, some may prioritize safety, while others prioritize convenience or environmental sustainability. These values can create tensions and conflicts that shape the development and adoption of the technology.

- ***Normative directionality***: The transition to AVs is normatively directional, meaning that it is guided by normative visions and aspirations of what a desirable future should look like. For example, the vision of a future with zero-emission vehicles and reduced congestion is a normative direction that guides the development and deployment of autonomous vehicles.

Based on the assessment above, the transition to AVs can be addressed as a socio-technical transition because it demonstrates relevance not only in technology development and innovation but also to regulatory, social and economic, and urban planning factors, which align with the STT framework.

To study socio-technical transitions of a particular system, it requires substantive knowledge of the empirical domain and theoretical sensitivity (Geels, 2012a), as well as interpretive creativity and logic. Therefore, a theoretical grounding in wider academic fields is crucial. STT relates to and overlaps with the following research areas: the new mobilities paradigm (2.4) , sustainable mobility (2.5), and sustainability transitions (2.6), which are further elaborated on in the following sections.

2.5 The New Mobilities Paradigm

The discussion around mobility has also evolved in sociology, most notably by Sheller and Urry (2006) in the research domain known as the new mobilities paradigm. The new mobilities paradigm criticised the former approach in social sciences (and specifically in sociology) where travel and movement had been treated as a neutral set of technologies and processes failing to consider the impact of the car on the social life (Church et al., 2000; Sheller and Urry, 2000; Cass et al., 2005) and the overall effects the automobile has had on transforming "the time –

space ‘scapes’ of the modern urban/suburban dweller” (Sheller and Urry, 2006). Also the assumption of travel time as being ‘wasted’ is being challenged (Lyons and Urry, 2005), which will become particularly relevant to the discussion about humanless driving. The new mobilities paradigm draws upon and develops three other higher level theoretical frameworks (Figure 2-6): *complexity theories* (and its emergence into sociology), *sociotechnical transitions theory* and *social practice theory* (Sheller and Urry, 2016).

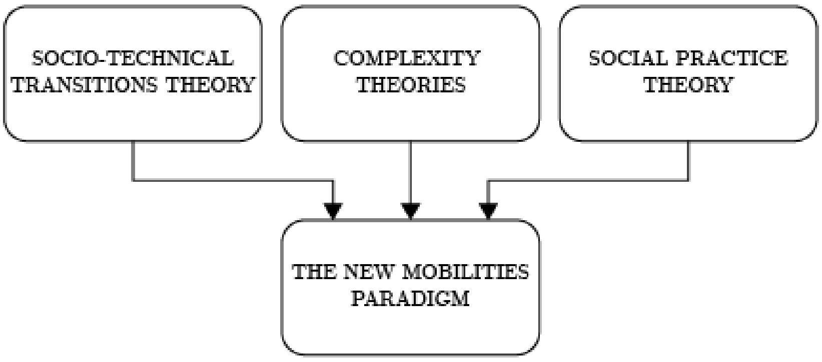


Figure 2-6 Theoretical concepts of the new mobilities paradigm

Within the new mobilities paradigm (also overlapping with the sustainability transitions area), concepts such as *post-carbon future* and *after the car* have been developed by core scholars. Having characterised ‘the car system’ as a complex adaptive system, Urry (2008) examined it as such and provided scenarios for it ‘tipping’ into an alternative (Urry, 2008; Dennis and Urry, 2009). The car system has created ‘the structure of auto space’(Freund and Martin, 1993), which has affected peoples’ mobility and the development of the urban environment, spreading distances between home, work, and leisure and creating health-threatening environmental conditions (Urry, 2008; Banister, 2011b). According to Urry (2008), the car (as a mode of mobility) is neither socially necessary nor inevitable, yet it has deeply established itself in urban and social systems, stemming from a path-dependent pattern.

The transition pathways they describe link the new mobilities paradigm to *socio-technical transitions* because they both address fundamental transformations in social and technology systems and aim to theorise about the nature of such change. Socio-technical transitions theory has influenced how mobilities transitions are described and imagined, allowing the mobilities studies to move beyond conceptualising mobilities as user behaviour or consumer markets (Sheller and Urry, 2016). Social practice theory in mobilities studies is associated by work by E. Shove, conceptualising social practices as consisting of materials, competences and meanings as well as interconnectedness between those (Shove et al., 2012).

Despite most applications and work so far in this domain has concerned itself with the ethnographic study method, there are obvious theoretical overlaps, which are applicable to the research question. Theoretical work by Urry and other mobilities scholars in post-carbon transitions has not only drawn upon a theoretical frame for socio-technical systems but has also added valuable criticism from new mobilities paradigm perspective that has affected the discourse of socio-technical transitions research and led to further discussion on power and agency in transitions (this is further addressed in chapter 3).

2.5.1 Complexity and emergence

The complexity discourse within social science began in the mid-1990s. Gulbenkian Commission's 1996 report (Wallerstein, 1996) called for social sciences to be more 'open', meaning being receptive to the future and being receptive to many possible futures. A more recent view on complexity and sociology also implies order and disorder of systems that should be acknowledged within the discipline (Urry, 2005, 2008; Sheller and Urry, 2016). Complexity approach refers to multiple inter-linked approaches and theories that can be applied to address complex, temporal, non-linear processes, often through the lens of complex adaptive systems, emergence, and evolutionary theory (Sengupta et al., 2016).

A significant concept from the complexity theory theoretical frameworks is ***emergence***. Emergence is a concept of fundamental importance within the field of complexity science, which seeks to explain how complex systems exhibit behaviour that cannot be easily attributed to the characteristics of their individual components. Emergent properties arise from interactions between components of a system, such that they manifest at a higher level of organization than that of the individual parts (Sayer, 1992; Kincaid, 2012; Gorski, 2013). The notion of emergence is prominent across research philosophies and frameworks of complex adaptive systems, socio-technical systems, and critical realism.

Within complex adaptive systems, emergence plays a critical role in the capacity of such systems to adapt and evolve over time. As the system interacts with its environment, emergent properties may arise that enable the system to better navigate and respond to changing conditions (see, for instance Holland (1998) who examines how complex systems, such as economies, ecosystems, and the brain, can exhibit properties and behaviours that cannot be predicted from the characteristics of their individual components.

Critical realism (a philosophy on science that is further discussed in this theses) also has a relevant position on emergence because emergent properties are often seen as an example of the dialectical relationship between structure and agency (Sayer, 1992; Easton, 2010; Archer et al., 2013). Critical realists argue that the behaviour of complex systems is not simply determined by the individual components that make up the system, but also by the broader social, economic, and cultural structures that shape these components, which in this thesis specifically is addressed through the notion of the morphogenetic cycle (Archer, 1995, 2020). In other words, emergent properties can be seen as an example of how the whole is greater than the sum of its parts. This perspective is consistent with critical realism's emphasis on the importance of understanding the relationship between structure and agency in shaping social phenomena (Sorrell, 2018).

In the context of socio-technical transitions, emergence is a key factor in explaining how new technologies, social structures, or other forms of collective action may emerge from complex interactions between various elements of the system (Holtz et al., 2015). Understanding emergence within such systems can help identify strategies for facilitating or accelerating transitions to more sustainable or desirable outcomes.

2.6 Sustainable Mobility

In the sustainable mobility domain scholars have criticised current transport planning agendas and policies because, despite the environmental and sustainability challenges becoming more prominent and causing issues and debates in the past, the overall approach to transport in cities has not shifted much (Banister, 2008).

Concepts of smart and intelligent mobility have also entered the discussion about the future of mobility, and they should be looked at together with the underlying sustainability discourse. Lyons (2016) discusses the potential dichotomy between the two paradigms highlighting the need to enrich the perspective on what smart and sustainable are and can be (Lyons, 2016). The need to steer mobility transitions in a sustainable direction has been emphasized repeatedly (Banister, 2008, 2011a; Wadud et al., 2016; Dudley et al., 2017; Porter et al., 2018; Sprei, 2018). Stone in (Porter et al., 2018) writes that governance is the key to achieving a mobility transition that 'leaves no regrets'. Furthermore, Sengupta et al. suggest that the opportunity to guide smart agendas toward sustainability relies on governments understanding of how to influence complex evolutionary or transition processes (Sengupta et al., 2017). Addressing the transition to AVs should therefore consider the normative sustainability agenda and ambitions (such as the SDGs outlined in section 2.2), which could offer an empirical grounding towards a better understanding of the transition process, dynamics and implications for planning and governance.

Studies have indicated that having access to a car is an important determinant of labour market outcomes in current automobility systems (Raphael and Rice, 2002). Meanwhile, the UK has ranked as the 4th most congested developed country in the world and the 3rd most congested in Europe with drivers spending an average of 32 hours a year in congestion during peak hours costing £30bn a year (Cookson and Pishue, 2018). Because of congestion, air quality, and social inequality reasons, the car as the dominant mode of transportation (especially, in cities) has been criticized by scholars in transport studies. In society, transport and mobility are associated with not only travel, commute, access to work, education and services, but also with certain freedom and status in society (Urry, 2004a). Furthermore, it enables access to more opportunities such as shopping, entertainment, and leisure is associated with better neighbourhoods and better quality of life (Banister, 2011b), and owning a private vehicle (a car) increases such access, especially in areas with less alternative mobility provisions. There is evidence suggesting links between public transport concentration (and access to public transport) to household income in urban areas (Barton and Gibbons, 2017).

A study by Pooley et al. (2006) concluded that new transport technologies often exclude many groups and individuals in society and therefore a purely technological fix to solve travel problems in cities might not be plausible. They also illustrate that innovation in technology, if demonstrated as a solution to some urban transport problem, can overshadow simpler and much more effective solutions. For an example they use the removal of Manchester’s tram system in the 1940s and then (re)introduction of Metrolink in the 90s. Parallels can be drawn to the current emerging AVs discourse, where technology hype can potentially overshadow the underlying issues and the lack of addressing them when talking about the new transport technologies.

Meanwhile, car dependence has increased, which is further aided by the ongoing decentralisation of cities. It is often further embedded into everyday life if there are no alternatives or options for education, shopping, and other amenities. Additionally, poor public transport provisions and considerations make people opt for private vehicles instead, which puts even more pressure on public transport providers and planners. Such processes have been described in the literature as path-dependency, which is shaped by lock-in mechanisms of systems.

Path dependency

Path dependency describes a key characteristic of socio-technical systems and developments. It can be conceptualised as a phenomenon where historical developments have embedded themselves so deeply in the dominant system that any future development is heavily restricted. The system of automobility can be characterised as path-depended because of vast physical infrastructures, deeply-embedded cultural and cognitive associations, standardized regulations, and investments (Geels, 2005d; Urry, 2008; Holtz, 2011) that set physical, regulative, and behavioural conditions for how any new introduction to the system of automobility can be designed and operated.

Lock-in

Lock-in mechanisms are processes that can be explained as positive feedback loops where incumbent technologies are widely adopted and diffused (Klitkou et al., 2015) and thus have an advantage over competing new innovations even if the newcomers offer a 'better' alternative. Lock-in is created by strong structural links between actors, systems, infrastructures, regulations and beliefs that produce the incumbent system and are resilient to change.

In contrast to techno-positive direction of the incumbent transportation systems actors, instead of looking for a technological solution, the sustainable mobility paradigm approach has called for actions to reduce the need to travel, encourage modal shift, encourage greater efficiency, and reduce trip lengths (Banister, 2008). Simultaneously, the sustainable mobility approach has criticised current government structures for being unable to respond to the current and future mobility needs (Hickman et al., 2013). Despite there being great aspirations toward sustainable mobility, the implementation has so far fallen short, which might be due to the necessary changes and implementations being beyond the realms of the current governance structures (Hickman et al., 2013). Church et al. (2000) suggest that local strategies based on in-depth knowledge of local conditions should be developed.

Docherty et al. (2017) discuss the significance of public value as the key governance aim for mobilities transitions. They set out modes and methods of governance that could be deployed to steer the transition and, through four thematic cases explore how current mobility governance challenges will change. It is an example of a socio-technical approach to sustainable mobility governance. The methodological framework they use comes from the sustainability transitions research field again demonstrating an existing overlap in literature, which will be explored further in this thesis.

2.7 Sustainability Transitions

Sustainability transitions (also referred to as transitions research) as a research field emerged at the end of the 1990s (Loorbach et al., 2017) and has been growing progressively over the last decades. In a seminal paper, Markard et al. (2012) described and summarised the emerging field of sustainability transitions, in which they also identified the leading theoretical concepts and methodologies underlining the field. Sustainability challenges (and future sustainability challenges) are the focus of the research in this field, and the research is concerned with how to promote and govern the transition toward sustainability. It has become a highly transdisciplinary field in which the core concepts of transitions bridge different disciplines and address grand societal challenges (sustainability being the core of those) (Loorbach et al., 2017). The Sustainability transition (as a goal) is described as a fundamental transformation toward more sustainable modes of production and consumption (Markard et al., 2012). The academic observations have made their way into policy in practice, for example, The European Environment Agency (EEA) (2015) explicitly argued that "living well within the limits of the planet requires a transition to a green economy," and that it is necessary to respond to “systemic challenges” and to integrate “policy approaches for a long-term transition” (European Environment Agency (EEA), 2015).

Sustainability transitions primarily conceptualise their sectors of interest (such as energy, water, transportation, sanitation, food, production) as socio-technical systems, following Hughes's (1987) conceptualisation of socio-technical systems as systems that are both, socially constructed and society shaping. Societal transitions are highly complex processes that unfold over timespans of decades, rather than years, and involve ‘wicked’[3] problems for societies. Such challenges require a systems approach to policy (Rip and Kemp, 1998). A systematic approach is needed to influence policy challenges that can bridge understanding of multiple co-evolving entities and systems with competing goals and visions. For studying change in these systems, transitions research adopts a broader perspective than other approaches to sustainable development and highlights the multi-dimensional interactions between industry, technology, markets, policy, culture and civil society (Holtz et al., 2015). The field of transitions studies has developed with two main interrelated agendas: (1) technological progress: to better understand how a structural change of large-scale complex societal systems comes about; and (2) transition management and impact: to guide particular societal transitions and to navigate developments towards sustainability goals (Voß et al., 2009; Markard et al., 2012; Holtz et al., 2015).

While sustainability transitions primarily investigate socio-technical transitions, there are also other conceptual approaches to sustainability transitions mentioned in the literature, namely socio-institutional and socio-ecological approaches (Loorbach et al., 2017). Socio-institutional approach refers to an approach within social sciences that aims to understand systemic changes in complex societal systems, often focusing on specific issues or geographic areas. It

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[3] The concept of wicked problems was introduced by Rittel and Weber (1973) and refers to (usually policy) problems that are complex and inter-related in nature and do not have a specific solution.

differs from the socio-technical approach by focusing on routines, powers and discourses that form the regimes and transitions (Loorbach et al., 2015). Socio-ecological approach primarily employs concepts from complexity sciences, biology and ecology. It uses resilience theory (Holling, 1973) to identify and analyse the 'tipping points' of systems. Socio-ecological emphasizes the planetary (environmental) resilience and its societal impacts on it.

Most recent theoretical additions to sustainability transitions have identified and encouraged a shift in the object and dimensions of sustainability transitions: from a focus on socio-technical systems to recognition of socio-ecological, socio-economic, and socio-political systems as equally relevant objects of transition (Loorbach et al., 2017). These debates are also relevant to socio-technical processes, where the agency of system entities, including physical artefacts needs to be addressed accordingly for the role they play in the overall transition processes.

2.7.1 Sustainability Transitions methods

Because sustainability transitions research deals with real-life phenomena, scholars have developed frameworks that allow the conceptualisation of complex processes and enable a theory-guided research process. There are four distinguished methods identified within sustainability transitions research. They are all individual research strands, with overlapping characteristics, and an agreed theoretical understanding of *niches* and *regimes* that are used in each of the approaches.

1. *Transition Management:* Transition management combines the work on technological transitions with insights from complex systems theory and governance approaches (Rotmans et al., 2001; Smith et al., 2005). Transition management scholars have proposed and applied an instrumental, practice-oriented model for influencing ongoing transitions into more sustainable directions. Guiding principles for transition management are derived from conceptualizing existing sectors as complex, adaptive societal systems and

understanding management as a reflexive and evolutionary governance process (Markard et al., 2012).

2. *Strategic Niche Management (SNM):* The deliberate creation and support of niches to drive a particular transition (Markard et al., 2012).
3. *Technological Innovation Systems:* A technological innovation system is a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or new product (Markard and Truffer, 2008).
4. *Multi-Level Perspective:* The foundation of the multi-level perspective (MLP) is the assumption that transitions are non-linear processes (Geels, 2012a) that result from the interplay of multiple developments at three analytical levels: niches (the locus for radical innovations), socio-technical regimes (the locus of established practices and associated rules), and an exogenous socio-technical landscape (Rip and Kemp, 1998; Geels, 2002, 2005d). The core MLP characteristics are: a co-evolutionary and systematic approach, actor-based approach; stability and change; complex dynamics (Geels, 2012a) (Figure 2-7).

2.7.1.1 Landscapes, regimes, niches

In socio-technical transitions, the transitions happen across three analytical levels: landscapes, regimes, and niches. The concepts come from ‘Technological Change’ by Rip and Kemp (1998) and were adopted by Geels (2002) towards framing the socio-technical transitions theory and multi-level perspective methodology. Most researchers in transitions research have accepted and adopted this framework in their research.

1. *Landscapes*: The sociotechnical landscape is the wider context, which influences niche and regime dynamics. It is a landscape in the literal sense, something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us (Rip and Kemp, 1998). The landscape level is the slowest changing level and contains many underlying drivers within the socio-technical transitions (such as culture and climate change). The change on this level is usually beyond the actions and impact of actors individually.

2. Regimes: A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, and ways of defining problems; all of them embedded in institutions and infrastructures (Rip and Kemp, 1998). The socio-technical regime forms the ‘deep structure’ that accounts for the stability of an existing socio-technical system (Geels, 2004). It is the meso-level, characterised by path dependence and lock-in mechanisms, which ensure the stability of the regime (Verbong and Geels, 2007a). In the automobility regime in the UK, the major actors are the Department for Transport and related governance agencies, incumbent manufacturers and service providers, policies, regulations, laws, and social activities associated with the automobility regime, such as the need for a personal vehicle because of lack of alternative provisions.

3. Niches: Niches are ‘protected spaces’ such as R&D laboratories, subsidised demonstration projects, or small market niches where users have special demands and are willing to support emerging innovations (Geels, 2011). Niche actors work on radical innovations that deviate from existing regimes. In the automobility regime, those can be, for instance, companies developing disruptive alternative services, technology and digital innovations, and data and AI driven prospects.

In sustainability transitions, transitions are defined as shifts from one regime to another regime (Geels, 2011; Markard et al., 2012; Loorbach et al., 2017), therefore the regime level is the primary concern for sustainability transitions scholars. According to Geels, the niche and landscape levels can be seen as ‘derived concepts’, because they are defined in relation to the regime, namely as practices or technologies that deviate substantially from the existing regime, and as an external environment that influences interactions between niche(s) and regime. MLP is an established methodological framework that conceptualises transitions as co-evolutionary processes that occur across all three analytical levels. Figure 2-7 summarises the MLP conceptualisation of the three analytical levels and the transition process.

Geels (2002) explains that socio-technical transitions usually take several decades to complete and are generally characterised by four stages:

1. Experimentation. R&D initiatives, pilot projects, demonstrations etc, often facing challenges and competition.
2. Stabilisation. In this phase, innovations establish in market niches and embed into users' everyday practices.
3. Diffusion (disruption). In this phase, the innovation diffuses into markets causing frictions and disruptions, and competition with incumbent technologies in economic, political, and cultural dimensions. At this stage, windows of opportunity can also present themselves as landscape and regime pressures from either external or internal pressures.
4. Institutionalising/anchoring. The new socio-technical system fully replaces the previous, the innovation becomes the standard and the norm in regulatory aspects and user perspectives and habits.

In literature, how a transition happens is conceptualised through transition

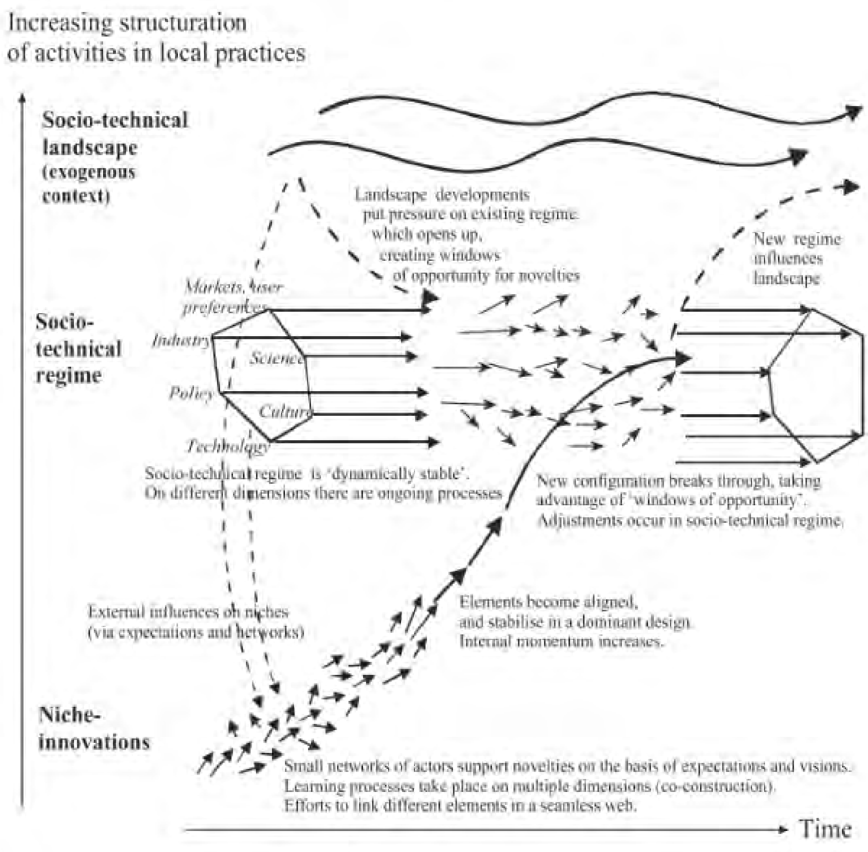

Figure 2-7 Multi-level perspective on transitions (Geels (2002))

pathways (Geels and Schot, 2007). Transition pathways describe theoretically the processes through which a socio-technical transition occurs. The pathways distinguish between transitions as a result of internal struggles (such as reconfiguration) and trajectories that are caused by exogenous landscape pressures (such as the transformation pathway). Transitions literature also acknowledges that, while those principles and stages are useful to conceptualise transitions, when applied to a specific case study the transition process might deviate from the description in terms of the time it takes to complete and the stages it goes through and the pathway it follows. A combination of pathways or sequences of pathways are also possible in real-life observations.

Table 2-2 Summary of transitions pathways and their characteristics (from Geels and Schot (2007))

pathway	**reproduction**	**transformation**	**de/re alignment**	**substitution**	**reconfiguration**
pathway description	On-going incremental processes of change within the socio-technical regime without external disruptions	If there is a moderate landscape pressure, incumbent actors will respond by modifying the direction of development paths and innovation activities	sudden landscape changes resulting in a number of other competing options emerging from niches, eventually establishing a new regime	Replacement of one dominant technology within the socio-technical regime by another as a consequence of interaction between all three levels	Replacement of a set of technologies by an alternative array of inter-related technologies which fulfil same or comparable functions

2.8 Related research in sustainability transitions, MLP and closely related literature

This section reviews empirical literature in transportation that has relevance to transitions research and the research question of this thesis. The use of MLP in other case studies is demonstrated, establishing it as an appropriate analytical framework to address a socio-technical transition.

Studies on regimes, structures and transformations predate MLP and the current sustainability transitions discourse in academic literature. For example, study on transportation politics in 1919-1936 Manhattan, highlighted power struggles between technology companies (namely GM) and politics, resulting in undesired results (Schrag, 2000). Even earlier, in 1994, Nijramp discussed environmentally sustainable transport and roads towards it. He suggested that, perhaps, “a phase of deregulation followed by one of environmentally sustainable regulation seems to be the only way to ensure a balanced position of modern transport systems”(Nijramp, 1994:270), which, speaking in transitions terms, suggests a directed regime-level transition of the socio-technical system of automobility towards a sustainable trajectory.

Currently MLP is the most commonly used analytical framework in sustainability transitions studies and socio-technical transitions studies and has therefore produced significant empirical work in many socio-technical domains, including mobility studies.

Transitions studies in the energy sector

The energy sector has been a prominent subject of study in the transitions domain providing both, empirical insights, and theoretical developments in the field. For example, Grubler (2012) examined historic transitions in energy systems, such as transitions form wood to coal and from coal to gas. The study identified key factors that facilitated or hindered these transitions, such as technological innovation, economic incentives, and political and social factors. A study on ongoing energy transition (Verbong and Geels, 2007a) has looked at longer span transition and identified liberalisation and Europeanisation as key drivers of the energy sector transitions since the 60s. Kern and Smith (2008) analysed energy transition policy in the Netherlands by applying a transition management model that is primarily based on MLP. Their work is insightful regarding analysis of existing policy strategies and challenging the approach taken by policy makers by reviewing whether, in practice, it opens up possibilities for structural change. In the UK context, a transition pathways study for a low carbon electricity system was done by Foxon et al. (2010). They used MLP to discuss future pathways to low carbon electricity grid in the UK and identified potential 'tipping points' as well as highlighted niche-regime interactions that would shape such transitions. Another UK study looked at the activities of the Carbon Trust and assessed their effectiveness for changing dominant practices through MLP framework (Kern, 2012).

As illustrated, transitions frameworks have been employed to study transitions of the same system over large spans of time and locations. Furthermore, the frameworks have also been useful to focus on particular activities, innovations, and actors.

Relevant work in the development and use of the MLP framework

Geels, who is the author of the MLP framework, published the first socio-technical transitions studies using MLP. The study of the transition from sailing ships to steamships in British oceanic transport (1780–1890) is the earliest MLP case study and demonstrates the process of analysis, identifying the transition as a stepwise process of reconfiguration (rather than a radical collapse of a system) (Geels, 2002). A study on the transition from horse-drawn carriages to automobiles in American urban passenger transportation (1860–1930), also by Geels, used the same framework and identified the trajectory of niche accumulation for the emergence and diffusion of automobiles (Geels, 2005d). Other studies in the transport domain by Geels were done on the transition from piston engine aircraft to jetliners in American aviation (1930–1975) (Geels, 2005c) and pathways linking air pollution and the American car industry (1943–1985) (Penna and Geels, 2012). Geels has also applied MLP to case studies in areas other than transport, such as Austrian biomass district-heating (1979–2013) (Geels and Johnson, 2018); transition in water supply and personal hygiene in the Netherlands (1850–1930) (Geels, 2005a); analysis of the German and UK low-carbon electricity transitions (1990–2014) (Geels et al., 2016), providing valuable analytical material and proving MLP usefulness in a number of research areas. For the research question presented in this thesis, these studies provide an insight on how a ‘typical’ MLP study can be structured in terms of system boundaries, identification of actors and regimes, assessing the impact of events and decisions, and identification of policy and other interventions towards sustainable trajectories.

Applications of MLP in transport studies

In the transport and mobilities domain, MLP has been applied to study transitions to electric mobility (Dijk et al., 2013); European battery electric vehicle uptake (Berkeley et al., 2017); UK and Germany electric mobility transition pathways (Mazur et al., 2015). Kanger et al. (2019) linked the technological diffusion process of Electric Vehicles (EV) with societal embedding, emphasizing that the trajectories of future mobility depend on these processes. Moradi and Vagnoni (2018) applied MLP to current mobility regimes in Italy to identify the driving and restraining roles of transition dynamics and potential transition pathways. Roberts (2015) applied an analytical socio-technical transitions model to British and American road and rail transport during the twentieth century bridging transitions theory and theory of frame resonance demonstrating how both, positive and negative discursive storylines can have a stabilising and de-stabilising effect on transitions. Pel and Boons (2010) applied MLP together with critical systems thinking framework to analyse traffic management systems in the Netherlands as an infrastructure operation case study and identified that actors can change the system definition and system boundaries in the transition process, and as this change happens new dynamics ensue that can potentially lead to unexpected futures.

Lyons et al.(2012) analysed intelligent transport systems as a transition in information services, characterising bottom-up user innovation (and user generated data). For examples they use user-generated targeted information services (such as train delays, cycle lanes) built upon self-help communities’ ideas, and which have the potential of disrupting existing information services. A narrative-based transition analysis on political transitions, value change and motorisation in 1970s

Portugal was done by Sousa and Marques (2013), providing an interesting case study on a transition driven by simultaneous political, social and environmental crises. These are also examples of multi-level studies without explicitly naming MLP as a methodology, however, they employ comparable strategies.

Transition pathways

Another aspect of MLP is the characterisation of transitions pathways, which allows assessing a transition based on theoretical transitions pathways models introduced by Geels and Schot (2007). In empirical studies, Elzen et al. (2002) applied socio-technical scenarios to evaluate their usefulness in developing policy recommendations and they illustrate how the methodology can lead to scenarios in which new concepts and combinations can emerge as the result of plausible new linkages under specific conditions. Shackley and Green (2007) and Foxon, Hammond and Pearson (2010) applied transition pathways to study united kingdom's energy system. their analysis identified most likely transition pathways for the energy transitions, which in turn enables a more directed policy action and intervention. Geels, amongst others, has applied MLP to studies on future transition pathways. A conceptual study on sustainability transitions in the electricity sector with socio-technical pathways (Verbong and Geels, 2010) described three possible transition pathways and indicated the implications for infrastructures toward sustainability. Gould (2017) developed a study on transition pathways and affecting factors to electric vehicle fleets. Electrification of automobility as a regime transition has also been studied by Orsato et al. (2012). Van Den Bosch et al. (2005) did a case study of the transition to a fuel cell transport system in Rotterdam, which in addition to MLP includes elements of stakeholder engagement, back casting, road mapping and scenario building methods.

Transitions pathways have also been employed in transport research, with a focus on sustainable urban mobility (Bergman et al., 2008; Moradi and Vagnoni, 2018). Similarly to studies in the energy sector, in those studies authors have highlighted how identification of current (and projected future) pathways provide an outlook on the more likely transition outcomes and potential areas of intervention with most impact. For example, Bergman et al. developed an agent based model of transition pathways based on historic transitions and suggested that adding assessment of impacts would be useful in future transitions models. Moradi and Vagnoni used transition pathways to theorise about future scenarios of urban mobility identifying three potential scenarios and the more desirable scenarios (based on stakeholder input). In the context of this thesis those studies demonstrate how MLP (and socio-technical transitions frameworks more broadly) can be applied to identify useful empirical insights and also further theoretical understanding of large scale socio-technical change.

Other studies relevant to the research question

While the growing literature on MLP applications in large socio-technical systems grows and provides valuable contributions and insights (as demonstrated above), there is currently limited research on autonomous mobility within socio-technical transitions and applications of MLP to the self-driving cars paradigm. There is also a lack of comprehensive studies that employ the MLP method regarding ongoing and future transitions despite literature suggesting it as a useful approach (Geels, 2012a).

Fraedrich et al. (2015) and (2018) and Martin (2021) have looked at some aspects of AVs transition from a socio-technical perspective, however, there is still a research gap in both, studies on on-going and future transitions and socio-technical analysis of AVs transitions.

While there is a lack of socio-technical transitions studies on autonomous driving, there are studies in other methodological areas on certain aspects of autonomous driving and some wider-scale future assessments that relate to this transition. (Gruel and Stanford, 2016) have offered a unique method in relation to humanless driving by employing a systems dynamics (Forrester, 1958) model, assessing the AVs future as a series of feedback and reinforcement loops. A number of studies have focused on shared mobility enabled by AVs technology and/or environmental issues that the technology could solve. Fagnant and Kockelman (2014) used an agent-based model to assess shared mobility impacts on emissions, fleet sizes and travel distances. Alessandrini et al. (2015) used a combination of methods (Delphi, trend analysis, stakeholder interviews, roadmaps) to develop a vision based on automated collective public transport. (Greenblatt and Shaheen, 2015) reviewed the history, current developments, projected future trends and environmental impacts of AVs and HAV technology and on-demand mobility, naming considerations for future policymakers and stakeholders. The International Transport Forum (in association with OECD) has published a series of reports on shared mobility. They have developed agent-based simulation models to test the impacts of shared mobility options on traffic in selected locations (Lisbon (OECD, 2015), Auckland (Martinez and Furtado, 2017), and Helsinki (Furtado, 2017)), providing comprehensive insights on shared mobility potential. Other studies (Brown et al., 2014; Wadud et al., 2016) have reviewed a wide range of potential mechanisms through which vehicle automation may affect transportation energy use and emissions. Other reviews have identified policy and legal actions required in regard to AVs technology (Fagnant and Kockelman, 2015). Some do not specifically discuss humanless driving, but offer reviews of transport systems and sustainability (Nunen et al., 2011; May, 2015); planning for sustainable mobilities (Freudendal-Pedersen et al., 2017); shared mobility and electric vehicles (Bergman, 2017) which are valuable for understanding of the application o the framework and the use of specific methods and methodologies.

As stated earlier, the empirical literature does not offer many perspectives on ongoing socio-technical transitions. With some exceptions (such as study on the (ongoing) sustainable mobility transitions through comparative niche development study of the UK and Sweden (Nykvist and Whitmarsh, 2008) and a study on introduction of hydrogen and battery-electric vehicles (van Bree et al., 2010)) that demonstrate the potential of applying sustainability transitions framework to a large scale ongoing socio-technical transitions, there is a significant gap in literature. The research question of this thesis seeks to shed some light on an ongoing socio-technical transition. The existing empirical literature base reviewed in this section offers an insight on how such studies can be constructed in terms of scope, scale, abstraction, methods and data, which will be useful for the empirical part of this thesis.

2.9 Summary

This chapter has established that sustainability is a normative objective, which ought to feature prominently in discussions concerning the future of mobility, given the deleterious environmental effects of transportation. Changes in automobility are inextricably linked to several interrelated research areas, including the new mobilities paradigm, sustainable mobility, and sustainability transitions. The transition to AVs constitutes a complex socio-technical process with multiple dimensions and levels, encompassing both technological and social factors. Accordingly, sustainability transitions have evolved as a well-established research domain, aimed at directing transitions towards sustainable trajectories. The Multi-Level Perspective (MLP) framework has proven to be a valuable analytical tool for examining transitions across different scales, particularly in the context of sustainability transitions. However, the applicability of the MLP framework in socio-technical transitions, particularly with respect to autonomous vehicles, remains an understudied area.

To address the transition to AVs as an ongoing socio-technical process, it is necessary to examine analytical approaches and boundaries. This study seeks not only to describe the transition but also to explicate and comprehend the implications of its evolving trajectory. Achieving this objective demands an intricate understanding of transition trajectories, internal rules, causation, relationships, and other factors that can elucidate observed phenomena. A comprehensive elaboration of the analytical framework is required to establish its theoretical underpinnings and delineate how it can be operationalized in the context of the ongoing transition to AVs in the UK.

Subsequent chapters in this thesis will delve deeper into the conceptual foundations of the MLP framework and propose a refined approach to its application in the case study section.

3 Multi-level perspective: understanding theoretical foundations and application to the ongoing transition to AVs in the UK

The previous chapter identified multi-level perspective (MLP) as a useful and well-established framework through which to investigate socio-technical transitions. As demonstrated, several studies have successfully employed the framework to understand transitions in different socio-technical systems, including automobility. There is, however, a gap in the literature when it comes to addressing ongoing socio-technical transitions. This thesis seeks to address that gap by investigating an ongoing transition. It is therefore important to first establish ***how*** an ongoing socio-technical transition should be addressed. The following chapters address this as follows:

- **Chapter 3** (this chapter) establishes the core foundational arguments of MLP and identifies and furthers critiques of these arguments in relation to the research question. This chapter finds that, in relation to ongoing transitions in the system of automobility, MLP employs a conceptualisation of structure that does not fully account for all causal and structural powers in a transition. It identifies literature that has offered criticism from a critical realism position and offers an alternative conceptualisation that has a more balanced view of the relationship between structure and agency in a transition.
- **Chapter 4** furthers the discussion of using critical realism in MLP and identifies how and why critical realism can be used to re-focus MLP towards the identification of causal mechanisms. This chapter also develops and presents the SRPM framework, which is an analytical framework that can be used to study socio-technical transitions and that is used in the case study of this thesis.
- **Chapter 5** identifies a step-by-step methodological process to apply the analytical framework, as well as data sources and specific methods for each of the analytical steps.

3.1 Introduction

The previous chapter identified that MLP has emerged as an engaging and prominent framework to study socio-technical systems and transitions, especially in the context of sustainable future trajectories. The sustainability transitions research domain is expanding and growing (see Köhler et al. (2019) for a review of Scopus data on sustainability transitions publications). In the MLP context, the most significant contributions have been made by Frank Geels (2002, 2011, 2020 and others) who introduced and developed the framework and others (Genus and Coles, 2008; Markard and Truffer, 2008; Smith et al., 2010; Avelino, 2017; Loorbach et al., 2017) who have offered theoretical critiques and elaborations. The framework due to its wide-spreading popularity and applicability also attracted a significant number of contributions and criticism relating to foundational arguments, the role of agency and power, and others, which are addressed in later sections of this chapter. The debate has raised many crucial discussion points about the core foundational aspects of MLP. Because of the increasing interest and popularity, many scholars are entering the area of transitions research from domains that they have established themselves. This has led to many theoretical contributions and suggestions on how to expand, interpret and combine various theoretical and methodological frameworks in the transitions research. Scholars have made contributions to MLP from areas such as behavioural – institutional change (Whitmarsh, 2012); roles of users (Axsen and Sovacool, 2019); political dimensions in transitions (Roberts and Geels, 2018); multi-actor dynamics (Wittmayer et al., 2017); systems dynamics (Walrave and Raven, 2016), and others.

In contrast, fewer contributions have been made to the theoretical foundations of transitions research. Most recently, Geels (2020) has clarified and elaborated on the conceptualisation of agency in MLP. In the same paper, he also identifies the general theories that form the foundation of MLP. However, some ambiguity still remains about the understanding and interpretation of MLP concepts such as rules, regimes, structure, and system. It is however important to establish and explain the core assumptions about the framework to enable further theoretical and empirical work that eliminates ambiguities. This chapter addressed that gap by investigating, clarifying, critiquing, and establishing core ontological positions of MLP. This will contribute to:

1. Overall discussion on theoretical foundations and position of MLP, which so far has been mostly focused on adding new concepts rather than clarifying the existing, with notable recent exceptions by Geels (2020)and Sorrell (2018).
2. Developing a concrete analytical framework that can be used to investigate ongoing transition processes.
3. Addressing the research question. The vast majority of empirical MLP studies have focused on past transitions. To actively contribute to the wider sustainability transitions agenda, which is to guide transitions toward sustainable trajectories, there is a need to develop and test the MLP framework so that it can provide valuable contributions toward guiding ongoing and future transitions. This requires a clear framework that can be applied, re-applied, and evaluated as transitions progress and evolve.

This chapter follows this order:

- introduces sociology domains that MLP is built on: sociology of technology; historical sociology; analytical sociology;
- identifies and elaborates on general theories relevant to MLP;
- demonstrates how MLP is operationalised as a middle range theory and how it relates to the higher level general theories;
- addresses the lack of clarity to the central concepts of MLP: rules, regime, structure, and system and introduces relevant critiques, namely from critical realism (CR) that can be applied to clarify the terminology and overcome the shortcomings of the traditionally agency-centric approach of MLP;

3.2 MLP within social sciences and sociology

The study of socio-technical transitions sits within the realm of social sciences, and sociology more specifically. Sociology is also a large domain which has developed in many different areas, each with its own theoretical and methodological approaches. Transitions studies are concerned with understanding and explaining the co-evolution of society and technology. The primary sociology domain in this area of study belongs to is the ***sociology of technology***. Looking at

MLP specifically, it crosses over to the domain of ***historical sociology***[4], which is primarily concerned with the processes involved in large-scale change (Lawson, 2006) and involves the notion of causality. Causality, explanation and causal mechanisms point to ***analytical sociology*** as another sociology domain that MLP builds upon. It is useful to first look at these domains to underpin the foundational arguments and their implicit claims about causality and explanation. The review below is not a comprehensive review of the entire domains and theoretical debates within them but rather a summary of relevant arguments to MLP and transitions. The aim of the review is to explicitly identify core theoretical positions of MLP, which will then allow discussing and critiquing those positions towards a clearer analytical framework that is better suited for the research question of this thesis.

3.2.1 Sociology of Technology

Sociology of Technology (often also known as Science and Technology Studies and Social Construction of Technology (SCOT))[5] is a sociological discipline that conceptualises technology as socially constructed. Compared to other sociology strands that are primarily concerned with human behaviour and social relations, the sociology of technology acknowledges the influence of material and technological dimensions in addition to more philosophical constructs of agency and structure. SCOT originates from Pinch and Bijker's article and is centred around agency (Pinch and Bijker, 1984). SCOT originally presents a framework that consists of four core elements:

1. Interpretive flexibility (Klein and Kleinman, 2002). This suggests that because of different social circumstances the technology design and

[4] Some authors use the term historical sociology, while others prefer historic sociology, both refer to the same domain of sociology.

[5] SCOT is a sub-concept/theme of Science and Technologies Studies (STS), however, in MLP literature SCOT is the primary STS concept that is broadly used and therefore in this context they are sometimes used interchangeably in transitions literature.

development is an open process that will therefore produce different outcomes depending on circumstances.

2. Relevant social group. This refers to "all members of a certain social group who share the same set of meanings, attached to a specific artefact" (Pinch and Bijker, 1984:414). The manifestation of agency of each actor comes through the meaning they impart to the artefacts. From the SCOT perspective, technological innovation is deemed successful/acceptable when all involved social groups accept that the new technology works for them in that particular iteration.
3. Closure and stabilisation. Technological innovation is a process that opens up conflicts and controversies when social groups have different views of the artefact. The design process is closed and resolved when the final form of the artefact is agreed upon and stabilises. Closure mechanisms are identified and demonstrated as (Pinch and Bijker, 1984; Hughes, 1987; Klein and Kleinman, 2002):
    a. a rhetorical closure mechanism: a declaration is made that no additional design work is necessary; or
    b. a redefinition closure mechanism: unresolved problems are redefined so that they no longer concern the social groups.
4. Wider context. The socio-political and cultural context in which the technological development process takes place. The background provides some context and conditioning to the involved social groups but does not play an active role in the innovation process.

As demonstrated, because of the agency-centric approach, SCOT does not fully address system-level power differences and constraints that influence actors' actions. Bijker (1997) also added another element to SCOT, which is the technological frame. The technological frame can include "goals, key problems, current theories, rules of thumb, testing procedures, and exemplary artefacts that, tacitly or explicitly, structure group members' thinking, problem solving, strategy formation, and design activities" (Bijker (1995:125) in Klein and Kleinman (2002:31)). The technological frame can act as an enabler and also discourage certain actions, which is specifically relevant in actor and innovation aspect. While not explicitly stated in the SCOT context, such a notion acknowledges the existence of structure and offers a way to balance the otherwise agency-heavy approach of SCOT. Structures as constraining frames link to critical realism and specifically M. Archer's morphogenetic cycle (see discussion in the following chapter) that suggests that structures are independent entities that shape and are shaped by actors. The role of technology in the conceptualisation of agency, power, and structure is also central to MLP, illustrating the link between the two domains.

3.2.2 Historical Sociology

> *"Historical sociology does not have a particular subject matter. Rather, it is a way of doing sociology that recognises change as the true subject of the discipline." (Lachmann, 2013:140)*

Historical sociology is a field of social inquiry that investigates change over time. It is one of the principal sub-disciplines of sociology and it has evolved into many strands of inquiry. While the review of the entire field of historical sociology is beyond the scope of this research, it is useful to identify some core assumptions and developments to illustrate how MLP relates to this field and its inherent foundational arguments.

1. Recognition of the significance of path dependency: understanding that contemporary conditions are inherited from the past, which in turn constrain and enable the actions of actors in the present day; causal dependences that link contemporary events and processes to prior occurrences (Abbott 1990, 2001; Aminzade 1992; Arthur 1994; Ertman 1997; Isaac 1997; Goldstone 1998; Mahoney 2000; Katznelson 2003; Pierson 2004; Sewell 2005 in Lawson, 2006). Mahoney (2000) identifies two types of path dependency sequences: (a) self-reinforced sequences that are characterized by the formation and long-term reproduction of a given institutional pattern and (b) reactive sequences that are characterised as temporal and causally connected events where the final event (the outcome) is the outcome/phenomenon being investigated.
2. (Changing) Temporal context must be accounted for in research. This can be illustrated through Sartori's (Sartori, 1970) illustrates this through a 'ladder of abstraction' model, which allows to both, identify causal regularities and account for the empirical context. He proposed a view of abstraction through which the 'ladder' ranges from general abstractions to empirical examples, and he argued that social science research should start at the middle and ' climb' up or down the ladder of abstraction to understand

whether the findings fit more with empirical material or higher level general concepts (Lawson, 2006).

3. Encouragement of “empirically sound, comparative work” in order to “direct disciplines away from static, snap-shot approaches to a more vibrant account that can make sense of the dynamism of social action and social change” (Lawson, 2006). While individuals are constrained by the social structures of the past, they respond to (and create) changing contexts and re-construct social orders.

In terms of methodology, historical sociology supports many approaches. Calhoun (1998) argues for a “composite explanatory strategy” in historical sociology, especially when studying change over time in multi-faceted phenomena (such as the global spread of capitalism in his example). In the composite strategy, different types of explanation – covering law, narrative, and mechanism – can play a part (Table 3-1).

Table 3-1 Covering law, narrative, mechanism explanations (by author)

Covering law	Explanation through universal laws. The research follows deductive reasoning.
Narrative	Explanation through an account of conditions and events that sufficiently account for the studied phenomenon.
Mechanism	Explanation through causality, and high-level law-like regularities that cause observed events to happen.

Lachmann (2013) highlights that in historical sociology ‘regardless of the method used, the best works share a sensitivity to temporality, an understanding that when something occurs – its place in a sequence of events – is ***crucial to explain causality*** [emphasis added]’. And Goldstone (1998) emphasises that “good historical analysis is distinguished not by any one method, but by choosing the method of explanation best suited for its explanatory goal”. The explanation is usually constructed through narrative (see Griffin (1992) for a comprehensive discussion on narratives, theories and explanation in historical sociology). The narrative approach is also the most commonly used approach in empirical MLP studies, and it is usually applied to explain the observed phenomena (see chapter 4 for further discussion on views on causation).

3.2.3 Analytical Sociology

Analytical sociology is primarily concerned with "***explaining*** [emphasis added] social facts such as network structures, patterns of residential segregation, typical beliefs, cultural tastes, common ways of acting etc" (Hedström and Bearman, 2009). Analytical sociology

> *"explains by detailing mechanisms through which social facts are brought about, and these mechanisms invariably refer to individuals' actions and the relations that link actors to one another" (Hedström and Bearman, 2009).*

The quote above summarises the core focus of analytical sociology. *Explains by detailing mechanism*s refers to mechanism-based explanation and *invariably refers to individuals' actions* points toward the doctrine of methodological individualism, both of which are the core positions and focal points of analytical sociology.

1. Causal mechanisms. On an ontological level, mechanisms could be understood as recurrent processes that link specific initial conditions with specific outcomes (Mayntz, 2004). Epistemologically this, therefore, inherits the generalisability of causal propositions. Mechanism based explanation as an analytical focus goes beyond analytical sociology (see chapter 4 for further elaboration). In analytical sociology, there is no consensus on what exactly is meant by mechanism, and many authors have offered their own definitions (see Mahoney 2001, Bearman and Hedström, 2009, Kaidesoja 2013 for reviews of those definitions). While there are differences between the various authors, they are all underlined by an emphasis on specifying in detail how observed phenomena are brought about. Mechanisms are understood as consisting of entities with their properties, and the activities they engage in either individually or together with other entities (Machamer et al., 2000; Hedström and Bearman, 2009). From a mechanisms perspective, the explanation should contain an identification of the types of entities and activities through which the observed phenomena are believed to have been

brought about. In analytical sociology, mechanisms are supposed to only occur in and between the individual actors (Little, 2012), which links to methodological individualism.

2. The other core position of analytical sociology is the support of methodological individualism. Methodological individualism was introduced by Max Weber in *Economy and Society* (Weber et al., 1978). It claims that social phenomena should be explained by demonstrating them as a result of individual actions and motivations. Weber critiqued treating social collectives (states, associations, businesses etc.) as if "they were individual persons" (Weber et al., 1978:13) and argued for treating those collectives "as solely the results of and modes of organization of the particular acts of individual persons, since these alone can be treated as agents in a course of subjectively understandable action" (Weber et al., 1978:13). Importantly though, methodological individualists do not seek to privilege the individual over the collective but rather to prioritise the action-theoretic level of explanation (Heath, 2020). Some proponents of analytical sociology have aligned with a version of methodological individualism called structural individualism. Bearman and Hedström (2009) describe structural individualism as "a methodological doctrine according to which social facts should be explained as the intended or unintended outcomes of individuals' action". It differs from methodological individualism in that it attributes explanatory significance to the social structures in which individuals operate and are embedded and by emphasising the explanatory importance of relations and relational structures.

Causal mechanisms are implicit in much of MLP theoretical literature and are addressed later in this thesis (chapter 4) in relation to a refocused MLP approach. Methodological individualism, however, is not a workable approach in MLP. In transitions literature/research however causal powers are attributed to actors such as firms, organisations, governments, lobby, and social groups. From an analytical sociology point of view, in any such entity, the powers can be traced back to individuals and any collective dynamics that emerge can be traced back to individuals' actions. However, as Kaidesoja (2013:314) argues, "it is impossible to ontologically reduce the cognitive capacities of collective agents involved in these mechanisms to those of their individual members or the aggregates of the latter". This is a critical argument in transitions research which investigates macro-phenomena in which institutions and social groups and other collective agents have causal powers. Especially in historical research of large scale change, actions and agency are attributed to organised social groups and structures rather than individual actors, for example, in political processes (Tilly, 2003), corporate competition (Stinchcombe, 1998) behavioural science (PEDERSEN and DOBBIN, 1997), evolutionary economics (Nelson and Winter, 1982). Other domains and critical realism in particular reject the doctrine of methodological individualism and offer a position on a mechanism-based explanation of emergence[6] that is more suitable for MLP and transitions research. This is discussed in more detail in chapter 4.

3.2.4 Sociology domains: a brief summary and relevance to MLP

As demonstrated above, the particular domains of sociology offer rich theoretical insights and approaches to research, and the three domains discussed above have influenced the foundation of MLP. Capturing and acknowledging spatio-temporal context is a challenge shared between all domains, which is also expressed through the landscape analytical level and transitions dynamics in MLP. From SCOT, the four core positions are reflected in MLP and transitions research:

- Relevant social group aligns with the 'social' in the socio-technical system;
- Acknowledgement of the wider context playing a role in technological development processes aligns with the 'landscape' level in MLP;
- Interpretive flexibility acknowledges the specific context in which each transition operates and closure and stabilisation theorise about when a transition 'has happened' – when a new dominant regime has been established.

From historical sociology:

- Path dependency is a key mechanism that characterises the stabilisation of the dominant regime in transitions literature (Geels, 2004; Geels and Verhees, 2011);
- The concepts of causal regularities and the ladder of abstraction are evident in MLP's conceptualisation of analytical levels and sociotechnical

[6] See section 2.4.1 for a brief discussion on emergence

systems. Abstractions allow working with complex multi-actor systems and events.

From analytical sociology:

- The concept of causal mechanisms has appeared in transitions literature (for example, in Geels, 2002; Geels and Johnson, 2018; Roberts and Geels, 2018; Turnheim and Geels, 2019), however, it has not been given explicit explanatory priority over other approaches. This thesis argues that the identification of causal mechanisms should be the primary objective of MLP, and that is discussed further in this chapter.

The domains summarised above differ in the approaches and focus, but they share a common objective, which is ***to explain.*** While approaches towards explanation differ due to different conceptual areas being given priority, the ambition of research fundamentally remains focused on causality. Due to the complex and varied nature of the social enquiry, there is no ‘one fits all’ method or methodology identified that would solve the research inquiry. Some areas focus more on empirical observations (such as the narrative approach), while others use a general theory as a starting point. Often, in order to find appropriate frameworks, mid-range (middle range) theories are required, which allows research to be both, empirically significant and theoretical – creating, testing, and evolving the knowledge. The following section focuses on general and middle range theories.

3.3 General theories and middle range theories

Having established sociology domains that form the foundation for MLP, in this section, I discuss MLP in the context of general theories and their relevance to MLP as a middle-range theory and heuristic.

The use of theory is a key aspect of doing research in any area of social sciences (Chijioke et al., 2020). The use of a theory is a useful way to abstract complex social phenomena, and general theories also offer a ‘starting point’ for exploration and explanation of such events (Kiser and Hechter, 2015).

Mahoney (2004) conceptualises ***general theory*** as

causal agent + causal mechanism

Merton (2007) explains that ***middle range theory*** is principally used in sociology to guide empirical inquiry and claims that middle range theories are "intermediate to general theories" (Merton, 2007:448) in that the latter is too removed from some particulars to properly account for what is observed and not generalised. The middle-range theory still involves abstractions but "they are close enough to observed data to be incorporated in propositions that permit empirical testing" (Merton, 2007:448). Hedström and Udehn (in Bearman and Hedström, 2009:31) describe Mertonian middle range theories as:

> *" [..] theories occupying the middle regions of the two-dimensional space [see Figure 3-1]. That is to say, a clear, precise, and simple type of theory which can be used for partially explaining a range of different phenomena, but which makes no pretense of being able to explain all social phenomena, and which is not founded upon any form of extreme reductionism in terms of its explanans. It is a vision of sociological theory as a toolbox of semigeneral theories each of which is adequate for explaining a limited range or type of phenomena."*

Figure 3-1 demonstrates the position of middle range theories in the dimensions of generalisability and exclusivity. The horizontal axis represents the explanans[7] and their degree of isolation. The vertical axis refers to the explanandum[8] and the generality of a theory. As demonstrated in the graph, grand

[7] Explanans – that which contains the explanation (Latin)

[8] Explanandum – that which needs to be explained (Latin)

(general) theories are characterised by a high level of generalisability and inclusivity and describe the theories that claim to cover (and explain) all phenomena in a sociological inquiry. Examples of such theories can be found in rational choice theory, behavioural theories, evolutionary theories, and others. On the other side of the graph, there are empirical generalisations described as thin and thick descriptors respectively by Hedstörm and Udehn. Thin descriptors explain a phenomenon through specific accounts of events of the observed phenomena, while thick descriptors also consider some broader factors, such as social, cultural, and economic factors.

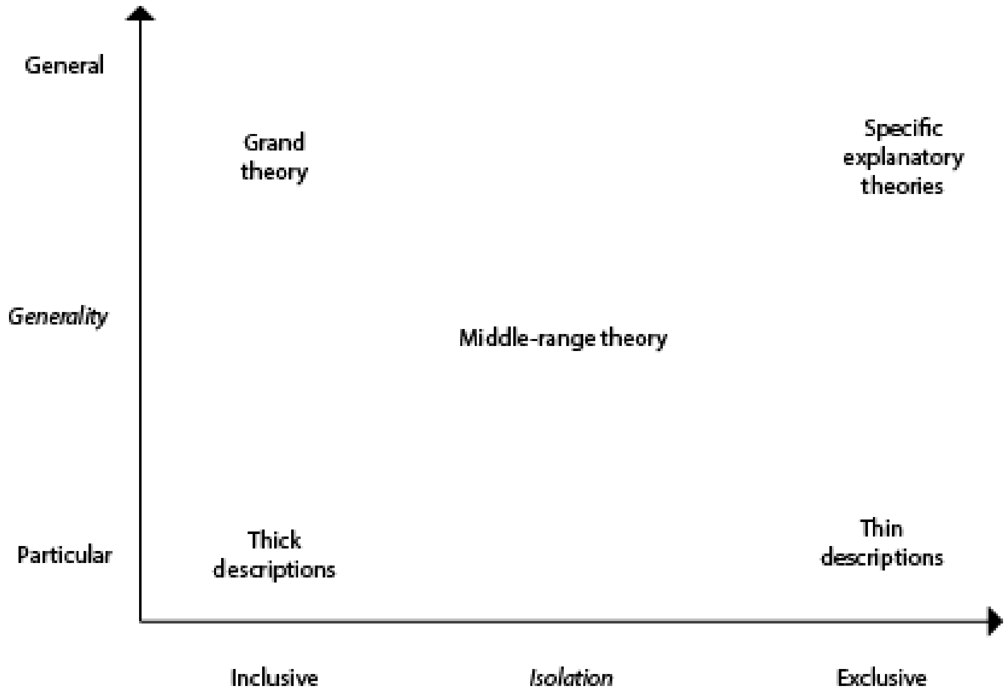

Figure 3-1 Generality, isolation, and the defining characteristics of middle range theories (Hedstörm and Udehn, 2009)

Middle range theories sit in the middle of the four extremes represented in the graph. Merton described them as "sufficiently abstract to deal with differing spheres of social behaviour and social structure, so that they transcend sheer description and empirical generalization" (Merton, 1968:68) in the explanandum dimension and he argued that the focus should be on "certain elements believed to be important and intentionally ignore others" (Hedström and Bearman, 2009:31) in the explanans dimension in order to provide partial explanations of delimited aspects of social phenomena. Middle range theories are therefore useful frameworks that allow a level of abstraction and generalisability but do not force the sort of reductionist account of social patterns, behaviours and structure that fundamentalist theories do:

> *"Middle-range theory involves abstractions, of course, but they are close enough to* observed data to be incorporated in propositions that permit empirical testing. [..] theories of the middle range hold the largest promise, provided that the search for them is coupled with a pervasive concern with consolidating special theories into more general sets of concepts and mutually consistent propositions" (Merton, 1949 in Merton, 2007:458)

3.3.1 Positioning MLP as a middle range theory

Mahoney's conceptualisation of general theory can be used to classify theories based on those two properties – causal agent and causal mechanism – and the scale at which the theory operates (Table 3-2). When discussing the foundations of MLP, Geels (2010) refers to what Mahoney calls general theory as ontology "ontologies postulate a certain causal agent and primary causal mechanism" (Geels, 2010:496). Geels also refers to MLP as a middle range theory and heuristic (for example, in Geels, 2007, 2010, 2011).

Table 3-2 Typology of general theories in historical sociology (adapted from Mahoney, 2004; Geels, 2010)

(General) Theory	**Domain/scale**	**Causal agent**	**Causal mechanism**
Functionalist theory	Macro	Social system	Needs/requisites
Rational choice theory	Micro	Individual	instrumental rationality
Power theory	Meso	Collective actor	Resources
Neo-Darwinian	(radically) micro	Gene	Contribution of fitness
Cultural theory	Meso and macro	Collectivity	Semiotic practices
Evolution	Micro/meso	Agents in population	Variation (search), selection, retention
Neo-institutional theory; structuralism	Macro and meso	Taken for granted deep structures (belief systems) (macro); field actors (meso)	Interactions, reproduced patterns, conflicting institutional logics, tensions. Actors can adapt and/or act strategically
Interpretivism/ constructivism	Micro	Individual actors with varying ideas and interpretations	Social interaction, construction of shared meaning, sense-making, learning, debates
Relationism	Meso	Network of ongoing relations	Interaction, co-construction, translation, alignment

MLP roots in evolution and interpretivism/constructivism domains (Geels (2010, 2011), and neo-institutionalism/structuralism (Geels, 2020), which are all general theories following Mahoney's conceptualisation (see table above).

In ***evolution theory***, the causal agent is a population of heterogeneous agents and the causal mechanisms are: variation, selection, and retention. In evolutionary economics[9] (Nelson and Winter, 1982) the causal agents are firms, institutions, and organisations. Causal agents are further conceptualised as boundedly rational agents. Causal mechanisms here entail market competition,

[9] Evolutionary economics is a sub-domain of evolution theories that is particularly relevant to socio-technical transitions

problem solving, and incremental and localised changes. In MLP those conceptualisations are expressed in the regime level, which describes the existing rules, regimes and actors in the dominant socio-technical system/regime.

Interpretivism/constructivism is the second ontological domain of MLP. In this ontology, the causal agents are individual actors. Geels (2010a, 2020) identifies Giddens' (1986) structuration as the interpretivist approach that is significant to the MLP foundation[10]. In structuration, actors are seen as knowledgeable agents who interpret rules in their given context. The causal mechanisms in this ontology are learning, and sense-making. In transitions, the beliefs (interpreted knowledge by agents) of incumbent actors are significant to the transition process. If the actors believe that the existing regime is the preferred trajectory, the activities of those actors (investments, policies, strategies) remain targeted towards incremental change within the regime level. However, a change in beliefs and search for a new solution can push those agents towards supporting niche-innovations and accelerating transitions.

The neo-institutional theory is built into MLP because transitions in most cases have a strong link to changes in institutions, which is the focus of neo-institutional theory. The neo-institutional theory has its roots in Meyer and Rowan's (1977) work on institutionalised organisations. The idea of rules and regimes has some relation to this framework (see the following section that elaborates on rules and regimes). The institutional theory allows accounting for not only economic but also institutional contexts (Geels, 2020) because, in institutional environments, organisations compete for social fitness rather than economic efficiency (Powell, 1991). The institutional theory also introduces the context of organisational fields, which is a concept that identifies an arena as a field in which various actors (and systems, and relations) operate. The organisational field approach has enabled a move within the neo-institutional framework "from understanding institutions as

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[10] Geels also acknowledges SCOT approach as particularly relevant interpretivist approach to transitions

things towards institutions as processes, enacted by actors via ***causal mechanisms*** [emphasis added]" (Davis and Marquis (2005) in Geels (2020)). The relationship between the ontological domains and the three general theories is demonstrated in Figure 3-2.

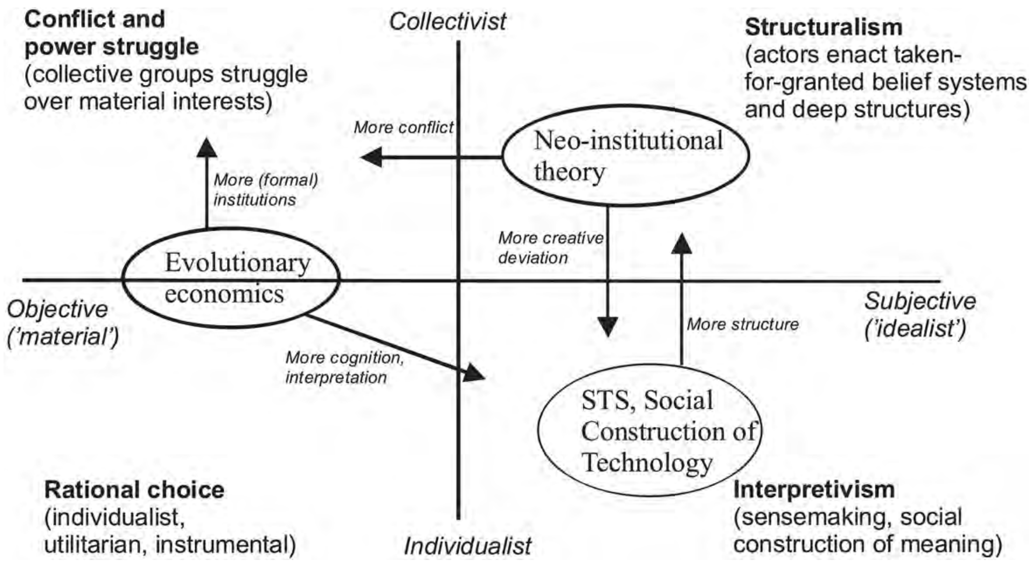


Figure 3-2 Positioning theories (in circles) with regard to ontological assumptions and characterizing recent conceptual elaborations (as arrows) from Geels (2020)

As a derivation of these three general theories, MLP is thus a middle-range theory. Geels (2010) further identifies this position as an *inter-ontology crossover*, in which theories aim to interplay between a number of ontologies, which is only possible when ontological assumptions are not too different (Geels, 2010). The inter-ontology position allows middle range theories, such as MLP, to explore dynamic mechanisms that align with various foundational arguments from a range of 'fitting' theories. Because MLP addresses transitions, which are multi-dimensional phenomena and involve a range of actors and structures, the inter-ontology crossover is a useful position to adapt.

3.4 MLP: clarification of agency, rules, regimes, systems, structures

The debate on structure and agency is central to social sciences (Archer, 1995). This section aims to unpack the foundational assumptions embedded in foundational ontologies of MLP in order to provide clarity on the use of terms and identify potential ambiguities that require further discussion and clarification. This will allow for clear identification of systems, structures, processes, boundaries and other elements in the empirical part of this thesis. This section consists of two parts. The first part identifies the base assumptions about structure and agency in MLP, which is based on structuration. The second part explains how notions of regime, system, and rules are employed in socio-technical transitions as means of explaining stability and change.

3.4.1 Agency and structure in socio-technical transitions

In empirical work on sustainability transitions, there is evidence of different actor typologies in transitions (systemic, institutional, governance, intermediary) with varying roles and functions that change over time and depend on the transition phase they are in (Fischer and Newig, 2016).

Geels (2020:3) defines agency as:

> *"…agency, which is defined as the capacity of an actor to act (Giddens and Sutton, 2014)… agency is thus more foundational than action, because it refers to core characteristics or properties of actors."*

He then later elaborates this in three points (Geels, 2020):

- The capacity to act can be related to many different characteristics or properties;
- He rejects methodological individualism[11] and calls it unworkable in socio-technical transitions;

[11] Geels acknowledges that both, individual actors and organised groups (firms, collectives, nations etc) have capacity to act. While the position of methodological individualism is not workable for the research question explored in this thesis, for researchers exploring transitions modelling

- Agency is situated in and shaped by structural contexts.

The structure-agency model in socio-technical transitions theory that Geels originally follows comes from Giddens's structuration theory, which is known as the duality of structure model (Figure 3-3). The diagram summarises how agency and structure recursively re-produce and transform practices – that is how a transition comes about in the MLP context. Lloyd (1991) summarises Giddens's account of structurationism as:

1. A central place is given to the conscious but decentred human agent who has social structuring power.
2. Neither the human agent nor society has primacy - each is constituted in and through recurrent practices.
3. Institutions are structured social practices that have a broad spatial and temporal extension. Structure as institutionalized relations is the outcome of the social practices it recursively organizes.
4. Social conduct and social structure are fundamentally temporal and specifically environmentally located.
5. The forces for social change have to be looked for in the causal interrelationships among action, consciousness, institutions, and structures.

In structuration theory understanding, the structure is internal to agents and it refers to internal rules. The structuring of socio-technical systems through the notion of rules is a central argument of MLP.

through agent-based model applications this is a useful and valid position to explore. It links with interest in modelling in analytical sociology, and could be a useful parallel path of inquiry in MLP and transitions research. This path of inquiry has already been addressed in literature (see, for instance, Bergman et al., 2008; Haxeltine et al., 2008; Holtz et al., 2015; McDowall and Geels, 2017; Papachristos, 2018; Hansen et al., 2019), however as that position is linked to methodological individualism, it is not relevant to this study.

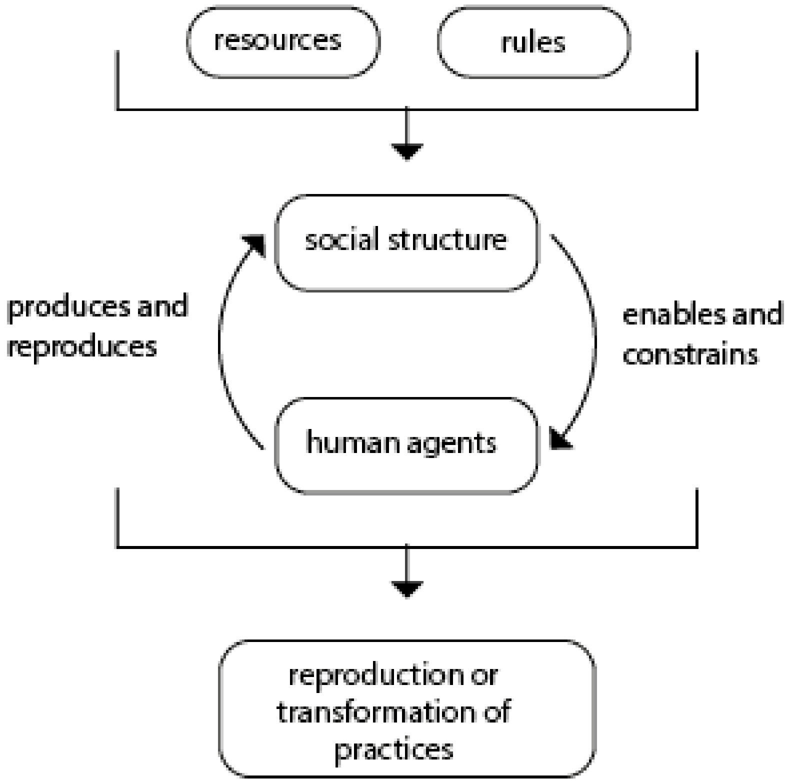


Figure 3-3 Giddens duality of structure model (by author)

3.4.2 Rules, regimes, system

Rules, regime, and system are central terms in transitions literature. They are used to describe stability and change in socio-technical systems.

The socio-technical system is the focus and also the unit of analysis in empirical transitions research. In MLP, both terms - socio-technical systems and socio-technical regimes – are fundamental to the approach. In empirical case studies, they are sometimes used interchangeably, however, each term carries a distinct meaning. Geels (2011:31) clarifies that:

- (Socio-technical) ***system*** "refers to tangible and measurable elements (such as artefacts, market shares, infrastructure, regulations, consumption patterns, public opinion)";

- (Socio-technical) ***regimes*** "refer to intangible and underlying deep structures (such as engineering beliefs, heuristics, rules of thumb, routines, standardized ways of doing things, policy paradigms, visions, promises, social expectations and norms)" and that it "accounts for the stability of an existing socio-technical system". So 'regime' is an interpretive analytical concept that invites the analyst to investigate what lies underneath the activities of actors who reproduce system elements. (Geels, 2011)

The definition of system in this instance, however, is confusing because it omits actors (or entities) such as organisations, institutions, or firms, but they are discussed in MLP case studies as being actively involved in transition processes. And the regimes definition is inconsistent with the distinct types of rules and institutions defined by Geels. In MLP institutions are understood also as rules, and those rules are what form the sociotechnical *regime* in MLP. The focus on rules can be traced back to Nelson and Winter (1982) who expressed them as cognitive routines that encourage incremental innovations. While this notion comes from evolutionary economics, it overlaps and is further elaborated by Geels (2004, 2020) from the neo-institutional perspective and organisational sociology specifically. Geels (2004, 2020) identifies three types of rules based on Scott (1995): regulative, normative, and cognitive (**Error! Reference source not found.**). Regulative rules are usually written in the documentation and enforced by the state or other institutions; normative roles are enacted through approval or disapproval by other individuals within a norm cycle (Sorrell, 2018); cognitive rules are the taken-for-granted beliefs and assumptions.

Table 3-3 Tree types of rules (institutions) by Geels (2004) based on Scott (1995)

	Regulative	**Normative**	**cognitive**
Basis of compliance	Expedience	Social obligation	familiarity
Mechanisms	Coercive	Normative pressure	Learning, imitation
Logic	Instrumentality	Appropriateness	orthodoxy
Basis of legitimacy	Legally sanctioned	Morally governed	Culturally supported
examples	Formal rules, laws, sanctions, protocols, standards, procedures	Values, norms, role expectations, duty, codes of conduct	Problem agendas, beliefs, bodies of knowledge, models of reality, categories, classifications, search heuristics

As stated earlier, in MLP theoretical literature, rules are referred to as ‘intangible’. Defining rules as intangible, however, does not fully align with the notion of normative and regulative rules. Furthermore, it can be argued that even cognitive rules, while less formal than the others, are still definable and somewhat tangible in the sense that they can be identified and even quantified. In terms of explanatory priority, MLP focuses on the socio-technical regime rather than the socio-technical system, which is implied in the definition of transitions as a shift from one regime to another. As Svensson and Nikoleris (2018) and Sorrell (2018) identify, the focus on the regime and inherently the rules that form and stabilise the regime, the 'technical' in 'socio-technical' is neglected, which also aligns with the overall criticism of SCOT and its over-focusing on agency and overemphasis of rules from previous sections. Undoubtedly, the material features (infrastructure, investments, etc) play a massive role in any socio-technical processes, especially in transitions in automobility.

The following section elaborates on these critiques and introduces a reframed view of socio-technical transitions that allows to better address ongoing transitions.

3.5 Multi-Level Perspective: approach, criticism, and usefulness for application in an ongoing socio-technical transition

This section introduces and discusses critiques on MLP from other domains. The aim of this section is to identify critiques and suggestions that are most applicable to the research question.

So far, this thesis has established that the Multi-Level Perspective (MLP) offers a multi-dimensional and multi-layered approach to studying a technological innovation (or a transition) that allows looking at complex interactions between multiple systems and scales. This, as Geels (2019:189) highlights, allows conceptualising the technological innovation as an entrance point for studying "society in the making". MLP looks at technology as a process of innovation, diffusion, social embedding, and decline, which in its approach embeds various social, cultural, political, legislative and other aspects of technological innovation and socio-technical processes.

Criticism and comments from a multi-disciplinary field have enabled discussion and applications to cover many research areas. Socio-technical transitions and MLP in transport studies have been emphasized and further developed in recent years. Geels (2012) showed a basic MLP description of transport systems, suggesting that alternative transition paths are possible for sustainable future mobility. He implies that transport planners and policymakers pin their hopes on technical solutions, which currently do not suggest a broad transformative change toward sustainable mobility, which reflects arguments presented by Pooley (2006) and Banister (2008, 2011a) in mobilities research. Therefore, the niche-regime influences and effects are crucial to understanding potential pathways towards sustainable urban mobility. There have been suggestions that MLP can be used to project innovations and transitions in order to identify policy, social and economic levers or turning points, which would then stimulate sustainable transitions (Bergman et al., 2008; Köhler et al., 2009; Whitmarsh, 2012). However, the area is lacking empirical work to challenge and test the theory. Transitions are characterised by nonlinearity, multilevel dynamics, co-evolution, emergence, and variation and selection (Loorbach et al., 2017), implying the need to think and analyse beyond linear causalities. Particularly in transitions relating to mobilities, where non-linear coevolution within different domains shapes and disrupts the systems, an approach that allows looking at multiple areas and scales is most relevant.

MLP emphasizes that the transitions start and evolve from niche innovations (Geels and Schot, 2007), suggesting the main drivers of transitions being 'outside' of the main system (or regime). However, this poses a challenge to the current goal-oriented sustainability narrative. In comparison, the former transitions (such as that from sail ships to steam ships) happened because of an innovation that offered something that the existing regime did not have (improved speed, less dependency on weather etc.) and 'took over' the regime by offering novel cost-effective solutions. Sustainability transitions, in order to be successful, might start from regime and landscape level pressure (for example, climate actions, and policies) and thus evolve new types of transition dynamics; therefore, the niche innovations might not always be the main driver of transitions. As argued earlier, there are suggestions that technological change is not always a successful driver for sustainable (or otherwise improved) change (Pooley et al., 2006).

The new mobilities paradigm has also challenged sustainability transitions theory by placing more emphasis on cultural aspects of change, as well as examining wider processes of socio-technical change beyond transportation (as technology), including mobile communications and securitization (Sheller and Urry, 2016). MLP engages strongly with policy and regulatory landscape (Verbong and Geels, 2007b; Kuzemko et al., 2016; Geels et al., 2017), however, the suggestion to involve more aspects of societal and cultural change as drivers or catalysts for transitions is a valuable critique that should be taken into consideration in socio-technical transitions studies.

Despite Geels (2012b) suggesting MLP is an actor-based approach, critiques from sociology have stated that MLP focuses too much on structure, rather than agency (Shove and Walker, 2010; Shove et al., 2012; Sheller and Urry, 2016). Furthermore, as identified in the previous section, when describing regimes, Geels often describes them as structures, which causes confusion regarding the clarity of roles of regime, structure and agency within the MLP framework. Such ambiguity in the use of terminology is also frequent in MLP empirical applications.

Earlier in this chapter structuration theory was identified as the foundational logic of structure and agency in MLP. In relation to studying an ongoing transition and studying transitions in transportation specifically this notion causes a number of potential shortcomings, which have been highlighted and discussed in literature by (Sorrell, 2018) and (Svensson and Nikoleris, 2018) and are summarised and elaborated on below:

1. In Giddens model (social) systems have no causal properties of their own (Sorrell, 2018), which can lead to the mischaracterisation of causal powers in transitions.
2. The way structure is accounted for in MLP overemphasises internal rules (Sorrell, 2018) – normative, regulative, and cognitive rules (discussed earlier in this chapter).
3. Overemphasis on external rules in turn undermines other powers and leads to under-emphasis on external social relations (Sorrell, 2018).
4. Structuration does not allow to adequately represent the artefactual aspect and power of sociotechnical systems (Sorrell, 2018; Svensson and Nikoleris, 2018). This in turn can lead to the mis-conceptualisation of causal mechanisms within the socio-technical regime and transition. For instance, in transportation studies, the lock-in mechanism brought about by extensive existing physical infrastructure is difficult to adequately represent in the structuration model.
5. Neglect or underrepresentation of (political) power (Smith et al., 2005; Avelino and Rotmans, 2009; Meadowcroft, 2009; Kern and Markard, 2016; Sorrell, 2018; Svensson and Nikoleris, 2018).
6. MLP relies too much on the narrative explanation, which loses the ability to objectively recognise driving mechanisms and causes (Svensson and Nikoleris, 2018). While this is consistent with traditional interpretivist

> ontology, it raises serious concerns about the knowledge claims that can be made about causal mechanisms and, most importantly, about causation claims that can be used to understand and inform ongoing (and future) transitions.

Another criticism of MLP is that it is more concerned with describing *how* transitions happen rather than the effect of the transitions. It has been criticised for being too descriptive and not analytical (Smith et al., 2005), which, as a result, leads to the analysis being too narrative-based. Furthermore, the narrative-based approach does not fully explain why and how the niche innovations succeed or fail. This critique is particularly relevant to the issue of ongoing transitions. Because it is an ongoing process, some outcomes are not yet observed and therefore the narrative approach might not be sufficient to fully understand an ongoing process.

From critiques identified in this chapter, the most significant discussion in relation to the research question of this thesis comes from a critical realism perspective, which can provide an alternative causality-driven approach to studying transitions through MLP. In comparison to other critiques, the critiques and suggestions from critical realism address the foundations of MLP, rather than suggest additions or corrections to specific parts of the framework. While the other critiques also offer useful insights, they are not as useful in allowing to form an approach towards studying an ongoing transition because they accept the base foundational arguments of MLP and structuration. Based on the arguments above, the MLP foundations on structuration theory are not optimal for a socio-technical analysis of an ongoing transition process. Furthermore, in more recent theoretical work, Geels (2020) also appears to move away from structuration and even introduces Archer's morphogenetic cycle as a possible direction for MLP. The morphogenetic cycle is based on critical realist epistemology and therefore offers the possibility to align MLP with the critical realist research paradigm and develop a framework based on causality (this is further addressed in the following chapter).

3.6 Summary

The critique of the MLP framework's applicability outlined in this chapter has significant implications for the study of the ongoing transition to AVs in the UK. The identified inconsistencies in defining "regime" and "system" could impede the accurate characterization of the existing transportation system and its constituent elements. This could, in turn, hinder the identification of appropriate interventions needed to direct the transition towards more sustainable trajectories. The overemphasis on rules and underemphasis on external social relations and material aspects of socio-technical systems may also limit the MLP framework's ability to identify the diverse range of factors that influence the transition to AV.

The identification of these criticisms underscores the need for a re-focused approach to the MLP framework, which emphasizes entities and causal mechanisms in explaining transitions. The proposed re-focused approach will be developed in the following chapter, taking into account the critique outlined in this chapter. The significance of these findings lies in their potential to improve the MLP framework's analytical power, particularly in studying complex socio-technical transitions such as the transition to autonomous vehicles. By addressing the identified criticisms, the re-focused approach will seek to enhance the framework's utility in guiding transitions towards more sustainable trajectories.

4 Towards a framework for studying ongoing socio-technical transitions: development of mechanisms–focused analytical framework

MLP was only introduced approximately two decades ago, and the literature on it is still evolving. This thesis provides a critical perspective on the limitations of its applicability for the study of ongoing transitions and develops an analytical framework to address some of the critiques. The critiques and the new SRPM analytical framework in this chapter are discussed in relation to and tested in the empirical part of this thesis, which investigates the ongoing transition to AVs in the UK. The transition is occurring in the wider sustainability discourse. This necessitates analysis beyond explanation and cognition of the process to theorise potential trajectories, outcomes and appropriate policy interventions. The use of the analytical framework to identify causal relationships and mechanisms within an ongoing transition aims to address this potential.

This chapter presents the argument for a re-focused MLP approach that is based on critical realism and causal mechanisms specifically. The chapter starts with a discussion on causation and its significance in the context of the research question. It then further elaborates on critical realism from a perspective that aligns it with the MLP framework and presents its core principles. Next, the MLP and CR theoretical models are mapped to demonstrate how the two domains align and how they can be interpreted from a socio-technical transitions perspective. Then, the notion of causal mechanisms is explicitly introduced and discussed in relation to the research question. Examples of known causal mechanisms that can be used as starting points for theorisation about transition processes are presented.

Finally, this chapter presents a new analytical framework – SRPM (developed by author) that is based on the criticism and discussion of MLP in this thesis and can be applied to study ongoing transitions. The chapter also presents a discussion on explicit implications and guidance for research methodology and empirical application of the framework.

4.1 Understanding views on causation

As demonstrated in the previous chapter, understanding 'why things happen' is a primary objective of many sociological domains. In socio-technical transitions the focus is on the explanation of how a change came about, which, while not explicitly stated in the literature, at its core is about causality. While causation has not been addressed as a primary research objective, there is a strong implication of such ambition in the theoretical literature. For example, Geels (2011:31) claims that "'regime' is an interpretive analytical concept that invites the analyst to investigate what lies underneath the activities of actors who reproduce system elements". The call to investigate 'what lies underneath' resonates with the notion of causal mechanisms that seek to 'open up the black box' (introduced later in this chapter). Despite this, in MLP research so far there is no significant emphasis put on causality as an explanatory approach.

To understand the position of MLP on causation it is worth looking at causation from a research paradigms perspective, because each paradigm carries implicit meanings and understandings of causation, or, in other words – why and how things happen, however, the notion of causation is often not recognised and discussed in the theoretical literature. Views on causation differ between research paradigms, and the key differences are summarised below.

Positivist research is guided by general universal laws, which therefore interpret causation as regularity, identified through induction and deduction, where one event is always followed by another and thus demonstrates the law (Mingers and Standing, 2017). Positivist research does not address explanation of why events happen. Interpretivism, in contrast, views the social world and events occurring in it as constituted by subjective human viewpoints and interpretation. In this context, causality is therefore used as a means of understanding actors views and actions in specific contexts and events. Transitions research and MLP specifically typically align with the interpretivist/constructivist research paradigm, which views the social world as constructed by humans and inherently subjective. This however raises questions about generalised claims that can be made from interpretivist research. MLP follows abduction logic of inquiry or research strategy, which is consistent with the interpretivist research paradigm and seeks to test and derive social scientific theories from social actors' accounts (Blaikie, 2009). As illustrated in this thesis so far, MLP theorises about transition processes and offers a conceptualisation of processes that can be seen as generalised – such as stability and destabilization of socio-technical regimes, niche acceleration, and others. This contradiction is also highlighted by Mingers and Standing, who propose a mechanism-based approach to causation in interpretivist research. Mingers and Standing (2017) make a further case for a critical realist understanding of causation, which echoes points made by Sorrell (2018) and Svensson and Nikoleris (2018) specifically in MLP and transitions context. The objective to re-focus MLP to causation and causal mechanisms specifically falls into the realm of critical realism.

Before addressing causal mechanisms later in this chapter, it is worth noting that there are two distinct positions on causation in social sciences ontologically (Mahoney, 2004; Goertz and Mahoney, 2012; Beach and Pedersen, 2013; Biesbroek et al., 2017):

1. Causation as a regular association. From this perspective, causation is understood as a regular pattern where X → Y without any notion of the causal process through which X produces Y. In this model, the researcher speculates about the observed association by relating it to earlier studies or general concepts from literature.

2. Causation rooted in causal/generative[12] mechanisms. In this approach, X produces Y through a particular causal mechanism that can be

[12] Causal and generative mechanisms are used interchangeably in this thesis. Causal mechanisms are more common in analytical sociology literature, while generative mechanisms come

demonstrated. Here, causality is not just a description of a certain variable (X), but instead it requires a demonstration of the dynamic and interactive influence of processes that produce the observed outcome in a specific temporal context under specific conditions (Biesbroek et al., 2017). This position is further applied in this thesis and is elaborated on in the following sections.

To summarise, critical realism offers a more explicit positioning towards causal mechanisms, while MLP (from the interpretivist paradigm position) is not explicit about understanding causation and uses it more contextually. Being explicit about causation in socio-technical transitions would enable a more analytical view of how transitions happen and being explicit about causal mechanisms would enable theorisation about the generalisability of findings and claims. To align MLP with critical realism the following areas are addressed next in this chapter:

1. Aligning MLP analytical levels with critical realism ontological domains (section 4.2), re-defining the notion of regimes (section 4.3), and alignment with the morphogenetic cycle model (section 4.4), which offers a useful view of structure in a process of change;
2. Establish what causal mechanisms are, what causal mechanisms have been identified in the literature, and how they can be approached in MLP context (section 4.5).

4.2 Mapping MLP and CR concepts

The previous section identified that critical realism offers a view on causation that has the potential to be successfully employed in transitions research. The critical realism (CR) approach re-focuses the primary research objective on causal mechanisms. This section introduces CR as a research philosophy and maps it against MLP thus demonstrating the applicability of CR to MLP research.

from critical realism literature. In this thesis, they both refer to the same idea of causal mechanisms that is identified further in this chapter.

4.2.1 Introducing critical realism

CR is a philosophical research approach to understanding the world developed by Roy Bhaskar. CR ontology stratifies reality in three levels (Figure 4-1):

Empirical level: the level in which we experience events and observe phenomena.

Actual level: events occur, whether observed or not.

Real level: at this level causal mechanisms and structures that cause events on the empirical level to happen exist.

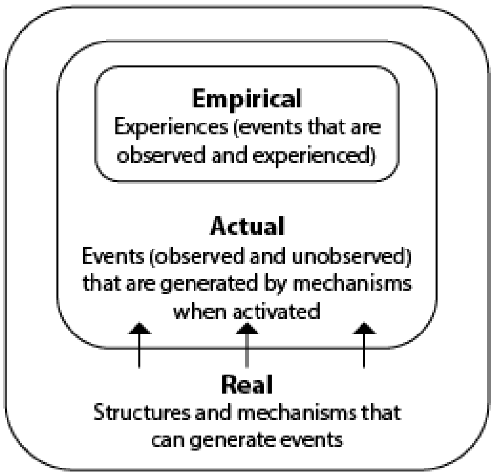


Figure 4-1 Critical Realism domains (source: Mingers (2004))

The notion of the 'real' level implies the existence of a world independent of our experiences and social structures and actors. The mechanisms on the real level produce events that can be observed at the empirical level. Bhaskar points out that "causal mechanisms exist only in virtue of the activities they govern and cannot be empirically identified independently of them" (Bhaskar (1979:49) in Fletcher (2017:183)).

In the transitions context, this illustrates how certain practices and structures, and systems are created, reinforced, and transformed over time. A structure is "a set of internally related objects and practices" (Sayer, 1992:92). This aligns further with Archer's (1995) conceptualisation of the morphogenetic cycle, in which structure and agency shape each other (see the following section for elaborations on the morphogenetic cycle). Existing structures constrain and/or enable actions and activities of agents, and agents transform and/or reproduce the existing systems. A structure always predates the actions that transform the structure (Archer, 1995).

The notion of systems here also links to the complexity theories framework and complex systems specifically (section 2.4.1). Systems theory recognizes emergence as a fundamental feature of complex systems and seeks to understand how emergent properties arise from the interactions between system components. Systems theory proposes a method of modelling complex entities that result from the interactions between multiple components. This involves abstracting certain structural details and focusing on the dynamics that define the system's characteristic functions, properties, and relationships (Laszlo and Krippner, n.d.). The concept of systems theory, specifically the method of reduction to dynamics, is relevant to socio-technical transition research. By abstracting certain details and focusing on the dynamics of the system, systems theory can provide insights into the processes of socio-technical change and how such transitions can be facilitated. Systems theory applied to socio-technical transition research highlights the interplay between structural properties and individual agency. Structures can constrain or enable agency, shaping the trajectory of transitions. Meanwhile, agents such as policymakers, industry actors, and civil society organizations can change the structure of the system over time, linking back to the morphogenetic cycle.

Ontological and methodological separation of structure and agency is a central ontological notion of this thesis because it accounts for existing structures with causal powers and causal powers that entities have, which interact with the structures over time. Entities can be individual actors or sets of actors – structures – that have different causal powers to those of individuals. This relates to another key ontological argument that is central to CR ontology, which is emergence (Wynn and

Williams, 2012). Entities at a higher level cannot be understood simply as a summative action of lower-level entities. Therefore, it is important to acknowledge the level of analysis in research design. For example, when studying a phenomenon at organisations level, the observed outcomes cannot be traced to individuals who make up the organisations because the higher-level causal powers are not reducible to lower-level entities. In socio-technical transitions research, the unit of analysis is a socio-technical system(Köhler et al., 2019). Therefore, to investigate a transition process, the system needs to be identified and analysed at the appropriate level that accounts for the emergent properties of the system and its parts. An emergent entity can be expressed as consisting of three core parts: 1) the parts themselves; 2) the necessary relations between the parts; 3) the causal properties it has as a result of 1) and 2) (Sorrell, 2018).

Emergent properties of structures and entities are expressed through necessary relations between them. CR distinguishes between necessary and contingent relations between entities. In necessary relations, the object is dependent on its relation to the other. Sorrel (2018) explains this with Sayer's (1992) example of tenant and landlord: a person or an organisation cannot be a tenant without a landlord, therefore this relationship between the two entities is necessary. Following this, structure in CR can be explained as the set of the necessary relations between the entities (or parts of an entity). Contingent relations, on the other hand, are "neither necessary nor impossible" (Sayer, 1992:89). These relationships may affect one another but how or whether causal powers are actualised will depend on a variety of factors. In CR ontology the contingent conditions and relations may bring about certain effects and events, however, it will not provide regular association. This provides a crucial foundation for transitions research and can be applied to explain how structures can continue to exist even when their constituents undergo certain changes. As long as those changes are not directly relevant – or necessary – for the transition to happen, the structure will not lose its integrity. Simultaneously, external conditions can still affect the behaviours and actions of the system entities. In CR ontology events are understood to be the results of operations of multiple causal mechanisms that are associated with the contingent combinations of multiple entities (Sorrell, 2018). While CR authors have produced a vast theoretical base and the empirical applications are rather sparse, Bhaskar (2014:v) reflected that “applied or practical critical realism [..] should be the heartbeat of CR.” This can both, help researchers to better understand CR by immersing themselves in an applied study and to produce empirical findings that build our understanding of the word.

4.2.2 Aligning CR and MLP domains

MLP contextualises socio-technical systems and socio-technical transitions in three analytical levels – landscape, regime, and niche. The focal level of analysis is the “regime” level that is seen as consisting of entities that exist in a specific configuration – the system. The other two levels – landscape and niche – are seen as external to the socio-technical regime but with the ability to impact events and trajectories of transitions.

The mapping of the two (Figure 4-2 and Figure 4-3) demonstrate that, while the domains and concepts come from different interpretations of reality and events, some meaningful parallels can be drawn and CR can be used to conceptualise socio-technical systems. The diagrams demonstrate that:

- Both interpretations acknowledge external/higher contexts and powers that have impacts on the observed phenomena. In MLP those are conceptualised as landscape developments and relate to the exogenous context that, while not directly having a role in the socio-technical system, impacts its developments and trajectories. In CR, the domain of real describes the level at which the causal mechanisms exist. The real level can also be seen as exogenous to the observed phenomena. While the meaning of this level in the two compared domains differs, it evidences that both account for conditions that exist outside of the observed phenomena (or system), but simultaneously have an impact on events that are observed.
- The regime level in MLP refers to the dominant socio-technical system, which is made up of relevant social groups and actors in a specific configuration that seeks to maintain stability within the system. In CR, the level of actual refers to events that happen, whether observed or not. Again, while not directly equal, comparisons and parallels can be drawn between

the two. Both describe events and systems that exist in the real world and can be observed.

- The niche level in MLP describes disruptive innovations with the potential to re-configure the dominant socio-technical system. In CR the empirical level refers to the phenomena that are observed. At this level, there is a direct link between the two domains. In both the research is focused on an observed phenomenon, which in socio-technical transitions context is the specific observed transition. In this context, MLP is particularly useful because it offers a theoretical way of abstracting the observed real-world phenomena.

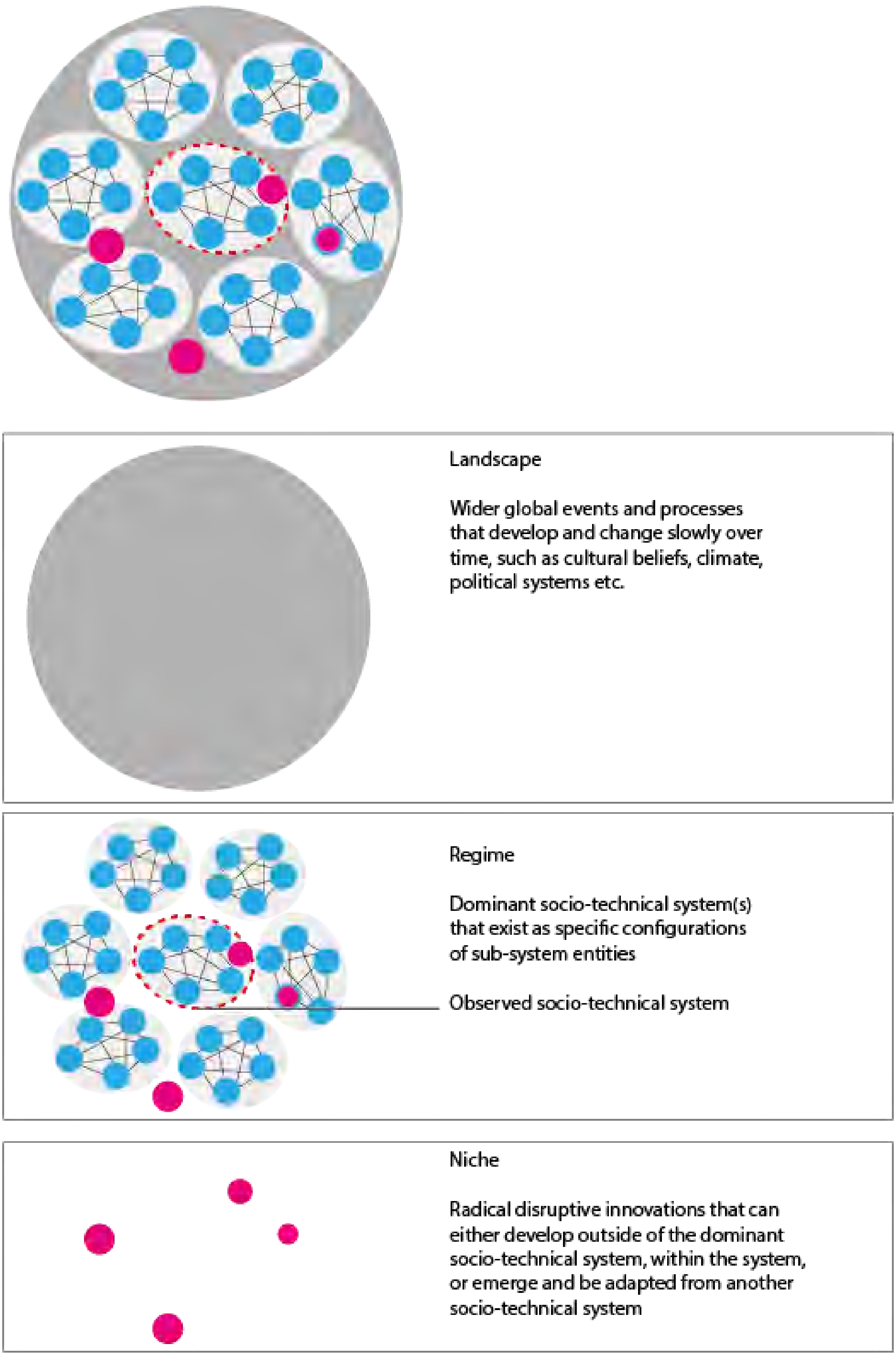
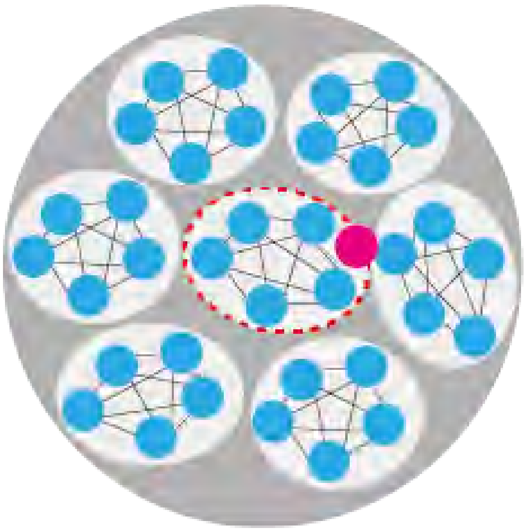
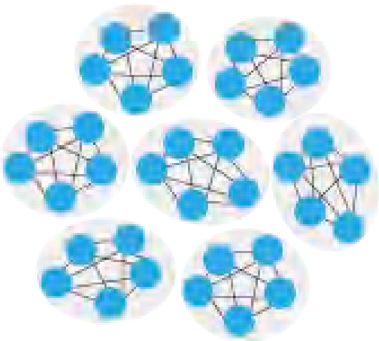


Figure 4-2 MLP analytical levels (by author based on Geels (2002))



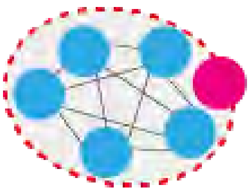
Real

Structures, mechanisms and powers that produce the events in the world



Actual

Factual events (observed and unobserved) that happen, whether observed or not. Enabled and constrained by mechanisms and structures that exist in the Real domain



Empirical

Observed events; phenomena that is the research subject

Figure 4-3 Critical level ontological domains mapped (by author)

The mapping also reveals the key ontological challenge between the two, which is the status of structure. This is because MLP builds upon structuration's interpretation of structure, while CR interprets structure as relational among social entities and as an autonomous existence at higher levels. Figure 4-4 shows a simplified comparison between the two. In MLP structure is seen as rules, institutions, and resources that govern the regime and its actors. And, in turn, agents enact, create and change those conditions. The duality of structure, which comes from structuration (see the previous chapter for discussion) implies that agency cannot be analytically separated from structure.

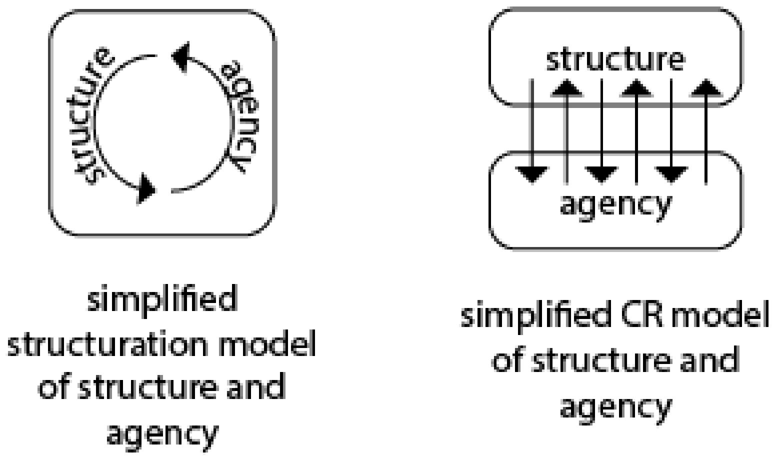


Figure 4-4 Simplified comparison of relationships of structure and agency in structuration and in critical realism (by author)

In CR structure is seen as an analytically autonomous entity (Archer and Archer, 1982), meaning that it can be separated from agency despite it being inherently linked to agency. This is due to CR ontological position of emergence. This has two implications:

- Firstly, these nested hierarchies create higher-level structures that in turn have irreducible 'downward causation' powers. In order to conceptualise and analyse those powers, it is necessary to understand them as autonomous entities.
- Secondly, higher-level outcomes cannot be reduced to individual actions of lower-level entities.

The notions of nested hierarchy and emergent properties of structures are a useful position to adapt for MLP studies because they allow to better conceptualise powers at different levels, while the traditional MLP model has a tendency to overemphasise internal rules as they are not analytically separable from actors (Sorrell, 2018).

This section has demonstrated that the CR approach can be aligned with MLP and can be explored to re-focus MLP towards the exploration and identification of causal mechanisms.

4.3 Applying critical realism interpretation of socio-technical systems to MLP: redefining 'regimes' to systems

Following the discussion in the previous chapter about key criticisms of MLP and the illustration of CR and MLP mapping in the previous section, and Sorrell's (2018) suggestion, I 'drop' the notion of regime and will use instead ***socio-technical system*** as the focal unit of analysis and as a theoretical framework, which contains in itself the rules and norms, (material and human) entities, and the relationships between them. Following that, a socio-technical system is defined as:

> *"[socio-technical systems consist of] emergent entities whose causal properties derive from necessary relationships between their constituent parts."* (Sorrell, 2018)

This definition of a socio-technical system:

- Allows for a broader interpretation of the inner workings of a socio-technical system, including causal powers of non-human and non-institutional actors.
- And it responds to critiques outlined earlier that criticised MLP for being too agency-centric and too focused on regime rules in its explanation of stability and transition processes.

4.4 Aligning MLP and the morphogenetic cycle

CR argues for three core positions on explanatory adequacy (Archer, 2020):

1. Ontological realism. This is a position that accepts that there is a real world that exists independently of our perceptions, theories, and constructions (Maxwell, 2011).
2. Epistemic relativism. Our understanding of the world is constructed from our own standpoint, and it is impossible to obtain a fully 'real' or 'correct' understanding of the world (Sayer, 1992; Easton, 2010; Owens, 2011).
3. Judgemental rationality. This position allows and encourages the exploration of various theories and frameworks in order to best represent the domain of 'real' (Bhaskar et al., 2010).

The causal mechanisms in CR philosophy exist in the 'real' level or domain. Therefore, the objective of any CR research is geared towards discovering and proving what causal mechanisms produced the observed outcome.

The morphogenetic cycle is a theoretical and analytical concept in CR introduced by Margaret Archer. She explains it as:

> *"The 'morpho' element is an acknowledgement that society has no pre-set form or preferred state: the 'genetic' part is a recognition that it takes its shape from, and is formed by, agents, originating from the intended and unintended consequences of their activities." (Archer, 1995:5)*

The approach provides a way of interpreting processes of change, such as socio-technical transitions, as a configuration of structures and agents that happen over time and at specific time periods, providing unique complex spatio-temporal contexts and outcomes. This links back to the discussion on path dependency in chapter 2 and historical sociology in chapter 3, which both also acknowledge that contemporary observations are constrained and conditioned by past events and developments.

While Geels (2020) has suggested the morphogenetic approach as a means of conceptualising and undertaking transitions and transition trajectories, he calls it 'complementary' to understanding agency. This implies that the framework could be aligned with Gidden's model of structure and agency or used to expand or extend the framework. However, this does not adequately acknowledge the fundamental differences between the two approaches at an ontological level since the two approaches treat structure and agency differently, which in turn affects how causation and transition are formulated and understood. While both approaches make assumptions of agency and structure being interlinked (Wynn and Williams, 2012), in Archer's critical realism model, (social) structure exists independently of human agency. Hence, while CR model also acknowledges that structure is a product of human agency, it treats it as a separate entity.

In contrast with Gidden's duality of structure and agency, the morphogenetic cycle approach is rooted in the argument that structure and agency "operate over different time periods is based on two simple propositions: that structure necessarily pre-dates the action(s) which transform it; and that structural elaboration necessarily post-dates those actions" (Archer, 1995:76), which is summarised in Figure 4-5. In this approach structure and agency themselves emerge, intertwine, and redefine one another.

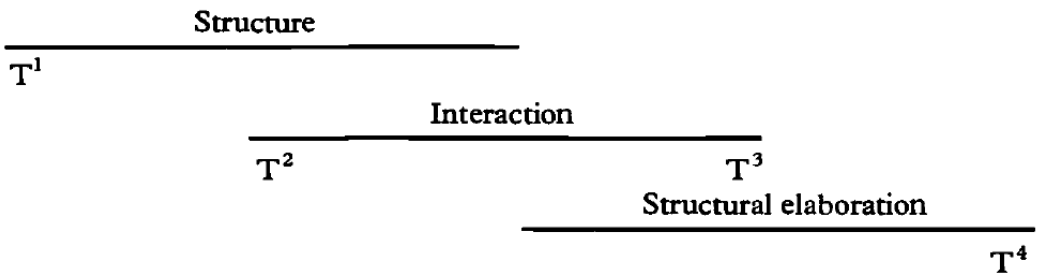


Figure 4-5 The morphogenetic sequence by M. Archer (1995)

In the transitions context, Geels offers an illustration of the morphogenetic cycle (Figure 4-6) which he calls field-level trajectories. As illustrated, he aligns the morphogenetic cycle with the evolution theory and the specific mechanisms (selection, variation, retention), which offers a meta-position in which evolutionary theory is aligned with the institutional theory. This cycle can be used as a single set of moves that reproduce and change institutions (institutions in this context refer to the regime level and rules in MLP). And, series or chains of such sequences can be seen as trajectories of change in analysis. The morphogenetic model allows capturing temporality and to understand how structure shapes, conditions, and enables agency. In this model, the specific actions and consequences between the structure and agency are exercised through mechanisms. An empirical example of the application of this in transportation studies is a study by Melia (2020) who demonstrates that the transport social structure predates and affects the actions of temporary social agents.

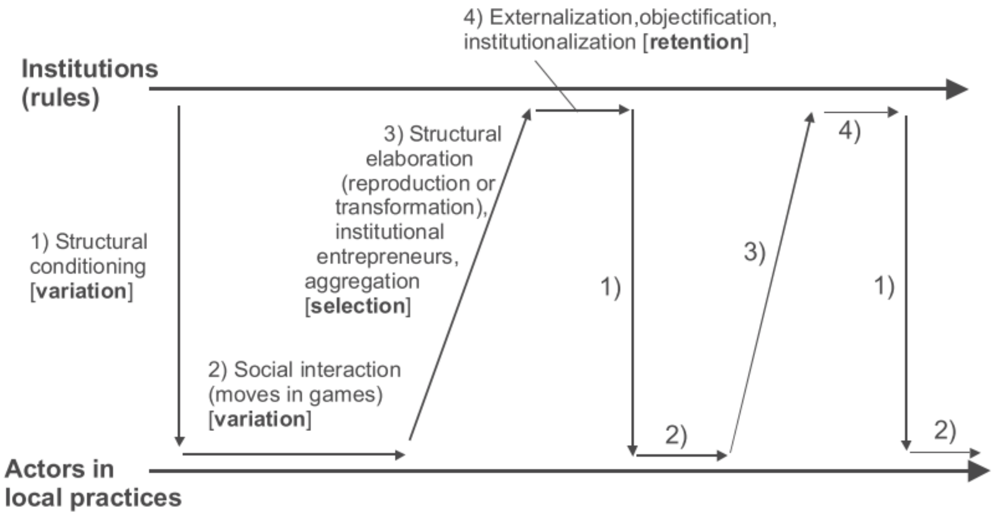


Figure 4-6 Geels (2020) example of the morphogenetic cycle

4.5 Causal mechanisms

As identified earlier in this chapter and the previous chapter, causal mechanisms form a core part of a general theory for a mid-range theory that is MLP. The call to identify and theorise transition mechanisms was identified early on (Geels, 2002) but very little research followed up (Geels and Schot, 2017). As stated in the previous sections, the idea of mechanisms has been mostly implicit, and I argue that it would be beneficial to the framework to refocus MLP towards explicit identification of causal mechanisms because such approach allows a more nuanced understanding of transition processes and dynamics, which is particularly useful in ongoing processes where the final outcome has not yet manifested.

Beach (2016) suggests that explicit focusing on causal mechanisms will result in:

- Better causal theories.
- Actual empirical tracing of causal processes in case studies, which enables researchers to draw stronger inferences from the observations.

Both arguments are relevant and applicable to the research question of this thesis.

While causal mechanisms are integral to many areas in social sciences and sociology specifically and have been developing within the relevant domains (Gorski, 2013), the conceptualisation of mechanisms differs between scholars and domains. This section covers the different notions of causal mechanisms in social sciences/sociology and positions causal mechanisms in MLP.

Mechanism-based view on causality has developed within analytical sociology (see chapter 3) and in critical realism. From a mechanism perspective, events (or transitions, or changes) occur as a result of causal mechanisms that have particular properties and causal powers (Mingers and Standing, 2017). There is, however, no unified consensus on what mechanisms are in literature. Multiple authors have reviewed definitions and approaches (see, for example, Hedström and Bearman (2009) and Kaidesoja (2013)). Gross (2009) identifies five conceptualisations of mechanisms:

1. Mechanisms as not necessarily observable structures and processes.
2. Mechanisms as observable processes that do not require the positioning of motives.
3. Mechanisms as lower-order social processes.
4. Mechanisms as triggerable causal powers.
5. Mechanisms as transforming events.

He then summarises the main points of agreement among those approaches, which I elaborate on below:

1. Social mechanisms are causal. If X -> Y, then the mechanism is the process/action/means by which X cause Y to happen, rather than just an observation. The difference between a mechanism and causal law (positivism) approach and corelation analysis is that the mechanism must explicitly demonstrate how X caused Y.
2. Social mechanisms unfold over time. This implies that mechanisms operate in a temporal context and can take short and long periods of time to unfold.
3. Social mechanisms generality. This means that theoretically same mechanisms always produce the same outputs. However, in social systems, which are open systems and bounded by spatio-temporality, mechanisms are not always invoked. This links to the previous point about mechanisms happening over time and at a specific time and also to the earlier discussion on Archer's morphogenetic cycle, which demonstrates that structure conditions and bounds the agency of agents, who in turn reshape the structure.
4. Mechanisms are composed of 'lower order' elements that are the aggregation of the phenomenon in question. Most mechanisms approaches will identify the components of the causal chain. In analytical sociology, the doctrine of methodological individualism dictates that only an individual can have agency and causal powers. However, in critical realism (and MLP), which denies methodological individualism, a multi-agent entity such as an institution possesses causal powers of its own, which are emergent meaning that the causal powers of the institution cannot be broken down to the individuals who make up the institution. So, for CR research, this point should be approached as the identification of entities with causal powers, but the conceptualisation of them as 'lower order' is problematic.

A mechanism view on causation is often described in the literature as "opening the black box" (Astbury and Leeuw, 2010; Imai et al., 2011; Stolz, 2016; Biesbroek et al., 2017), being about the "nuts and bolts" (Lawson, 2006; Gross et al., 2009) or "cogs and wheels" (Beach and Pedersen, 2013, 2018) of the observed (social) process.

While there are differences between analytical sociology's and CR interpretations of mechanisms, in empirical research the focus is on causality, which can be expressed through ideas from multiple domains. A key difference between analytical sociology and CR is the ontological view on causation. While analytical sociology advocates methodological individualism (Hedström and Swedberg, 1996), CR advocates a social ontologism position in that it recognises the nonreductive reality of emergent social entities (Gross et al., 2009). However, there are also agreements between the two positions. Both interpretations of causal mechanisms agree that social mechanisms are causal in nature[13] and that they unfold over time.

4.6 Known mechanisms from literature: a starting point for empirical research

Mechanism-based research has a significant body of literature, especially in information systems and nursing. Many mechanisms have therefore already been identified, which can serve as a starting point for a mechanism-based explanatory analysis. Some mechanisms link to specific theoretical domains and theories that the authors have applied. Selected ones are demonstrated in this section. Mechanisms such as the lock-in mechanism and path dependence are embedded in the theoretical model of transitions and MLP and describe the existing socio-technical system. Further, the general theories that form the basis of MLP each

[13] In an example X -> Y, the entities X and Y are not causal mechanisms themselves, but the process that leads from X to Y.

contain theorisations about causal mechanisms and causal actors. The table below summarises known mechanisms from literature, which were identified from:

- Transitions literature.
- Literature that links directly to socio-technical transitions (for example, authors offering and demonstrating causal mechanisms for another domain).
- Some CR literature (that is relevant to the research question).
- MLP case studies.
- Case studies from other domains that are relevant to transitions, for example, from case studies in information systems research and management research.

Table 4-1 summarises mechanisms identified in literature (Eyerman and Jamison, 1991; Tilly, 2006; Geels, 2010b, 2020; Bygstad and Munkvold, 2011; Melia and Melia, 2020) and categorises them by type. As shown, mechanism can have stabilising properties (such as lock-in and path dependence), they can describe change through internal, external, and evolutionary mechanisms. Relational, social, and behavioural aspects of socio-technical systems can also have causal powers.

Table 4-1 Mechanisms identified in the relevant literature (categorised by author)

Stabilising mechanisms	Relational mechanisms	Internal change mechanisms	Cognitive/ social/ behavioural mechanisms	Framing mechanisms	Evolutionary mechanisms
Lock-in	Coercive, sanctions, regulations	'internal push'	Social enactment	Cultural framing	Selection
Path dependency	Normative pressure	(self reinforcing) innovation mechanism	Sense-making	Discursive action / discursive struggles	Variation
Regime stabilisation	Ally; attack; subordinate; appease	(self reinforcing) adoption mechanism	Cognitive learning	Reorientation / strategic reorientation	Retention
	Disappear; enrich; expand; disintegrate	Mimetic, learning, imitation	Behavioural learning	Rhetorical closure mechanism	
		Recognise; understand; reinterpret; classify	Public opinion mechanism	Redefinition closure mechanism	
		self-fulfilling prophecy			

The mechanisms identified come from the literature that relates to the positioning of the research question of this thesis and can therefore be used as a starting point to theorise about the observed processes when analysing the ongoing transition to AVs in the UK.

4.7 Towards explicit causal mechanisms in socio-technical transitions research

What should be the primary purpose of a socio-technical transitions study and how should it be approached?

Geels (2011) identifies that MLP employs process theory as its explanatory style. Process theories focus on temporal sequences and identification of the critical events (Beach and Pedersen, 2013). Process tracing is a common methodology in MLP case studies, and it aligns with research in historical sociology that is concerned with historical explanation (Mahoney, 2015). It allows demonstration of how actors, events, and actions contributed to the observed outcome. Causality is sometimes referred to as mechanisms (see, for example, Mahoney's (2015) discussion on process tracing in historic explanation), however, in MLP literature the two have not been thoroughly discussed. The process theory approach in MLP has so far emphasised the empirical events rather than the causal underlying structures, processes, events, and mechanisms.

Other than suggestions toward agent-based modelling (Bergman et al., 2008; Papachristos et al., 2013; Holtz et al., 2015; McDowall and Geels, 2017; Moallemi and Köhler, 2019) and authors arguing for a critical realism mechanism-based explanation (Papachristos and Adamides, 2016; Sorrell, 2018; Svensson and Nikoleris, 2018), the process theory and narrative approach are the dominant approaches in MLP studies. Geels (2011) emphasises the specificity of causal narratives, which need to be guided by conceptual and theoretical frameworks, meaning that simply piecing events together is not sufficient to study transitions. In order to apply them appropriately, the researcher should poses "both substantive knowledge of the empirical domain and theoretical sensitivity (and interpretive creativity) that help the analyst 'see' interesting patterns and mechanisms" (Geels, 2011). While the call for interpretive creativity aligns with the interpretivist/constructionist research paradigm, there is also an implication to search for patterns and mechanisms, which again aligns with the critical realist research paradigm.

Refocusing MLP towards the search of causal mechanisms can not only identify mechanisms at play in the transition in question but also challenge assumptions of change. For example, Melia (2020) applied CR to the transport policy making process in the UK and found that, for example, economic factors alone are not sufficient to explain changes in transport policy despite that being the assumption in literature and empirical data (interviews). MLP approach has already established patterns of socio-technical change (socio-technical pathways) and, while they have a solid evidence base in literature, aligning observed processes with known theories alone does not allow theorisation about patterns and mechanisms previously unobserved. Looking for causal mechanisms in an ongoing transition process provides an opportunity to not only identify causal mechanisms but also to add to the theoretical understanding of socio-technical transitions related to new patterns and mechanisms of change.

4.7.1 Practical application of mechanism-based analysis

In terms of the practical application of mechanisms, it is not always empirically possible to identify all components of the causal mechanisms in the observed phenomena. Machamer (2000) for this reason introduces useful concepts of mechanism schema and mechanism sketch.

Mechanism schema is a "truncated abstract description of a mechanism that can be filled with descriptions of known component parts and activities" (Machamer et al., 2000:15). This can be expressed diagrammatically as a sequence that identifies the entities and actions forming the mechanism(s) (Figure 4-7 and Figure 4-8). While not always defined as a mechanism schema, a similar type of representation can be found in case studies that employ critical realism and mechanisms approach, such as the innovation mechanism in Figure 4-8. Mechanism schema contains a degree of abstraction. For example, by removing a specific detail of a case study or aligning an action with a theoretical construct.

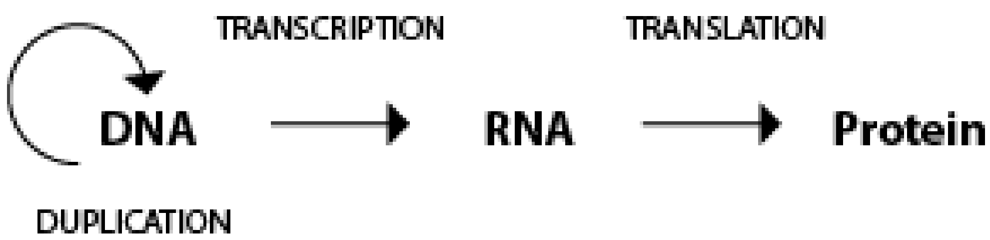


Figure 4-7 Example of a mechanism schema based on Watson (1965) in Machamer et al. (2000)

The mechanism sketch, in contrast, is defined by Machamer et al. (2000:18) as "an abstraction for which bottom out entities and activities cannot (yet) be supplied or which contains gaps in its stages". Beach (2016) suggests this might often be the stage to which real-world research gets to. The sketch then helps to identify further areas of inquiry to address. Because this thesis investigates an ongoing phenomenon with many unknowns, the mechanism sketch is a useful workable concept to employ. Mechanism sketch and schemata approach is applied in Chapter 9 of this thesis for the identification of causal mechanisms in the ongoing

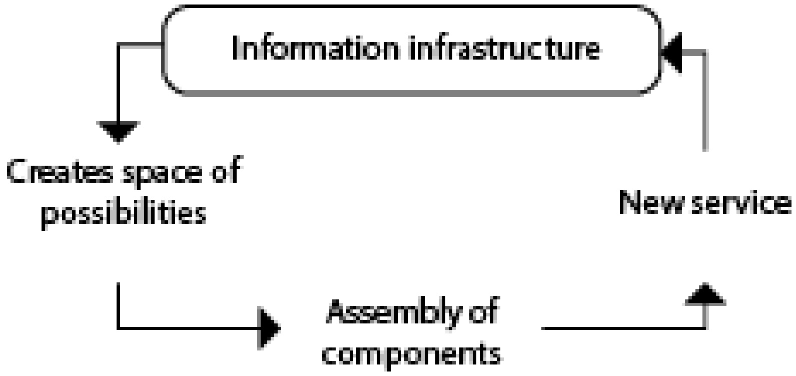


Figure 4-8 Example of a mechanism schema in social sciences by Bygstad and Munkvold (2011)

transition to AVs in the UK to illustrate mechanisms and components of mechanisms that have been identified in this transition.

4.7.2 Empirical application of CR research strategy

In terms of empirical application and research methods, CR literature offers a specific methodological framework but does not rely on a specific set of methods. In theoretical literature Bhaskar (2010) introduced the analytical process for CR known as the RRREIC model, which stands for: Resolution, Redescription, Retroduction, Elimination, Identification and Correction. Resolution refers to the identification of elements making up the complex phenomena observed. Redescription refers to theoretical redescription, and retroduction is concerned with identifying causal mechanisms. Elimination, identification, and correction refer to the iterative process through which explanations are tested and validated until the causal mechanisms are found. This however is a high-level theoretical concept rather than a step-by-step guide and provides a conceptualisation of how CR research design should be approached with allowing flexibility and space for interventions, adaptations and application of various methods and data.

Retroduction is the key 'step' of the research process in CR research. Retroduction requires identifying and verifying the existence of mechanisms which are found to have generated the observed events (Wynn and Williams, 2012). However, there is a lack of clear instruction on how to approach this step. Drawing on Lawson (1997:212) in Melia (2020:287) who assesses that "it is likely to operate under a logic of analogy or metaphor and to draw heavily on the investigator's perspective, beliefs and experience" and on other author's application of CR research framework (see the previous chapter) retroduction can be seen as a recursive process, which in itself embeds the *Elimination, Identification,* and *Correction* steps from Bhaskar's RRREIC model. While the description of the process is linear, multiple iterations and re-examination of facts and findings are required throughout the process. Explanations need to be "theoretically informed and empirically substantiated" (Brannan et al., 2016:15).

Because of the lack of instruction on how to tackle the retroduction stage in literature, this step draws guidance from selected CR case studies and follows steps that other authors have successfully applied in their research on case studies that have relevance to the research question of this thesis – Fletcher (2017), Melia (2020), Naess (2012), Wynn and Williams (2012).

As a step-by-step process, multiple models exist and have been evolved, applied, and tested by researchers. Table 4-2 shows the summary of four relevant examples to this thesis research question. While there are differences between the identified empirical applications, there are methodological steps that can be distilled and appropriated for the research question of this thesis. All approaches include the abduction step, which contextualises the observed phenomenon within a selected theoretical framework. Retroduction is used to not only identify causal mechanisms but also to iterate through the evidence and provide internal validation for the causation claims made. The step-by-step process for the empirical part of this thesis is developed, demonstrated, and explained in chapter 5.

Table 4-2 Examples of methodological strategies in four CR case studies (by author)

Blom and Morén (2011)	**Fletcher (2017)**
1. Observation/description 2. Division and sorting 3. Abduction/redescription/theoretical reinterpretation 4. Retroduction 5. Contextualisation/concretisation	1. Identification of demi-regularities. 2. Abduction (theoretical redescription). 3. Retroduction.
Bygstad and Munkvold (2011):	**Melia (2020)**
1. Description of events 2. Identification of key components 3. Theoretical re-description (abduction) 4. Retroduction: identification of candidate mechanisms 5. Analysis of selected mechanisms and outcomes 6. Validation of explanatory power	RREIC + added step of Recommendation

4.7.3 Aligning multi-level perspective, process tracing, and causal mechanisms

Because this study is rooted in MLP theoretical framework, the methodological approach should align with MLP. However, research strategy, methodological approach, and methodological steps or directions have not been thoroughly discussed in MLP literature. Geels (2011) even argues specifically against it:

> *"The research of complex phenomena such as transitions cannot be reduced to the application of methodological procedures and will always contain elements of creative interpretation" (Geels, 2011:36)*

And

"Frameworks such as the MLP are not 'truth machines' that automatically produce the right answers once the analyst has entered the data. Instead they are 'heuristic devices' that guide the analyst's attention to relevant questions and problems. Their appropriate application requires both substantive knowledge of the empirical domain and theoretical sensitivity (and interpretive creativity) that help the analyst 'see' interesting patterns and mechanisms." (Geels, 2011:34)

This approach has proven useful in historical transition studies (Geels, 2002, 2005b; Verbong and Geels, 2007b; Sousa and Marques, 2013) by providing comprehensive accounts of how transitions unfolded and highlighting major drivers, actions, actors and events within them. However, such accounts are stronger at a descriptive level, not analytical level (Squazzoni, 2008; Holtz, 2011; Sorrell, 2018).

While the reasoning that Geels provides above is valid as an approach, it poses some difficulty when it comes to replicating studies and doing comparative studies. Furthermore, as identified in the previous chapter, studying ongoing transitions can have a direct impact on the decision-making process, which would benefit from a clear traceable research methodology, which still allows flexibility to accommodate a range of research topics. To formalise MLP approach to a focused methodology with clear steps, MLP needs to be aligned with the existing understanding of research strategies. MLP and transitions research usually fits within the interpretivist (also known as constructivist) research paradigm, which is based on assumption that access to reality (given or socially constructed) "is only through social constructions such as language, consciousness, shared meanings, and instruments" (Myers, 2019). In MLP transitions as a process are seen as "emergent outcomes of interactions between social groups with myopic views and differing interests, strategies, and resources" (Geels, 2005d:453). A socio-technical transition is defined as a change from one dominant socio-technical regime to another (Köhler et al., 2019). MLP authors usually do not identify MLP research strategy in literature, but it largely aligns with abduction research strategy.

Abduction as a research strategy can be understood as a process of selecting or identifying a provisional hypothesis and then pursuing this through further identification (Kennedy and Thornberg, 2018). In MLP case studies, a transition is usually identified as a socio-technical transition and the studied further by developing a narrative, or a process theory, following MLP theoretical concepts, such as the analytical levels and transitions pathways. “Selective and creative” process is followed to identify how the data can be interpreted through known concepts, theories, and hypotheses and how it can then be applied to prove, challenge, or provide new insights into those theories and processes. Abduction also appears in CR literature as a methodological step (as identified in CR case studies in the previous section) and is defined as “inference or thought operation, implying that a particular phenomenon or event is interpreted from a set of general ideas or concepts” (Danermark et al., 2002:205).

In applied CR case studies both abductive and retroductive research strategies are employed. Abduction is required to construct an account of phenomena observed and entities and their activities involved in the observed process. In CR case studies abduction is identified as a key methodological step, which then leads to the retroduction step that identifies the causal mechanisms. Blom and Morén (2011) explain abduction as a means through which single events can be interpreted and expressed as more general phenomena through the application of theory. For a research question that covers a broad and complex phenomenon, such as transitions in automobility, the abduction step also provides a way to abstract the complex nature of reality and entities involved to a workable set of entities. Abstraction allows focusing on the phenomena at an appropriate scale and it provides a way of organising, understanding, and controlling research data and findings. Abduction also allows abstraction and conceptualisation complex phenomena and provides a starting point for an explanation, which can then be tested through the retroduction process.

CR advocates for a retroductive research strategy with the purpose to investigate particular social conditions under which a causal mechanism takes effect in the world (Fletcher, 2017). Sayer (1992:107) defines retroduction as a "[..] mode of inference in which events are explained by postulating (and identifying) mechanisms which are capable of producing them". CR also acknowledges that (some) mechanisms might not be observed through an empirical study or that an alternative explanation might exist. Compared to the interpretivist approach, CR research requires an attempt to prove the presence of a causal mechanism, while interpretivism accepts a more subjective view. Therefore, the key difference between retroduction and interpretivist approach is that with retroduction the researcher seeks validation of the observations and claims about causality. Another way of comparing the two is that the retroductive research strategy can be used to answer the 'why' questions, whereas the abductive research strategy can be employed to answer 'what' and 'why' questions (Blaikie, 2009). The difference in 'why' questions between retroductive and abductive approaches is that abduction provides understanding, rather than explanation because it provides reasons, not causes. Retroduction answers 'why' questions by demonstrating causality, most often through mechanisms.

Figure 4-9 summarises the key methodological differences between the traditional MLP approach and the strategy proposed in this thesis. The analytical framework that I propose in the following section aligns with the traditional approach, but it adds an additional methodological step – retroduction – which allows identification and description of causal mechanisms.

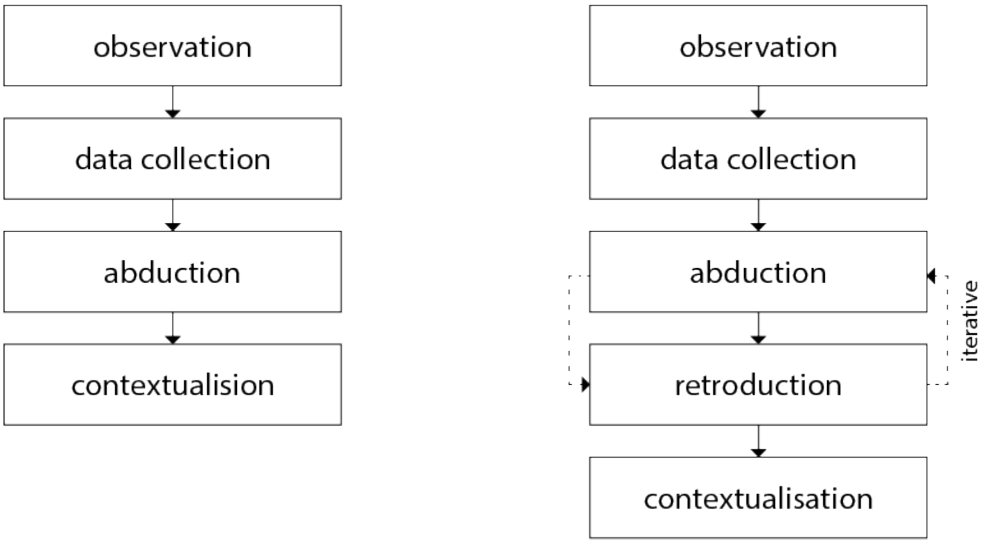


Figure 4-9 (Simplified) comparison of methodological approaches between MLP (left) and CR mechanisms (right) (by author)

4.8 An analytical framework for studying an ongoing transition: SRPM

This section presents an analytical framework that can be used to study an ongoing discussion. The framework is based on the following principles that are based on the discussion in this chapter:

- Research into ongoing transitions would be enriched by causal explanation, which can be achieved through a mechanisms-based approach.
- Re-focusing from process-tracing to mechanisms. In terms of explanatory accounts, this framework is designed as a mechanism-based framework, which differs from the traditional MLP approach. Process tracing is still used as a methodological approach for the first step of the analytical framework, but it is only used as a methodological tool to trace the transition process.
- From theory testing to theory building. MLP is primarily concerned with theory testing, in which it applies the abductive research approach to understand observed phenomenon through a theoretical lens. This framework, in contrast, enables theory building. By focusing on causal mechanisms, the researcher can not only align findings with an existing theory but also theorise about new possible explanations through causal mechanisms. This is particularly important in studies of ongoing transitions, where previously unknown or unobserved dynamics might be present.

The new analytical framework, which is called ***System-Rules-Pathways-Mechanisms (SRPM) analytical framework*** is developed following discussion in this chapter. It employs theoretical concepts from socio-technical transitions literature and a mechanism-based approach from critical realism. The framework employs abductive and retroductive research strategies. The four-stage analytical framework is summarised in Table 4-3.

Table 4-3 SRPM analytical framework (by author)

Analytical step	Analytical process	Process description; methods; data
1	**Identification of the socio-technical system and contextual conditions**	
	Theoretical abstraction of socio-technical system through a theoretical lens	This step requires application of a theoretical framework that allows conceptualisation and abstraction of the observed transition into constituent parts of: • the system • external contingent factors (the landscape and niche processes) that affect the transition process.
	Identification and analysis of external and internal entities that play a role in the transition process	Case study method: theory-based process tracing.
2	**Identification of internal and external rules and structures**	
	Identify how system entities condition and respond to the structure of the system	Entities and rules that shape the socio-technical system are identified following process described in the previous step. Theorisation about powers that shape the rules (structure) and structural powers that enable/constrain entities. Morphogenetic cycle is used as a frame for conceptualisation power relationships and moves.
3	**Theorisation about transitions pathways**	
	Use of inner system relations to theorise about the typology of the transition process	Interpret previous (steps 1 &2) findings to theorise about typology of pathway(s) that the transition is following
4	**Theorisation of causal mechanisms**	
	Identification of demi-regularities	Data analysis: directed content analysis.
	Development of mechanism schemata	Interpretation of findings (from steps 1-3) and identification of demi-regularities to theorise causal mechanisms. For an ongoing transition process where all outcomes might not be observable, mechanism schemata allow theorisation about and validation of potential causalities in the observed transition process.

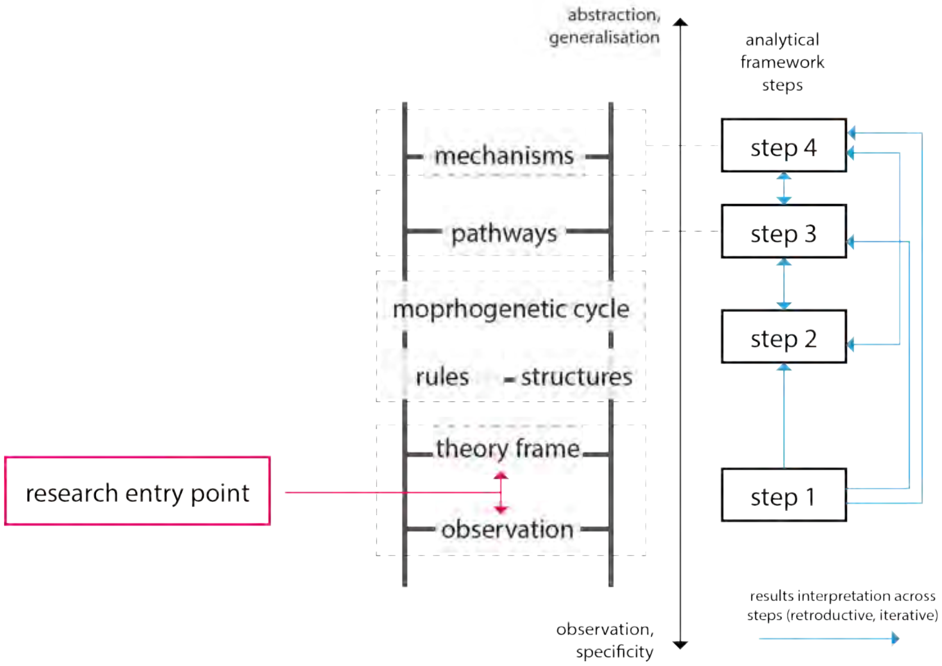


Figure 4-10 Alignment of analytical steps through the ladder of abstraction model (by author)

Figure 4-10 demonstrates the relationship between the analytical steps based on Sartori's ladder of abstraction model (identified in section 2.2.2). Because the research is aimed at theorisation about mechanisms – or theory building – it follows a path from specific observations to more abstract generalisations about the observed processes. At the same time, the research process is iterative and retroductive, meaning that during the analysis process each step is revisited when new relevant findings are identified.

4.8.1 Framework components

The first component of the framework identifies the socio-technical system that is undergoing the transition. Following the discussion on MLP and its interpretation of structure, this chapter identified that a socio-technical system for the purposes of this research is defined as:

"[socio-technical systems consist of] emergent entities whose causal properties derive from necessary relationships between their constituent parts." (Sorrell, 2018)

For analysis purposes the definition can be further broken down and explained as:

Constituent parts: the actors and sub-systems that make up the socio-technical system. Following MLP theoretical framework, this can be broken down into: infrastructure; markets and user preferences; policy; science; technology; culture (Geels and Schot, 2007).

Necessary relationships: this concept comes directly from CR and describes a relationship between entities that is necessary for the entities to exist in a particular configuration. For example, there is a necessary relationship between a vehicle and a driver. CR also distinguishes ***contingent relationships*** – relationships that exist but are not necessary for the event to happen. Contingent relations, however, can affect how events occur. For example, a government initiative can provide instruments to support a modal change, but whether and how it happens will depend on the beliefs and opinions of mobility users. Aligning this with the MLP framework, it can be explained as necessary relationships representing the socio-technical system that is being observed, and the contingent relationships as the landscape and niche processes that are relevant to the transition process.

Causal properties: causal properties that arise from entities and from how they are organised and configured. When active, the causal properties will have a tendency to bring about certain events (Sayer, 1992). The actual results, especially in social and open systems, will vary depending on the contingent and contextual internal and external relationships and factors.

In addition to the entities composing the dominant system, there are exogenous landscape and niche elements. ***Landscape*** refers to events, processes, activities, and beliefs that unfold over longer periods of time and are not directly involved in the transitions but provide a context in which actors operate and to which actors respond if landscape pressures arise. ***Niches*** refer to disruptive innovations that occur outside of the dominant system. In the context of the research question, it is important to identify "true niches" in this transition. By true niches here I mean innovations that:

- Are not driven by incumbent actors and regulators;
- Have disruptive potential.

<u>The second step</u> interprets the internal structural relationships o the identified system, its components and external influences. The ***morphogenetic cycle*** from CR and the notion of rules from MLP are used for this stage. The morphogenetic cycle allows interpretation of findings as sequences of internal and external actions and powers that account for temporal context. Structural properties that shape entities' actions and internal structural activities and processes are identified. Assessment is then made on whether these actions are leading towards structural elaboration or structural reproduction. Rules shed some light on internal relations within the socio-technical system. In this definition of the socio-technical system, it encompasses within itself the notion of ***rules*** (or regimes) – regulative, normative, and cognitive rules - from the original MLP interpretation of the socio-technical regime, and also material and social entities and relations that cannot be conceptualised within the notion of rules. The socio-technical system also allows material entities to have causal powers, and thus overcomes the analytical over-focus on rules in the traditional MLP model (see chapter 3 for full discussion).

<u>The third step of the analytical framework</u> theorises about the nature and trajectory of the transition through the notion of ***transition pathways***. Findings from the previous two steps are aligned with known theoretical descriptions of pathways and elements that do not align with the known trajectories are identified.

The fourth step theorises about causal mechanisms in the observed transition through the identification of demi-regularities and the development of mechanism schemata and sketches***. Demi-regularities***: In CR demi-regularities are used to identify tendencies (Danermark et al., 2002) that could signify the existence of mechanisms. Demi-regularities can be used to focus research design and direction and to assess and explain the results from analysis (Zachariadis et al., 2013). They can be effectively identified through data analysis, such as qualitative data coding (Fletcher, 2017). In the empirical part of this thesis a directed content analysis is used, where a specific dataset is coded following a theory-driven coding scheme. This also helps to identify and confirm boundaries of inquiry (Zachariadis et al., 2013). Findings are further interpreted into theories of causal mechanisms through developments of ***mechanism schemata and sketches***.

4.9 Chapter Summary

This chapter has made a significant contribution to the field of sustainability transitions research by developing an analytical framework that prioritizes the explanatory focus of MLP to causation and causal mechanisms. By emphasizing the importance of understanding the mechanisms driving the transition to AVs in the UK, the framework provides a more comprehensive approach to studying ongoing socio-technical transitions. Additionally, the framework allows for the testing and alignment with existing theoretical frameworks and the development of new theories of socio-technical processes.

This analytical framework represents a novel contribution to the sustainability transitions research area. While studies in this field have focused on understanding the dynamics and complexities of socio-technical transitions, they have traditionally not been guided by an explicit step-by-step process. By introducing the SRPM framework, this thesis provides a structured and rigorous approach to studying the transition to AVs in the UK, which can be applied to other ongoing socio-technical transitions. This contributes to the advancement of the field, enabling more accurate and effective evaluation of sustainability transitions and the development of strategies for achieving more sustainable outcomes.

The proposed framework will be applied to the empirical part of this thesis, where the transition to AVs in the UK will be studied. In the following chapter, the methodology, methods, data collection, and data analysis strategies will be outlined, building upon the SRPM analytical framework developed in this chapter. The combination of this framework and the empirical research will offer a deeper understanding of the ongoing transition to AVs in the UK, and provide insights for guiding the transition towards more sustainable trajectories.

5 Methodology: developing a process for empirical application

5.1 Introduction

The research questions of this thesis are:

WHAT ARE THE CAUSAL MECHANISMS SHAPING THE TRANSITION TO AVS IN THE UK? WHAT ARE THE IMPLICATIONS OF THESE FOR FUTURE MOBILITY IN THE CONTEXT OF THE SUSTAINABLE MOBILITY AGENDA?

The aim of this thesis is to identify causal mechanisms that are present in shaping the transition to AVs in the UK and to understand the implications of those findings in the context of broader discourses in the mobility sector.

So far, this thesis has established that the transition to AVs is a socio-technical transition, and MLP has been identified as an appropriate theoretical lens for abstracting the observations. The previous chapters have presented an argument for a re-focused approach to studying ongoing transitions. An analytical framework has been developed that can be applied to study transitions. The SRPM framework provides a high-level theoretical approach to identifying causal mechanisms. The framework is both – specific enough to enable a systematic approach to study a transition process, and flexible enough so that it can be applied to other case studies, not just the study presented in this thesis.

This chapter identifies the specific methodological steps that are used in the empirical part of this thesis. It establishes ontological and epistemological positions, prescribes methods and data for each of the analytical steps, and establishes the scope and focus of the case study presented later in this thesis.

5.2 Research philosophy

5.2.1 Ontological position: focusing on causal mechanisms

As identified previously in this thesis, the primary focus of the empirical study is to identify causal mechanisms. Therefore, this thesis takes a critical realist (CR) ontological position, in which the notion of mechanisms is a core theoretical axiom. The ontological position has direct relevance to the research design and to defining the scope of this study. In CR ontology events are the outcomes that the research investigates, thus leading to the investigation of the process through which those events occur, produce, reproduce, or are absent. Processes are then explained through accounts of mechanisms that produced the events. CR accepts that human knowledge is capable of only capturing a small part of reality and that the world exists independently of our knowledge of it (Sayer, 1992).

5.2.2 Epistemology: explanation through accessing causal mechanisms

> *"The purpose of a critical realist study is to explain a given set of events by uncovering the hypothesized existence of mechanisms which, if they existed and were enacted, could have produced these events" (Bhaskar (1975, 1998) in Wynn and Williams (2012:794)).*

The epistemological focus of this thesis is on explanation; the basis of the explanation is formed around causal mechanisms. This is based on CR epistemological paradigm, which seeks to answer the question "what caused those events to happen?" (Easton, 2010) about the observed phenomena.

The social world is a complex and open system. Multiple entities interact and mechanisms may or may not be activated when they interact. In order to 'make sense' of large complex systems, such as transportation, the use of theory is a useful tool that allows abstraction and conceptualisation of the research subject. While CR does not support any particular theories, Bhaskar (1978)acknowledges that initial theories can facilitate a deeper analysis, which can then support, elaborate, or deny a theory to aid the discovery of an explanation of reality. Sayer (1992)further elaborates that our knowledge of the world is fallible and theory-laden. The research question of this thesis is addressed through theories from socio-technical transitions, which allow abstracting socio-technical systems and their parts into analysable entities. In this study, those theories are the general theories that form the basis of MLP (as demonstrated in the previous chapters) and subsequently MLP as the middle-range theory that is derived from the general theories.

While CR does not specify methodologies and methods, its epistemology is concerned with explanation through causal mechanisms. In order to validate claims of mechanisms, a retroductive research strategy is inherently required from the epistemological perspective.

5.2.2.1 Epistemological approach to the of mechanisms: a case based process mechanism study

The research question(s) for this thesis require an approach that is explanatory in its nature. This type of research is therefore most suitable for a case study approach (Yin, 2009). The case study approach allows disentangling a "complex set of factors and relationships" (Easton, 2010), which is inherently what the research question of this thesis is about. The case study is the transition to AVs in the UK.

In order to specify a methodological approach, it is necessary to identify the type of the study. Schmitt (2020) conceptualises mechanisms based on the evaluation interest of the study. The classification (Table 5-1) distinguishes between two types of mechanisms – behavioural and process mechanisms and two types of methodological approach – case-based and variance-based approaches. Behavioural mechanisms are concerned with the description of specific changes of behaviour in individuals or groups. Process mechanisms "describe a cause-effect relationship across multiple steps of the theory of change" (Schmitt, 2020:15). Aligning with Machamer (2000), Schmitt then elaborates that a process mechanism would be conceptualised as a "sequence of interactions in which actors engage in activities, transmitting causal forces from intervention to outcome" (2020:15). Such conceptualisation is useful for this study in that it allows defining and narrowing down methodologically the type of mechanisms that are to be identified. Simultaneously, it is worth noting that there are no ontological clashes between the typologies and, if needed, multiple types and approaches can be combined ain a realist study. This study fits in the bottom left corner of the mapping shown in Table 5-1, summarising this as a ***case-based process mechanism study.***

Table 5-1 Types of mechanism methodological approaches from Schmitt (2020) with the relevant approach for this thesis highlighted

		Methodological approach	
		Case-based	Variance-based
TYPE	Behavioural mechanisms	Realist evaluation	Experiments, causal mediation analysis
	Process mechanisms	Process tracing, contribution analysis, related theory or change approaches	Experiments, causal mediation analysis

5.3 Case study context

This research investigates the transition towards AVs in the UK. The UK context is chosen due to its potential for providing valuable insights into the governance, technology, and societal aspects of this emerging technology, with implications for policy, industry, and society. The UK has actively promoted the development and deployment of autonomous vehicles, receiving significant investment and policy support from the Government, making it a crucial case study for the transition to AVs both in the UK and globally. In comparison to other countries, the UK's approach to AVs regulation is viewed as more permissive and flexible. While the US has adopted a decentralised approach, with individual states implementing their policies and guidelines for AVs testing and deployment, the UK has a centralised approach, with the Government issuing national guidelines and regulations for AV. The UK's well-established and complex transport governance system significantly influences the development and deployment of autonomous vehicles. Consequently, understanding this system and how it interacts with emerging technologies can offer valuable insights for other countries and other transitions facing similar challenges.

The UK has been taking a proactive approach to the development and deployment of AVs, with a focus on creating a supportive environment for innovation and investment in the emerging AVs sector. The UK also has an established research and development community, with universities, industry, and government working together to advance the development and deployment of autonomous vehicles. This provides opportunities for collaboration and knowledge-sharing across sectors and disciplines. Specific actions and initiatives have been launched across governance, testing, legislative, and public opinion areas, such as:

- UK Government's Industrial Strategy: In 2017, the UK government launched an industrial strategy that included a focus on AVs as a key area of innovation. The strategy includes a £250 million investment in the development of AVs technology.
- Testing and Trials: The UK has been conducting testing and trials of AVs on public roads since 2015. In 2019, the UK government announced a new initiative called "Project Endeavour" which involves a collaboration between the Government, AVs developers and local authorities to test AVs in three cities across the UK. The UK also has four testbeds for testing AVs in different scenarios and use cases.
- Legislation and Regulations: The UK has been working to develop regulations for AVs to ensure their safe operation on public roads. In 2018, the Government introduced the Automated and Electric Vehicles Act, which includes provisions for insurance, data sharing, and other issues related to AV.
- Public Perception: The UK has been conducting public engagement activities to help increase public understanding and acceptance of AV. For example, in 2019, the UK government launched a public consultation on the safe use of automated vehicles in the UK.

Overall, the UK's supportive regulatory framework and collaborative approach to developing autonomous vehicle technology, as well as its diverse range of stakeholders and potential use cases, make it a compelling case study for understanding the dynamics and trajectories of the transition to AV.

5.4 Developing a step-by-step research process: identification of methodological steps and relevant methods

This section develops and identifies a step-by-step methodological framework for this study that explains how the SRPM analytical framework is applied to the case study of this thesis.

Table 5-2 Aligning analytical framework with methodological strategy (by author)

analytical step	description	Methodological step	method	data	Empirical chapter
1	identification of entities	1.1	literature review; desk study	data gathering through online and library search to build the case study	6
	abduction: interpretation of observations based on MLP theoretical framework	1.2	theory-guided process tracing method	grey literature (49 identified sources)	6
2	Rules and structures (morphogenetic cycle)	2	data analysis and synthesis	findings from the first step of the framework	7
3	pathways	3	data analysis and synthesis; theory-based interpretation of findings	findings from the first step of the framework	8
4	demi-regularities	4.1	directed content analysis; secondary analysis of coding results	Grey literature (49 identified sources)	9
	mechanisms	4.2	development of mechanism schemata and sketches	analysis and interpretation of coding results	9

METHODOLOGICAL STEP 1.1: Description of the phenomena observed

The research process begins by introducing the observed phenomena and the research question.

METHODOLOGICAL STEP 1.2: Identification of the components of the socio-technical system and the scope of the transition

For this stage, a ***theory-guided process tracing method*** (Hsieh and Shannon, 2005) is employed. Theory-guided process tracing method identifies outcomes of the observed phenomena by producing an account of actors, entities, and events. A case study is a detailed analysis of an individual case with the purpose of acquiring knowledge on the research subject and to present it in a structured manner that reveals information about the subject studied (Yin, 2009). Data for a case study comes from a range of sources and is constantly analysed so that interim results can drive further data analysis (Fidel, 1984). For this study, the components of the socio-technical system were identified through a review of government publications and online materials. Abductive approach was used to abstract and organise the case study. Abduction requires a theoretical framework that is used as a lens to interpret observed phenomenon.

For this thesis, the theoretical lens is the MLP theoretical framework. This involves organising involved entities into the three analytical levels and understanding their roles and causal powers in this transition. The three analytical levels are:

a. Landscape
b. Socio-technical system[14]
c. Niche

METHODOLOGICAL STEP 2: Internal rules and the morphogenetic cycle

There are two elements for this step of the analysis: internal rules and the morphogenetic cycle.

[14] Chapter 4 demonstrates why socio-technical system is proposed instead of regime.

Internal rules. For this stage, findings from empirical observation are categorised as rules (regulative, normative, and cognitive) and the relationship between the rules and actors are identified. Relationships can be:

- Actors influencing rules
- Rules influencing actors
- Mutual influence
- Indirect (contingent) relationship

This step sheds some light on the internal dynamics of the socio-technical system that is ongoing a transition process.

Morphogenetic cycle. For this stage, the findings are contextualised within the morphogenetic cycle, which distinguishes three areas:

- Structural conditioning. Events, actions, processes, and beliefs that constrain the current configuration of the socio-technical system. These can be external (conditions that are outside of the system) and internal (conditions that reside within the system).
- Internal system elaboration. Processes that are currently active in the transition are identified. Results from other stages of analysis are used.
- Outcomes. This is a more speculative stage where identified observations are aligned with either structural elaboration (change in structure/system) or structural reproduction (no change in structure/system). Because the transition process is ongoing, empirical observations and assessment cannot yet be made for this stage. Instead, assessment is based on theoretical knowledge (from literature and case studies) and interpretation (whether or not there are tendencies that can enable an assessment). If the potential outcome cannot be assessed, it is identified as yet unknown.

METHODOLOGICAL STEP 3: Alignment with transition pathways

Identified processes and evidence from other analytical steps are aligned with theories of transition pathways (introduced in chapter 2). Theorisation of new previously unidentified transition pathways is possible.

METHODOLOGICAL STEP 4.1: Identification of demi-regularities

This stage employs a ***directed content analysis method***. A set of pre-defined codes are used to analyse source material. For this study, the source material is grey literature, which consists of publications by government departments, research institutions and think-tanks that are relevant to the subject of the case study. The content analysis method, coding scheme, and data sources are further discussed in section 5.6.

METHODOLOGICAL STEP 4.2: Identification of causal mechanisms

Causal mechanisms are identified through a retroductive iterative process using findings from the previous step. Mechanisms are presented as mechanism sketches or schemata. Because the transition is ongoing, the accounts of mechanisms might not be complete, but, as demonstrated in the previous chapter, mechanism sketches and schemata can be used as tools to theorise about possible mechanisms, even when they have not fully manifested.

5.4.1 Validation of mechanisms and findings

In critical realist research, validation is done through the process of retroduction. Retroduction involves developing a plausible and plausible explanation or hypothesis that accounts for the observed patterns or phenomena through the notion of mechanisms. This is then tested against empirical evidence and refined based on empirical evidence and data (or lack of it). In CR research questions can be used to test mechanism claims and findings. In this thesis, when processes and mechanisms are initially identified, they are tested against a list of questions:

- Is the explanation consistent with the evidence of a causal mechanism that has been identified?
- Is there counter-evidence casting doubt on the explanation?
- Does the explanation relate to a change in an underlying social structure, for which there is evidence?

This validation process is done iteratively during the analysis as new mechanisms and links are identified or suspected.

If passed the validation stage, the causal mechanisms are described, and evidence is provided. Due to the nature of empirical observation, the validity of mechanisms cannot always be confirmed. In this particular case study, this is primarily due to the fact that the transition is ongoing and therefore observations are limited. Another aspect is data availability – for some aspects of this transition in order to prove or disprove mechanisms the necessary data might not always exist or be obtainable. To validate the claims about mechanisms in this study, the following principles are followed:

- Reliance on theoretical knowledge and literature. As illustrated earlier, theoretical concepts are used to abstract and guide the research. Similarly, descriptions of existing known mechanisms can be used to interpret observations, and they can be used as starting points when describing observed processes.
- Provision of evidence. When there is not enough data for a thorough validation, the evidence is presented to illustrate why the identified mechanism is thought to exist. This also enables further work and validation when new evidence and developments can be assessed.

Validation in critical realist research is also aided by triangulation, which involves using multiple methods and sources of data to confirm the findings. In this thesis the data is primarily qualitative (grey literature publications), but the publications and supporting information is supported by qualitative evidence where such evidence exists.

5.5 Defining the scope and approach for data collection and analysis

There are two distinct phases in the empirical study of this thesis, each of which requires a different approach to data collection and analysis:

- Abduction (theoretical redescription), which explores the ongoing transition to AVs in the UK through the MLP theoretical lens and employs a case study method.
- Retroduction, which seeks to identify causal mechanisms in this transition through the identification of demi-regularities and mechanism schemata.

For the abduction stage of the process, the case study approach aims to develop a comprehensive understanding of the transition and to also develop some more generalisable theoretical statements about the observed events (Fidel, 1984). In case study research data can be collected using multiple sources of data, which allows developing a holistic explanation through an iterative process Easton (2010).

The retroductive process requires a looking at the process iteratively and seeks to establish demi-regularities (Steinmetz, 2004; Mingers and Standing, 2017), which are “occasional, but less than universal, actualization of a mechanism, or cluster of mechanisms, over a definite region of time-space” (Lawson (1998:149) in Steinmetz (2004:390)). The next step is to explain these demi-regularities, and in this case study it is done through developing mechanism schemata, which are graphical representations of observed processes.

For this case study the main challenge to overcome in terms of the identification of mechanisms is the accountability of emergent causal powers. This means that findings need to refer to the specific actors and their causal powers, rather than general causal observations. For this reason, the scope was focused to actors at the governance level.

Following the theoretical position identified in the previous chapters, the scope and the sources for the empirical study were selected based on the following parameters:

- The ontological position of emergence establishes that observations and patterns at a higher level cannot be reduced to activities and powers of lower level entities. For example, activities by a government department cannot be reduced to activities (and opinions) of individuals working for that organisation. Based on this, the decision was made to seek records of activities by organisations and entities at the level that is appropriate of the research question, which is the national (UK scale) level.

- To avoid individual bias, a decision was made to use existing published material. Studies commissioned by specific organisations and departments were identified.
- Grey literature was identified as the most appropriate source for analysis because it captures views, decisions, and processes at the system level. This aligns with the ontological position on emergence identified previously – in order to explain a phenomenon at a socio-technical system level, the case study should focus on system-level entities and activities.

Grey literature was chosen because it allows overcoming of individual bias when it comes to providing an opinion on a specific subject matter compared to research methods such as interviews. While it must be acknowledged that published material also can contain bias, the range and scope of materials selected reveal higher level trends, patterns, and trajectories rather than individual person's views on the matter. Furthermore, identification and acknowledgement of bias allows theorising about causal mechanisms through the identification of actors and their objectives. For example, the Government investing in AVs R&D links to projected positive economic impact, yet the motivation behind investments names other factors, such as environmental and societal benefits. By acknowledging such dynamics, insights can be gained on not only actors and their motivations but also on wider transition dynamics and framing.

5.5.1 Data selection process

49 publications were identified for the empirical analysis of this thesis. First, an initial literature review was conducted to identify key publications by the relevant government departments. Then, reports and other types of documents - research commissioned by the Government[15] and reports published by research

[15] The Government in this thesis refers to the UK government, unless specified otherwise.

centres, think tanks, and other organisations – were identified. Publications not relevant to the UK were excluded. Next, additional sources were identified from sources mentioned in those reports. Finally, an online search for search strings such as '"autonomous vehicles" AND "report"' with synonyms identified in literature (for example, synonyms for 'autonomous vehicles' are 'driverless cars' and 'self-driving cars') was conducted. Sources found were assessed against research scope and focus and, if found relevant, were included.

Search process

The initial search was performed by February 2020. Later, new emerging publications were added manually, when identified (see Appendix A for full list of selected publications).

The search for grey literature was conducted as follows:

1. Gov.uk website search for terms mentioned above. To narrow down results, content type was specified to "guidance and regulation", "research and statistics", and "policy papers and consultations". Topic was specified as "transport" to further narrow down results. This returned 52 results, which were reviewed manually to identify relevant publications.
2. To ensure that the search was comprehensive, the same process was followed on websites of Department for Transport and Centre for Connected and Autonomous Vehicles. The search process did not identify new sources, because all publications had already appeared in the original search.
3. Transport Systems Catapult (and later Connected Places Catapult) websites were searched following a similar process. All results were reviewed manually to identify relevant publications.
4. Initially identified key publications were scanned for references to identify additional sources.
5. Websites of relevant organisations and groups that were referenced in other publications – Zenzic, SMMT, KPMG – were searched for publications following the keywords outlined above. Results were reviewed manually to assess relevance to the research question and objectives.
6. Google search engine was used to search for additional publications using the search strings identified above. Results were reviewed manually to assess relevance to the research question and objectives.

Initial scanning revealed that publications directly related to AVs are limited in terms of scope and numbers. Because AVs is a part of a larger sociotechnical system of automobility, the scope was extended to include publications that have significance in AVs discussion. Simultaneously, because transportation is a vast domain, some boundaries needed to be identified to limit the scope to a workable amount and keep it focused to the research question. To identify other relevant publications to include in the study, they were first scanned to determine if they contain any mention or relevance to the research question. The summary of types of documents include in the analysis and their scope is summarised below in Table 5-3.

Table 5-3 data sources and sourcing process (by author)

Source type	Reason for selecting and description	Sourcing process
Government publications	Publications by the Government and its departments (such as DfT, CCAV, Transport Scotland)	1. Research and statistics page on gov.uk using terms: - Connected and autonomous vehicles - Autonomous vehicles - Self-driving cars - Future mobility - Future transport - Transport strategy 2. Initial scanning of found publications to assess suitability for this study. 3. Scanning of references and bibliographies to identify potential further sources.
Government commissioned research	This category covers reports on specific topics related to AVs and CAV that were directly commissioned by the Government. Areas of priority in terms of commissioned research provide an insight in the priorities of the Government	1. Research and statistics page on gov.uk using terms: o Connected and autonomous vehicles o Autonomous vehicles o Self-driving cars o Future mobility o Future transport o Transport strategy 2. Reports referenced in government's publications
Publications by research centres, think tanks and similar	Organisations such as Zenzic, Connected Places Catapult, KPMG and others that are independent form the Government but have published significant reports that are relevant to the research question	Some publications were identified from scanning publications by the Government. Other publications were identified by using search function on specific organisation websites to identify additional publications.
Reports by industry bodies	Reports by SMMT, RAC and other automotive industry bodies	Some publications were identified from scanning publications by the Government. Other publications were identified by using search function on specific organisation websites to identify additional publications.

Law Commission	As a statutory independent body the Law Commission reviews the law. During the time when research for this thesis was conducted, the Law Commission was undertaking a regulatory review for AV. Publications available by Summer 2021 were included.	Publications available on Law Commission website about Autonomous Vehicles review (https://www.lawcom.gov.uk/project/automated-vehicles/)
Publications by combined authorities (and Greater London)	Combined authorities have certain decentralised powers in areas such as transport and economy strategies.	Initially transport strategies by local authorities were reviewed, but they were not included in the final analysis because: - Some did not have any specific position on CAV - Some only referenced information from national level frameworks and guidance - There was not enough evidence to suggest that CAV development sin any specific local authority levels would differ from general national direction

5.5.2 Categories excluded from data sources

The following categories were not included in the scope of this research:

News articles and other media publications. There has been a significant amount of discourse about self-driving cars in media. While those form a significant discourse of how AVs is presented to (and in some cases received by) the general public, this fits outside of the scope of the review. This is due to the nature of the analysis and research question. In terms of the nature of the analysis, it would be impractical to undertake the manual coding exercise on the number of articles that exist. In terms of the research question which addressed the causal mechanisms, there is an argument about the role of the media in mechanisms such as forming of public opinion. However, capturing such discourse falls out of the scope of the coding schema proposed for this research.

Technical reports. Documents that solely focus on a specific element of AVs technology (such as sensors, communication, technical specifications and requirements) were not included in the review. While the technological development is important to the overall transition process, at the scale of analysis the specific particulars about the technology do not add any useful insights. The socio-technical system is a meso scale unit of analysis, therefore only data that contributes to this scale was added. In the technology development area, the useful additions to this research are those that identify potential barriers (for example, cost or price-performance ratio) and niche innovations; however, those are mentioned in non-technical reports and publications that were identified previously.

Local and combined authorities. This is due to a) individual local authorities having no powers to make decisions that are outside of any national strategies and frameworks and b) lack of evidence to suggest that any individual local authorities have any specific AVs ambitions or objections. The lack of such considerations, however, could be considered as a factor in the later chapters and discussion on causal mechanisms, but this needs to be done in relation to regulative powers that those authorities hold. The combined authorities in the UK were initially included in the review because they are passenger transport executives in the UK and are responsible for public transport within large urban areas. While doing this research I was involved as a researcher in a CAV R&D project in Manchester (which is one of the combined authorities) and I experienced the CAV initiatives at this scale. Due to this experience, I initially scoped all combined authorities (currenttly there are six passenger transport executives in England - Greater Manchester Combined Authority, Liverpool City Region Combined Authority, South Yorkshire Mayoral Combined Authority, North East Combined Authority and North of Tyne Combined Authority (North East Joint Transport Committee), West Midlands Combined Authority, West Yorkshire Combined Authority.) In line with the scoping strategy outlined above I was searching for official publications that would outline policy and strategy that relates to AV. However, in this process no sutiable sources were identified. For example, despite Manchester's involvement in CAV projects and development of CAV principles and other strategies within the project, there were no public outputs. Notably, the Greater Manchester Transport Strategy 2040 does not involve any mention of automated or autonomous vehicles.

Similar search was also performed for other authorities known to participate in CAV projects (Oxfordshire, South Gloucestershire). Those searches also did not result in any publicly available publications despite these authorities being involved in a number of CAV R&D projects.

5.5.3 Time and topic focus

Topic focus: focusing on road based private transportation in built-up areas.

The research question specifically addressed the transition to autonomous vehicles. It is important to acknowledge that this is not the only development happening in the transport domain and many developments are happening simultaneously. For example, discussion on CAV is often aligned with discussion on EV and MaaS. The focus of this study is on the AVs transition and is therefore focused on areas of transportation that have a direct influence on driving practices. This includes private vehicles and spaces where humans interact with transport most – built up areas. Furthermore, following an initial review at the beginning of this research, no publication should be identified that address those categories specifically and/or exclusively. Therefore, a decision was made to exclude the following categories from the study:

1. Air mobility.
2. Rail transport.
3. Water based transport.
4. Freight.

Time focus: identifying the emergence of AVs discourse in UK governance

Transitions to AVs is a process that spans over many years and affects many organisations, firms, interest groups and social actors. While it is difficult to pinpoint the exact moment when AVs appeared in the debate about future mobility in the UK, a significant event that kicked off the narrative was the report "Pathway to driverless cars" published by DfT in 2015 and the announcement by the Government in 2017 that we should expect AVs on UK roads by 2021. Since then, law, policy, insurance, manufacturing and other sectors have produced their reviews, reports, briefings, papers and other publications adding to the discussions. Therefore, the 2015 report date will be used as a starting point. During the data collection process earlier references were added if they were identified relevant to the scope.

5.5.4 *Identified grey literature for analysis*

The grey literature identified for the coding exercise consisted of both, specifically AVs related publications and also more general transportation related publications. Through this process, 61 relevant publications were identified (see Figure 5-1 for a summary). Then, publications were reviewed to determine which would be included in the further study. 12 publications were identified as unsuitable. 4 of these were publications related to London and were therefore specific to local-level and were later excluded, while 8 were reporting on specific aspects of technological solutions, which were beyond the scope of the research question. Remaining 49 publications[16] were further categorised into three groups:

- Publication by the Government and its departments and agencies;
- Studies commissioned by the Government and its departments and agencies
- Publications by other entities.

The three groups were coded separately, but the same coding scheme and approach were used.

[16] See Appendix A for the full list of publications that were used for analysis.

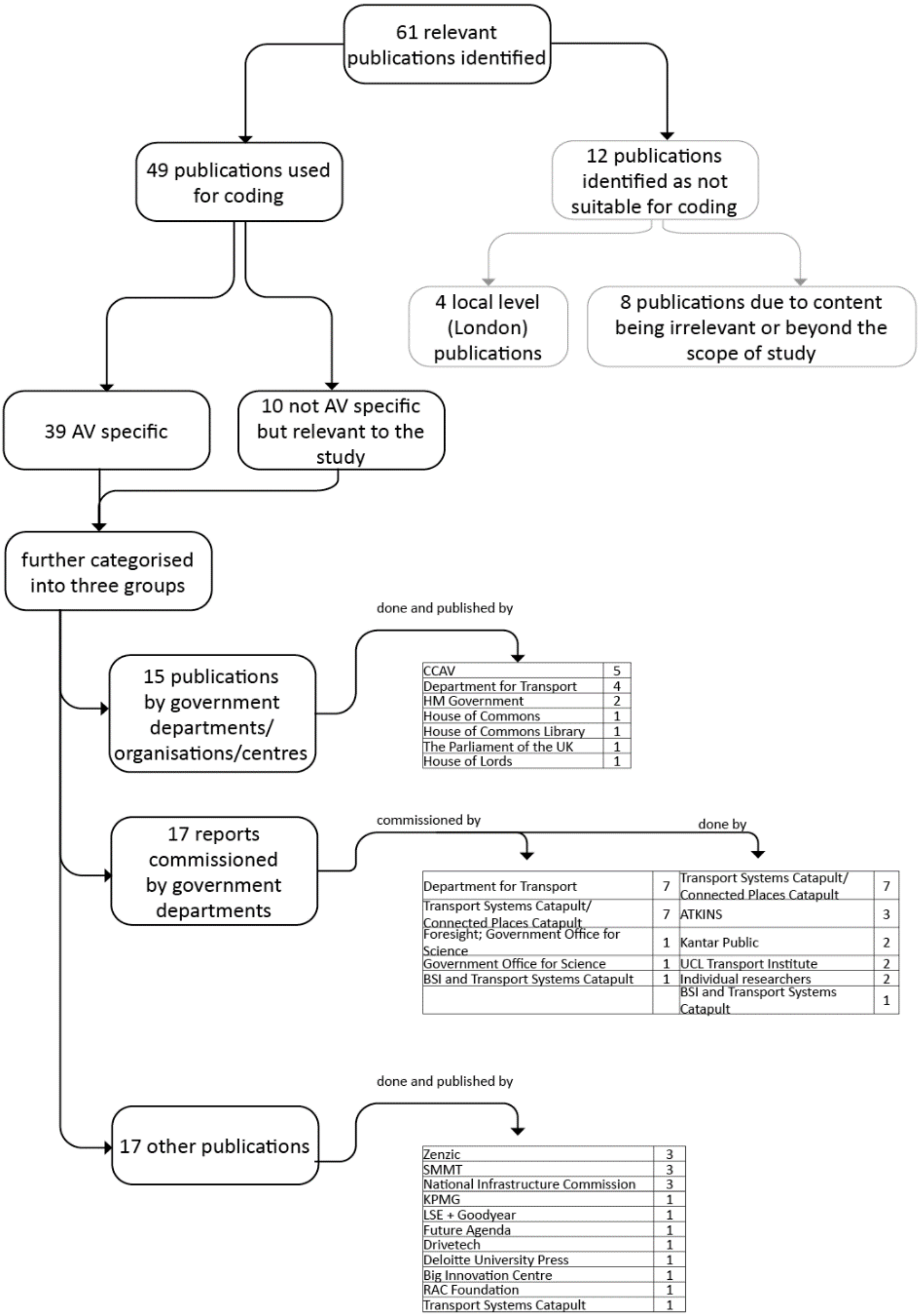


Figure 5-1 Summary of grey literature sources for analysis (by author)

5.6 Content analysis: using directed content analysis to identify demi-regularities

Content analysis is chosen as a research technique to analyse the publications identified for this study. Content analysis entails a range of techniques, which depend on the subject of analysis and research ambitions. Because this research is concerned with a particular research question and pre-specified theoretical approach and framework, this thesis will follow a partially pre-defined coding scheme. This section describes the selected approach and presents the initial coding scheme.

5.6.1 Coding approach: directed content analysis

As identified earlier in this chapter, the fourth step of the analysis process employs a qualitative coding strategy to identify demi-regularities that allow to theorise about causal mechanisms.

The coding scheme is a collection or set of all codes and coding categories applied to the body of text analysed. When using a coding scheme, the selected texts are all manually coded, which means that the researcher looks for information that relates to a code and makes a note of it. For this research, NVivo software was used to conduct the coding exercise. While content analysis can be quantitative where the researcher quantifies the codes by counting (Lewis-Beck et al., 2012) and draws conclusions based on those findings, in a CR study that seeks to identify underlying causal powers and mechanisms, the quantitative approach would not provide all necessary information regarding agents, actions, and causal powers, and therefore a qualitative approach to coding is used.

This process is different from a more traditional grounded theory approach to coding, which would follow an inductive approach and start from “the ground up” without any prior framework towards data analysis. Such approach develops theories from the data rather than align findings with existing theories (see, for instance, Corbin and Strauss (2012)). CR, on the other hand, actively engages with theories (and accepts that they can be incomplete or flawed (Sayer, 1992; Vincent and O'Mahoney, 2018)), and CR also encourages the researcher to be familiar with the subject of study. In line with suggestions from authors such as Fletcher (2017), Gilgun (2011) and Saldana (2014), the list of codes was modified, updated, changed and supplemented with new codes during the process. Therefore, the coding exercise follows a pre-set coding scheme, that is updated if new codes or categories are found in the data.

Hsieh and Shannon (2005) offer a useful categorisation by coding approach. They distinguish conventional, directed and summative content analysis types. Table 5-4 summarises the key differences between the three approaches. In line with this description, this study fits in the directed content analysis approach. This approach has previously been used in CR guided studies - Fletcher (2017) in a CR study on Canadian farm women's experiences with agriculture also successfully used the directed approach and followed a theory driven coding scheme to inform further study on causal mechanisms.

Table 5-4 Coding approaches (from Hsieh and Shannon (2005)) with the approach used in this thesis highlighted

Type of content analysis	Study starts with	Timing of defining codes or keywords	Source of codes or keywords
Conventional content analysis	Observation	Codes are determined during data analysis	Codes are derived from data
Directed content analysis	Theory	Codes are defined before and during data analysis	Codes are derived from theory or relevant research findings
Summative content analysis	keywords	Keywords are identified before and after data analysis	Keywords are derived from interest of researchers or review of literature

5.6.1.1 Theory informed initial coding scheme

Theoretical codes can be derived from prior theory (Maxwell, 2012). The theoretical codes in this context are the pre-identified mechanisms, characteristics, agents, and actions from existing literature on MLP theory.

As established earlier, the general conceptualisation of the dynamic of transitions can be followed along in all three levels: niche innovations build up momentum, and simultaneously changes in the landscape create pressure and 'cracks' in the system dynamics, which allow the niche innovations to 'break through' and reconfigure the dominant regime. At each analytical level change mechanisms can be identified. Literature concerning the application of MLP was reviewed to distil indicators and processes relevant for the analysis. For this study the key indicators/drivers of change in MLP literature (Geels, 2002; Geels and Schot, 2007; Shackley and Green, 2007; Kern, 2012; Geels et al., 2017) were identified and they were then used as starting point codes for analysis in NVivo. To filter out all relevant content, an initial coding stage was completed, in which all relevant sections were selected. For this stage, the codes were used descriptively to label information. Then, secondary coding was done, in which all references[17] from the first round of coding were looked at again and coded by applying the theory-based coding scheme. Table 5-5 summarises the initial theory-based coding scheme that allocates codes in the three MLP analytical levels.

[17] In NVivo software the term 'reference' is used to refer to the text that has been selected and assigned a code.

Table 5-5 MLP analytical levels and indicators (by author)

Landscape	System	Niche
Globalisation;	Strategies;	Opportunities for early deployment
market liberalisation;	policies;	Price/performance improvements
utility maximisation (by consumer);	support mechanisms;	Economies of scale
Climate change and associated government targets	importance given to particular technologies as a route to future improvement (such as low-emissions);	Development of complementary technologies
User attitudes and preferences	programmes	Support from powerful actors
	Impending changes	Learning processes

During coding, only text relevant to the research question is coded. While researchers who employ coding often seek to code the entire source material, in this study it was deemed to be unpractical because a lot of the literature studied covered topics broader than the research study. For example, the Industrial Strategy 2017 covers a wide range of topics beyond AVs and even transport, and therefore only relevant content was coded. During the coding process, it was also discovered that there is often repetition in some types of publications. When this occurred, the coding was only done once for each reference.

5.7 Meta-analysis of analysed publications and the coding process

In total, 49 publications were analysed (see Appendix A for the full list). As shown in Figure 5-2 , there has been a yearly increase[18] in publications that focus on (or include) driverless vehicles. The analysed literature was split into three sub-categories after initial review and scanning. The categories were:

- Publications by the Government and its departments and agencies;

[18] While there is a decrease in publications after 2019, at the time of writing this thesis it is not possible to assess whether it was due to Covid-19 pandemic or other reasons.

- Research and reports commissioned by the Government and/or its departments and agencies;
- Reports by other organisations.

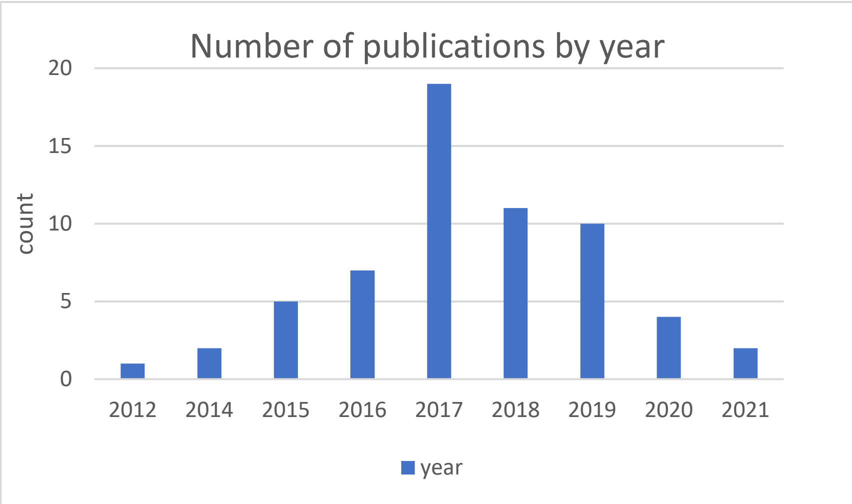


Figure 5-2 Number of publications by year (by author).

The initial and key strategic policy report – "The Pathway to Driverless Cars" by Department for Transport was published in February 2015. As shown in Figure 5-3 , most government publications and commissioned research was done following the initial report, which marks it as a significant development within the transition that set the narrative for further work and publications. Another key publication in the Industrial Strategy (2017), which set 'Future of Mobility' as one of its Grand Challenges. The Industrial Strategy identified CAV as one of the key areas for the Government and it set out the ambition that "the Government wants to see fully self-driving cars on the UK roads by 2021"(Industrial Strategy, 2017). Government's commitment to CAV development in Industrial Strategy can also be seen as a catalyst for CAV research and discourse, which reflects in the increase in publication numbers. Publications by other organisations also demonstrate a growing trend which aligns with the other two categories.

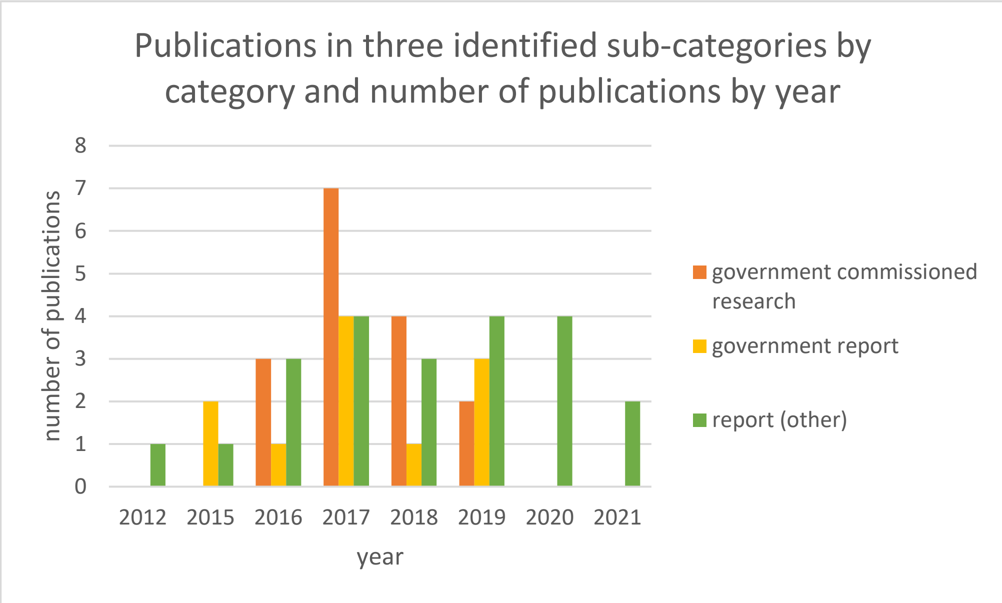


Figure 5-3 Count of publications in three subcategories by category and year (by author).

Coding process: frequencies and demi-regularities

Coding was done in two stages in NVivo software. First, publications were scanned for relevant content. Relevant content was selected by following the initial coding scheme (identified in the previous section) to mark information that would be relevant in understanding the transition process. These results were used to build the case study in chapters 6 and 7.

Then, a second round of coding was done to identify key themes. Identification of themes allows to start theorising about demi-regularities, or tendencies, that are then used to theorise about transition mechanisms in chapter 9.

Coding also allowed looking at key themes across publication by analysing coding density. For example, Table 5-6 shows mapping of coding density of selected codes (that relate to strategic approaches) across selected publications by the Government. This allows identification of publications that are most relevant to the specific themes.

Table 5-6 Coding matrix showing code frequency in publications (by author). Darker colour represents higher coding density.

	barriers	Support mechanisms	Strategies; policies; frameworks	pathway	uncertainty
Briefing Paper: Connected and autonomous road vehicles					
Code of Practice : Automated vehicle trialling					
The Pathway to Driverless Cars: Summary repot and action plan					
Future of Mobility: Urban Strategy					
Industrial Strategy					
UK Connected & Autonomous Vehicle Research & Development Projects 2018					
Pathway to driverless cars : Consultation on proposals to support Advanced Driver Assistance Systems and Automated Vehicles Government Response					

5.7.1 Qualitative findings: key themes in analysed publications

Category 1: Publications by the Government and its departments and agencies

In line with government's ambition, the publications reveal more enablers or 'support mechanisms' for the transition than barriers, with permissive regulations, thriving automotive sector and well established research and innovation base (Department for Transport, 2015; Clarke and Butcher, 2017) being the key attractors for UK's prime position in global (future) AVs market. Barriers to AVs implementation mentioned are market penetration of AVs and public perception, which is currently sceptical towards AVs (Clarke and Butcher, 2017).

Non-regulatory approach to testing and development of AVs technologies is set out, and the developments are instead guided by principles and code of practice. The Government has indicated that by “taking a step-by-step approach, and regulating in waves of reform” (Centre for Connected & Autonomous Vehicles, 2017) and “building futures thinking into our decision-making” (Department for Transport, 2019a) it will be able to reflect uncertainty and improve resilience as technology develops. Uncertainty about the unknown effects of AVs is acknowledged in the publications we analysed, with phrases such as “if channelled effectively”; “these benefits are not inevitable”; “the solutions for the distant future might not work now” appearing throughout the strategies. Attempts to account for uncertainty and incorporate it in decision making links to wider approaches in UK transport planning Marsden and Lyons (2019).

Category 2: Research commissioned by the Government

Figure 5-4 shows mapping of government funded research thematically in three categories: social; governance and future roadmap; technical/industry. The Government’s focus on technological innovation and its benefits to the UK economic growth is clear from the analysis, resulting in a gap in societal research, especially on relation between the society and technology as a co-evolving process.

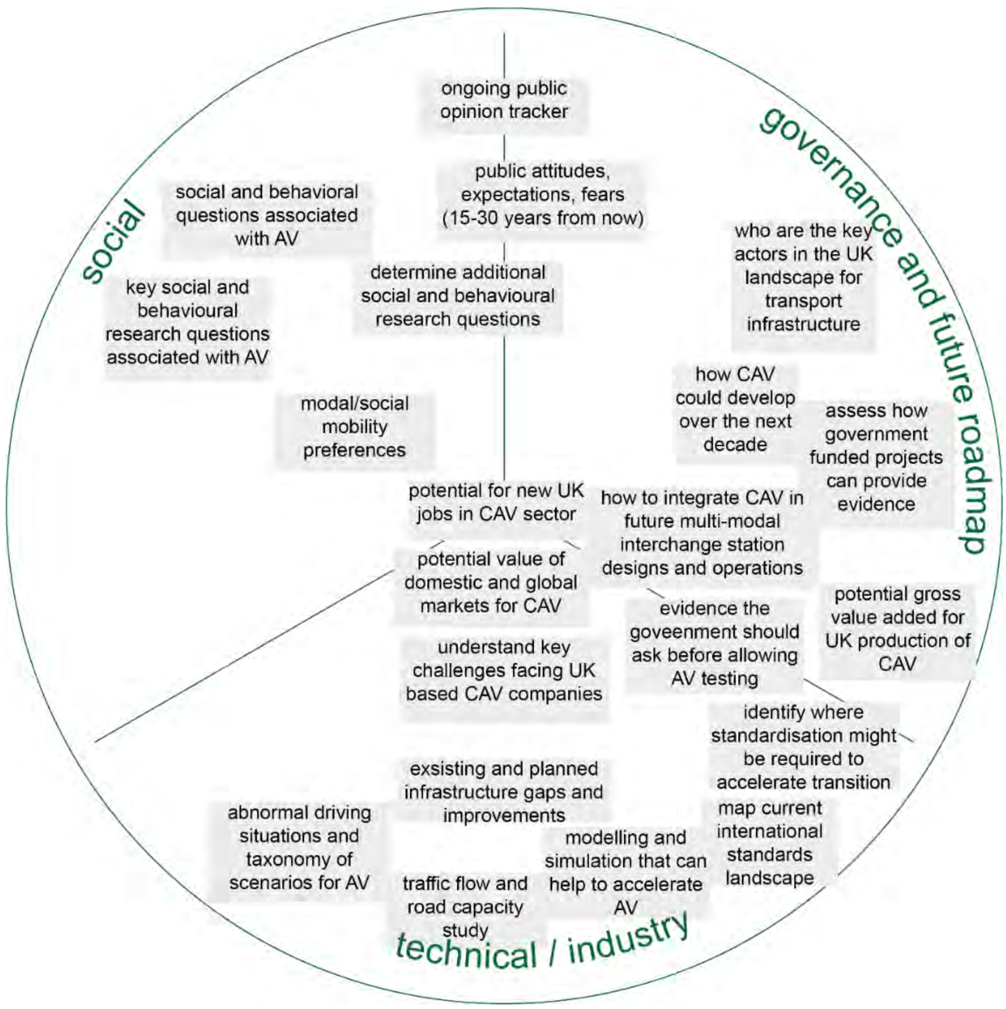


Figure 5-4 Thematic map of research commissioned by the Government (by author)

Some publications also identify the societal acceptance as a key consideration for successful AVs adaptation. Public attitudes tracker commissioned by DfT identified that there is a conflict between perceived advantages and disadvantages of AV, where respondents named issues such as safety concerns and not needing to pay attention to driving as both, an advantage and disadvantage of CAV.

Category 3: other publications

Leading industry bodies have provided their vision on AVs future in the UK. While it is not as aspirational as the 2021 goal set by the Government, it is in line with rapid ambitious technology development. SMMT roadmap forecasts automates shuttle services in some UK cities by 2022 and estimates Level 5 vehicles to be on roads in 2030-2035 SMMT (2019b) and Zenzic (2019) sees the UK “benefiting from connected and autonomous mobility” by 2030. In line with the optimistic position by the industry bodies, (KPMG, 2015) also recognise the promised benefits of AV, such as expanded industrial opportunities, increased productivity, and freeing up urban space.

In contrast, publications concerned with subjects other than technology development, highlight the potential barriers and issues associated with wide-spread AVs adoption. Societal acceptance and supporting infrastructure are among the concerns for swift AVs uptake (Tennant et al., 2016; Johnson, 2017). Publications focusing on societal outlooks on the transition also partially fulfil the thematic gap in research commissioned by the Government. For example, SMMT (2015) look into social groups who could benefit from autonomous mobility and Araujo, Mason and Spring (2012) consider the prospects for future AVs around the concept of ‘market making’. In those processes, the Government is expected to play the central mediator between government, industry and adjacent sectors (SMMT, 2015), as well as lead the necessary changes in road traffic laws, network coverage, and ensuring safe deployments (SMMT, 2019b). A common emergent theme is the need for some level of interdisciplinarity to ensure maximum benefit for all affected actors.

6 Landscapes, niches, and the socio-technical system: a perspective on the AVs processes in the UK

6.1 Introduction and chapter structure

The previous chapters developed an analytical framework (chapter 4) and specified the methods (chapter 5) for the empirical study of this thesis. This chapter presents findings fir the first step of the analytical framework – Identification of the socio-technical system and contextual conditions – and uses theory-guided process tracing method.

The aim of this chapter is to present the findings of the case study through a theory-informed lens. The socio-technical transitions theory (MLP specifically) describes socio-technical transitions as processes through which socio-technical systems undergo changes resulting in changed configurations. The changes are described in three levels – landscape, regime, niche. Earlier in this thesis I argued that the (socio-technical) system should be used instead of 'regime' because it offers a broader and more balanced view on the dominant socio-technical configuration. In the dominant socio-technical system, the actors and entities who are part of the system are interested in keeping the system stable and therefore develop in incremental stages avoiding sudden changes that could disturb the current configuration of the system. Meanwhile, slow moving landscape developments gradually develop challenges that the system needs to react to. And niche innovations are developing as alternatives to existing dominant technologies.

The chapter is organised in three subchapters:

1. Landscape, where key landscape developments in relation to the research question are identified.
2. Socio-technical system, where the transition process in the UK is investigated. This is further broken into six categories: policy and governance; industry; science; culture; markets and user preferences; infrastructure.

3. Niche innovations, which looks at developments and actors, which can be classified as niche to the system of automobility and this transition.

The chapter finishes with a summary of key findings.

6.1.1 Analysis principles

The transition to humanless driving is a transition in the socio-technical system of automobility. The socio-technical system of automobility describes the current private car dominated system with broad socioeconomic and environmental impacts (Sovacool and Axsen, 2018). It is a complex global system of many sub-systems – societal, manufacturing, governance, insurance, services, planning, and others – that are interdependently linked and self-reinforcing.

Therefore, these principles were followed when constructing the system analysis:

1. Time and topic focus as set out in previous chapter.
2. Focus on system of automobility specifically. System of automobility is a road-based personal transport system that revolves around the use of internal combustion personal vehicle – the car. Automobility differs from the wider system of transportation in that it excludes rail, air, and water transport as well as freight.
3. Due to ongoing real-world processes, AVs are often mentioned together with other innovations, namely ACES (autonomous, connected, electric, shared). Elements of those innovations are mentioned further in this chapter because they often appear together in future of mobility discourse. Nevertheless, this study is focused on AVs and data about other technologies is used at supplementary level.

6.2 Landscape processes: climate agenda and socio-economic trends

There is some ambiguity in literature about the definition and construct of landscape (see Raven (2010) for a review of definitions), however, the consensus in literature agree that landscape developments are those processes that cannot be directly influenced by the system or niche actors. The landscape layer accounts for the larger and slower developing contextual processes, such as politics, culture, climate. The landscape level reflects the dominant trends, values, and assumptions. In automobility and in AVs discourse the particularly significant developments and processes are identified in this section and related to the AVs transition. The landscape discourses identified fall into three areas: climate and politics; technology; socio-cultural, which are presented below.

6.2.1 Climate and politics

Political landscape: addressing the climate change

Growth of industrialisation and fossil fuels was a dominant trend that fuelled the growth of global economy. During the last couple of decades, the adverse effects of fossil fuel use has been acknowledged. Therefore, climate issues have been at the forefront of many international and national issues and strategies for several years and are becoming increasingly more prominent with nations agreeing on targets and contributions towards the climate issues. The shift in attitudes towards fossil fuels and economic growth has been driven by several factors, including:

- Scientific evidence: The scientific community has provided increasing evidence of the adverse effects of fossil fuel use on the environment, particularly in terms of global warming and climate change.
- Environmental activism: Environmental activists and advocacy groups have raised awareness of the environmental impacts of fossil fuel use and have pushed for greater action to reduce greenhouse gas emissions.
- Economic factors: The cost of renewable energy sources such as solar and wind power has declined significantly, making them increasingly competitive with fossil fuels.

- International agreements: The international community has increasingly recognized the need to reduce greenhouse gas emissions, leading to global agreements such as the Paris Agreement, which aims to limit global warming to below 2°C above pre-industrial levels.

Global agreements, starting with the United Nations Framework Convention on Climate Change (1992) and followed by the first global greenhouse gas emission reduction treaty - Kyoto Protocol (signed in 1997 and became effective in 2005) - have set the direction for dominant policy frameworks in the European Union and in the UK. Following that, in 2015 the Paris Agreement was announced, which the UK is also participating in.

The politics concerning climate change involves a wide range of actors, from grassroots activists to high-level government officials and international leaders. At times, politics can hinder progress on climate change by creating roadblocks, such as resistance to regulatory measures or the prioritization of short-term economic interests over long-term sustainability goals. However, politics can also provide a platform for change by mobilizing support, setting targets, and creating policies and incentives that encourage the transition to a low-carbon economy.

The climate change agenda has become increasingly prominent in recent years, with growing public awareness and concern about the environmental impact of human activity. This has led to increased political attention and action, including the establishment of ambitious targets for reducing greenhouse gas emissions and promoting renewable energy sources. Because the transportation sector is a major contributor to CO2 emissions and air pollution, decarbonisation efforts are also an integral part of transport policy landscape in the UK, which the AVs industry will need to align with[19]. At a national level, the UK has passed legislation directly

[19] For a review of UK transport policies concerning climate change see Marsden and Rye (2010).

related to climate change: the Climate Change and Sustainable Energy Act 2006 and the Climate Change Act 2008 which established a legally binding target to reduce greenhouse gas emissions by at least 80% by 2050 compared to 1990 levels. In addition to the Climate Change Act, the UK government has introduced policies and initiatives aimed at reducing emissions from the transport sector specifically. These include:

- The Road to Zero Strategy: This strategy, launched in 2018, sets out the Government's plan to reduce emissions from road transport, including a target for all new cars and vans to be effectively zero-emission by 2040.
- The Clean Air Strategy: This strategy, launched in 2019, sets out the Government's plan to reduce air pollution in the UK, which is a major public health issue. The strategy includes measures to encourage the use of low-emission vehicles and to promote cleaner public transport.
- The Transport Decarbonisation Plan: This plan, published in 2021, sets out the Government's vision for decarbonising the UK's transport system, including a target for all new cars and vans to be zero-emission by 2035.

However, progress so far has been uneven[20] and challenges remain in terms of political will, international cooperation, and the need for a fundamental shift in societal values and behaviour. Furthermore, as pointed out by Marsden and Rye (2010), there are uncertainties concerning who (in terms of Government bodies, legislative and policy actors, local authorities and others) is responsible for tackling greenhouse gas emissions and what contribution should each player make.

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[20] For example, the Climate Action Tracker (https://climateactiontracker.org/countries/uk/policies-action/) has ranked the UK's policies as 'almost sufficient' and that the UK is currently not on track to achieve its current climate targets.

Politics: neo-liberal ideology in relation to transport policy in the UK

Since 1980s British politics have been shaped by neo-liberal ideology. Neoliberalism is an economic and political ideology that emphasizes the importance of the free market and individual liberty. In the context of transport policy, this has often meant a focus on privatization, deregulation, and reducing government intervention in the transport sector. In the UK, neoliberal ideology has influenced transport policy in various ways, including the privatization of public transport services and the deregulation of the bus and rail industry in the 1980s resulting in fragmented and cost oriented industries in public transport sector. Transport Act 1980 deregulated intercity coach services in the UK and Transport Act 1985 required local authorities to transfer control of their bus systems to separate companies (with exceptions of London and Northern Ireland). This led to the fragmentation of the industry, with multiple private operators competing for passengers on the same routes. On the other side, the private mode of transport – the car – was 'strengthened' by active promotion of the associated freedom of owning and driving a car (Shaw and Docherty, 2014; Geels, 2018).

Another example is the emphasis on market mechanisms in addressing transport-related environmental issues. For instance, the UK government has introduced policies such as congestion charging and low emission zones, which rely on economic incentives to encourage individuals and businesses to change their behaviour.

However, it can be argued that neoliberal transport policies have led to a lack of investment in public transport infrastructure, and have failed to address issues of social and environmental justice. For example, the privatization of rail services has led to high ticket prices and reduced services on some routes, disadvantaging low-income passengers and those in rural areas. Additionally, market-based mechanisms may not adequately address the root causes of environmental problems, such as the over-reliance on private cars, and may disproportionately impact marginalized communities.

6.2.2 Technology

A brief summary of the history of self-driving cars

The concept of a self-driving car emerged a couple decades after the first mass-market car – the Ford Model T – was introduced. In 1939 World Fair the Futurama exhibit by Normal Bel Geddes introduced the idea of self-driving cars in then futuristic vision of 1960s. Then, in 1960s, during the ‘ space race’ scientists were working on landing vehicles on the Moon and driving them remotely, leading to development of the Stanford Cart by James Adams (Earnest, 2012). Also in the 60s, the UK’s Transport and Road Research Laboratory demonstrated a ‘self driving’ Citroen DS that reached 80mph on the test track and was controlled by magnetic tracks and sensors (Waugh, 2013). The first demonstration of sensor-based (rather than map following) and lidar enabled self-driving vehicles was presented by DARPA outside of Denver in 1985 paving the way to AVs that have been developed up until now. From 2010s most major vehicle manufacturers have been involved in some kind of autonomous driving systems development. Significantly, the vehicle that did “the world’s first self-driving test” on May 1st 2012 in Las Vegas, US (Harris, 2014) was using autonomous driving systems developed by Google – a technology company. Since then, more vehicle and technology companies have developed self-driving systems that are being tested globally. Governments have also moved to approve and enable AVs developments and testing through legislative and policy instruments enabling further testing and development.

Many systems required for autonomous driving already exist in isolations in vehicles we drive today – sensors, radars, automated driver assist features, and environment scanning equipment. While they do not yet combine in market-ready vehicles, research, development, and testing is nearing closer to vehicles that will be able to perform self-driving function in the future. At the same time, developing individual technology is less complicated than a full system integration, which is why Level 1 and Level 2 features are widely available in vehicles sold today, while

Level 3 features only exist in a handful of higher-end vehicles (such as the Tesla autopilot), and Level 4 and 5 systems are only at a developmental level.

6.2.3 Socio-cultural landscape

We live in a car-centric and car dominated society. Due to developments in mass production in early 20th century, the car became an ever increasingly prominent artefact of life leading to changes in land use patterns and daily activities (Urry, 2004b; Bertolini, 2017).

Population changes

UN have predicted that by 2050 20% of global population will consist of older adults (*The World Population Prospects: 2015 Revision*, 2015), which relates to one of the perceived benefits of fully self-driving vehicles - the ability for the elderly and disabled to live more independent lives (Smith and Anderson, 2017).

UK has estimated that in 2004 over 48% of the world's population lived in urban areas, and this is expected to grow to 61% by 2030 (UN, n.d.). Urban growth and transport are related and inter-dependent issues. Availability of infrastructure provides opportunities for urban development, while urbanisation and population growth place demands on transportation systems and the infrastructure (Aljoufie et al., 2011).

Socio-economic landscape: travel data and behaviour in population[21]

[21] Data used in this section is from the National Travel Survey (NTS), which since 2013/2014 only covers England. There are no comparable surveys and data sets available from the devolved governments. Because approximately 84% of UK's population live in England, the NTS data can be used at a capacity to illustrate overall population trends.

Statistics show that total trips taken and miles travelled in the UK are on a slight decline since 2002 (Figure 6-1), however the total number of cars on roads is increasing (Figure 6-3). Similarly, number of cars per household (Figure 6-2) show that the number of households with two or more private vehicles is increasing. In general population (aged 17+) 75% hold a driving license (Figure 6-4).

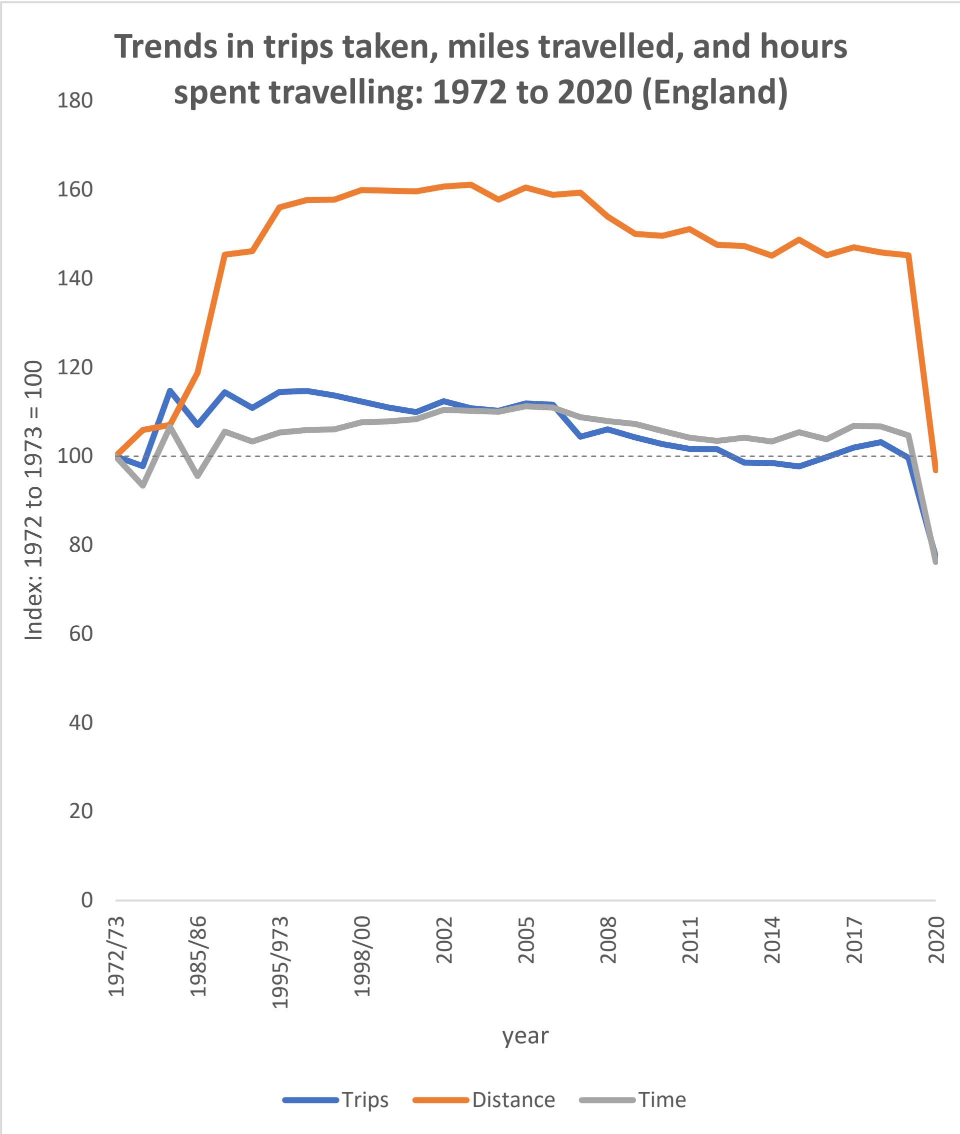

Figure 6-1 Trends in trips taken, miles travelled and hours spent traveling (indexed) (source: nts0101)

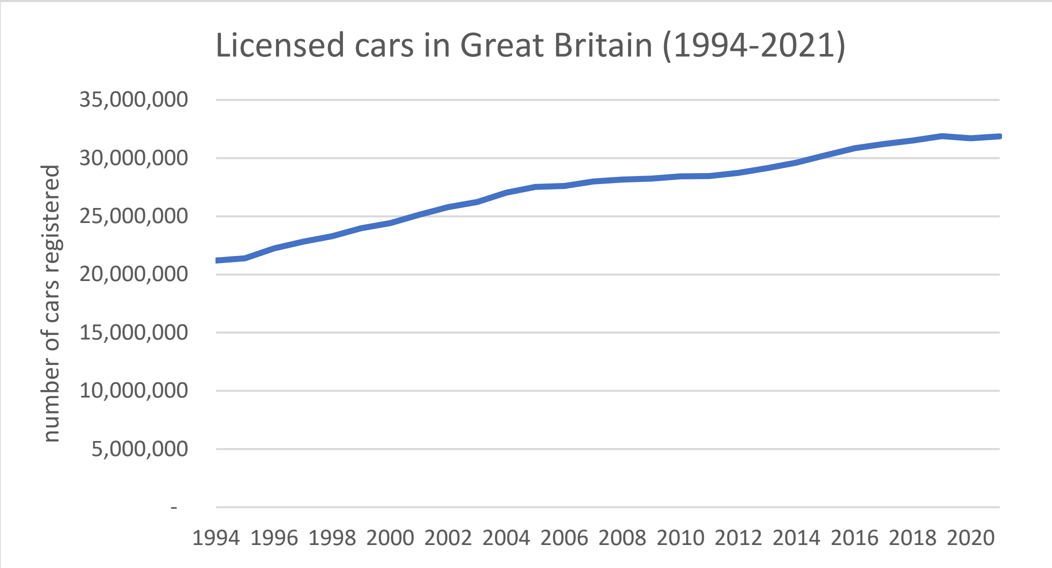

Figure 6-3 Licensed cars in Great Britain 1994-2021 (source:VEH0101)

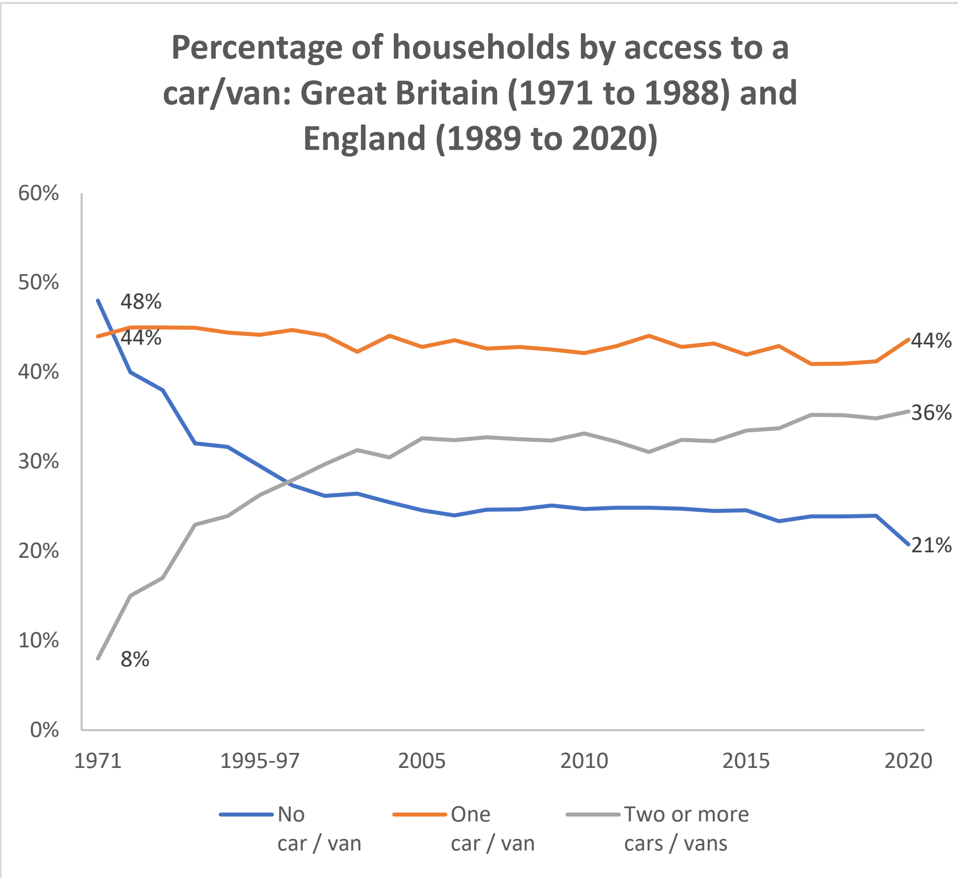

Figure 6-2 Household car availability (source: NTS0205)

Future of mobility: urban strategy (Department for Transport, 2019a) outlines travel trends that are relevant to the context of transition to autonomous vehicles:

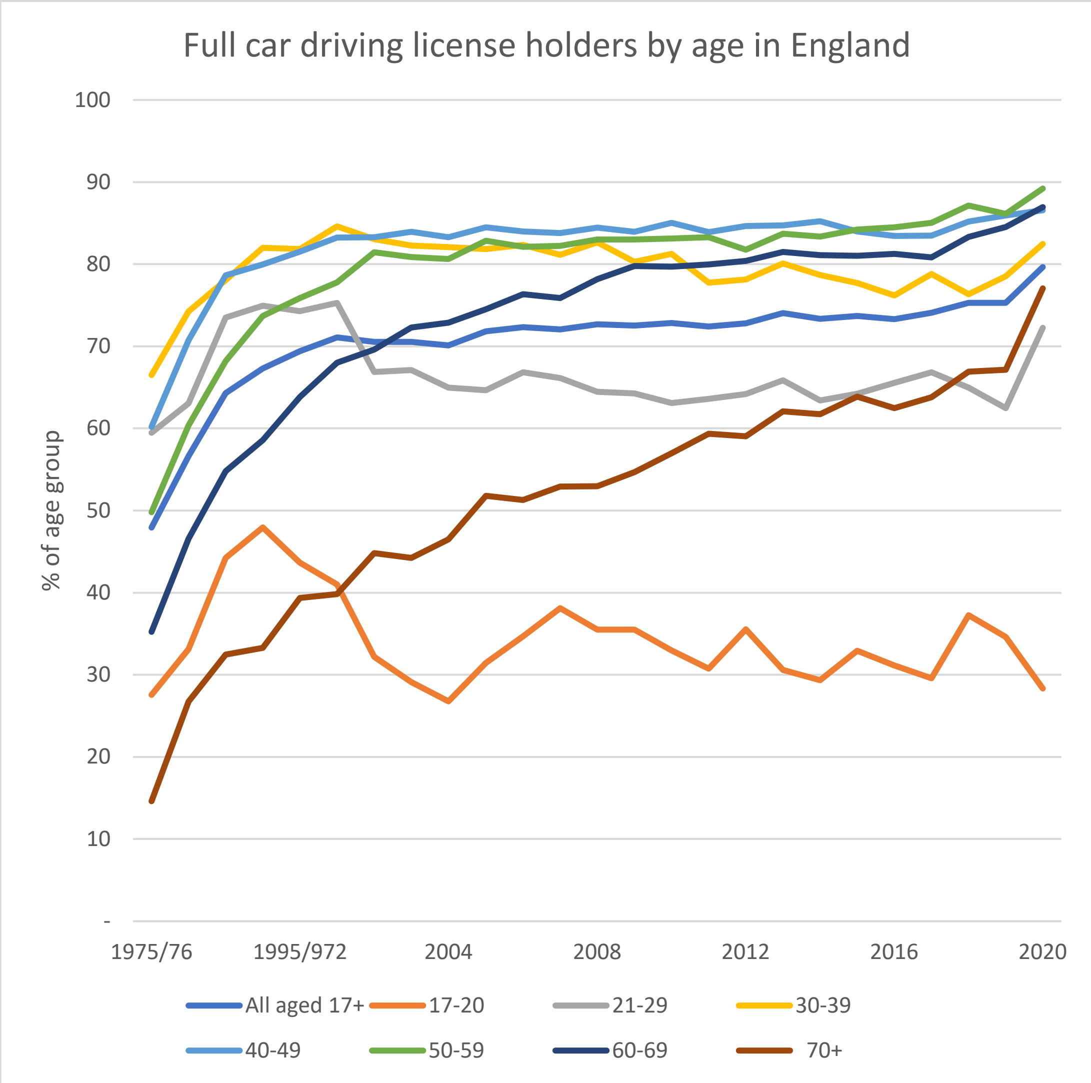

Figure 6-4 Driver license holders by age (data source: nts0201)

- Overall growth in road travel demand across England and Wales is forecast to continue over the coming decades. This is largely driven by population growth (p.21);
- Despite travel demand rising overall, it is falling at an individual level (p.21)
- One of the reasons behind reduced individual travel is a decline in commuting. Between 1995 and 2014, while England's population grew by 11% and employment grew by 18%, commuting journeys fell by 16%. Reasons for this include increases in flexible working, working from home, and part-time and self-employment (3.15).
- Shopping trips have decreased 30% over the past decade, coinciding with a rise in online shopping, which now represents almost 17% of total UK retail sales (3.16).

- The population is ageing and travel choices show clear generational differences: young people are less likely to own cars (3.18), while older people are relying on individual car more (3.19)
- The number of car club members across the UK increased almost eight-fold between 2007 and 2017, to nearly 250,000 members (p.23).

In terms of cultural relevance and association, statistics allow to illustrate the overwhelming dominance of the car in personal travel. National Travel Survey (DfT, 2021a)[22] collects and publishes statistics on travel including travel mode, purpose, and other parameters. Figure 6-5 shows that for distances over 1 mile, a private motor vehicle – the car - is the dominant mode, which establishes the car as the primary mode of transport for the majority of the population.

Recent surveys show that 74% of users agreed that motor vehicle use should be reduced for the sake of public health (Department for Transport, 2020). Active travel has been actively advertised by a number of actions by the Government – Infrastructure Act 2015, Cycling and Walking Investment Strategy (2017), Local Cycling and Walking Infrastructure Plans, however, levels of walking and cycling in England have not significantly changed over the last 15 years (House of Commons Transport Committee, 2019), and the status of the personal car as the main mode of travel remains unchallenged for journeys above 1 mile. Furthermore, British drivers are becoming increasingly more reliant on car as the main mode of transport (RAC, 2020). Car is the dominant mode in modal split in both, distance and number of trips (Department for Transport, 2019b) confirming the ‘locked-in’ status of the car within the automobility regime. Furthermore, national survey found that 38% of respondents do not use public transport at all as part of their commute (Department for Transport, 2020).

[22] National Travel Survey mostly publish data about England specifically on not the rest of the UK, however, there is no evidence that there are vast differences in devolved governments.

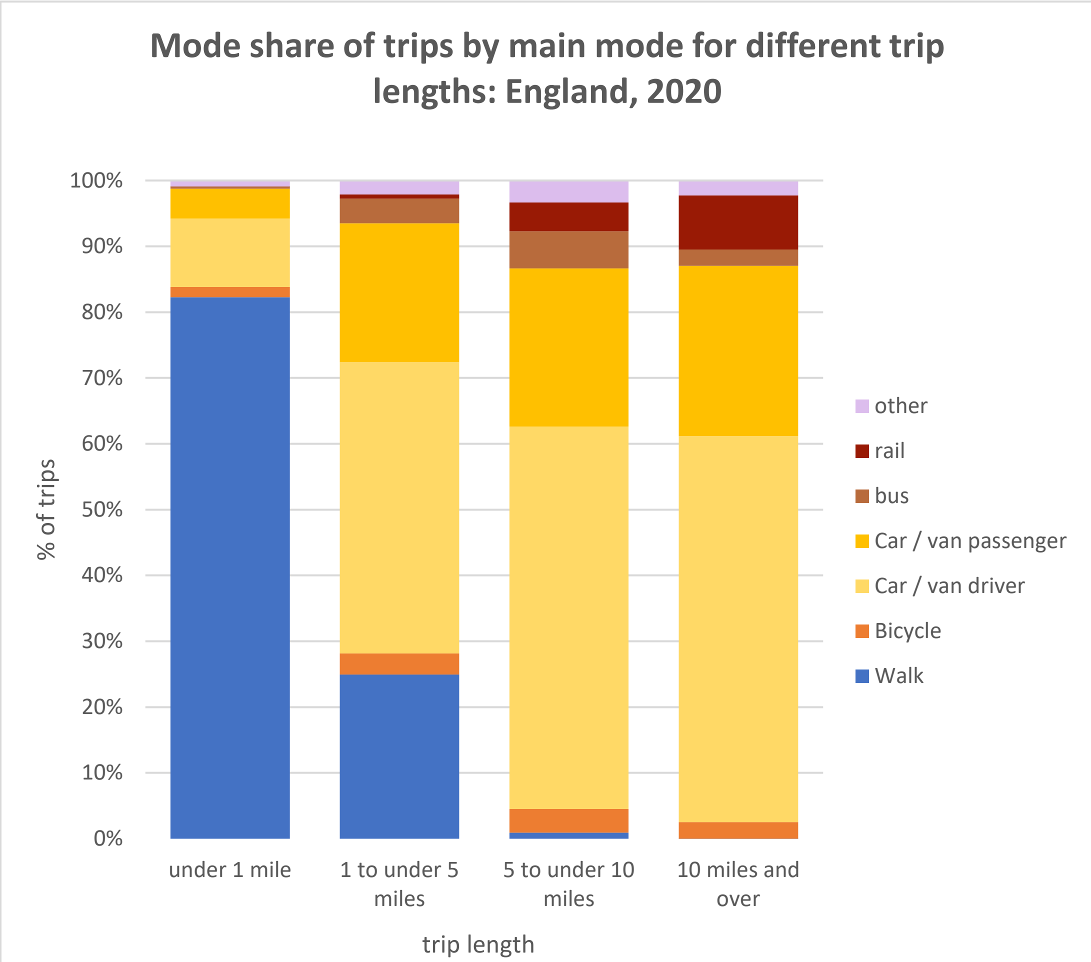

Figure 6-5 Mode share of trips by main mode for different trip lengths: England, 2020 (source:NTS0308)

6.3 Socio-technical system

A system characterised by lock-in and 'unsustainable' practices

Lock-in is common in the transportation domain, meaning that certain technologies, norms, and practices reinforce irreversible effects. For example, the increased use of car has led to increase in city and suburban regions, which, in turn, have increased demand for the use of cars in everyday social and economic activities.

The following sub-sections present components of the socio-technical system in the transition to AVs in the UK: policy and governance; industry; science; culture; markets and user preferences; infrastructure.

6.3.1 Policy and governance

In terms of broader transport policy, historically, the Government has followed the "predict and provide" principle. The first motorway – the M1 – was opened in 1959 signifying a key step towards the car dominated today. Soon after, the Traffic in Towns report by Buchanan (1964) was commissioned and published. The report set the trajectory of the UK transport policy for decades to come and proposals set in the report have resulted in many features of roads and cities today, such as ring roads and flyovers, traffic and pedestrian segregation, parking restrictions, multi-storey inter-city car parks, and others.

Historically, transport governance in the UK has been highly centralized, with decision-making power concentrated in central government. However, this has changed in recent years with the devolution of powers to local and regional authorities. The devolution of powers has led to increased experimentation and innovation in transport governance, with different regions (local and combined authorities) and cities adopting different approaches and strategies to address local transport challenges. There is a growing general recognition across the UK that sustainable and low-carbon transport modes are key to achieving a more sustainable and equitable society, which is reflected in their individual strategy publications (for example, Transport Manifesto by the North East Combined Authority; Transport Strategy by West Yorkshire Combined Authority; Greater Manchester Transport Strategy 2040), with the strategies being influenced by their individual specific geographic, economic, and social contexts. In the context of this thesis, however, there are no distinct strategies identifying their approach to AVs despite some of these strategies reaching as far as 2040.

Figure 6-6 summarises the key governance processes and documents that affect the transition to autonomous driving in the UK. Driverless vehicles were first mentioned in government plans in 2013 National Infrastructure Plan. The report also identified that the UK is following a light touch/non-regulatory approach to the testing and development of driverless cars (HM Treasury, 2013). At the same time, the Centre for Connected and Autonomous Vehicles (CCAV) was established.

Under the Coalition government DfT published the first key document specifically on driverless cars: The Pathway to Driverless Cars Summary report and action plan (DfT, 2015). The UK Government's approach and ambition has been to facilitate the conditions in which the UK can capitalise on the opportunity to develop and market AV. The Department for Transport's view is that the UK can position itself at the forefront of AVs research and development because of "permissive Regulations; thriving automotive sector; and excellent research base and innovation infrastructure" (Clarke and Butcher, 2017).

In 2017 the Government set out to "see fully self-driving cars on the UK roads by 2021" (HM Government, 2017:49).

December 2013 — National Infrastructure Plan 2013 announces that:
"[The Government] will conduct a review, reporting at the end of 2014, to ensure that the legislative and regulatory framework demonstrates to the world's car companies that the UK is the right place to develop and test driverless cars. It will also create a £10 million prize for a town or city to develop as a testing ground for driverless cars.

July 2014 — Innovate UK launches first UK driverless car funding competition

- **February 2015** — Three projects funded - VENTURER, UK Autodrive, GATEway

July 2015
- DfT publishes "The Pathway to Driverless Cars: Code of Practice for testing"
- Centre for Connected and Autonomous Vehicles (CCAV) established

November 2016 — House of Lords launch Inquiry: Connected and Autonomous Vehicles: The future?

- **March 2017** — House of Lords, Science and Technology Select Committee publish Connected and Autonomous Vehicles: The future?

March 2017 — Competition launched to establish a CAV test bed in the UK

September 2017 — Meridian Mobility launched (later rebranded as Zenzic in May 2019)

October 2017 — Winners of CAV testbed competition announced: 4 consortia led by HORIBA MIRA, Millbrook Proving Ground, TRL and the Warwick Manufacturing Group

October 2017 — First reading of Automated and Electric Vehicles Bill (AEV Bill) in Parliament

November 2017 — Industrial Strategy White Paper published with 'Future of Mobility' one of four Grand Challenges and announces that "The government wants to see fully self-driving cars on the UK roads by 2021" (p.49)

March 2018 — Government and Law Commission of England and Wales and the Scottish Law Commission launch a three-year review of driving laws in preparation for self-driving vehicles

May 2018 — AEV Bill Committee stage: House of Lords

July 2018 — AEV Bill receives Royal Assent and becomes and Act of Parliament (law)

March 2019 — Future of mobility: urban strategy published. It presents principles that the Government will follow to "seize the opportunities from the changes happening in urban transport"

- **January 2022** — Code of Practice: automated vehicle trialling updated to provide more clarity on government's expectations for responsible trials of autonomous vehicles

January 2022 — Law Commission automated vehicles joint report published and laid before Parliament and the Scottish Parliament.

Figure 6-6 Timeline of CAV related governance processes (by author)

6.3.1.1 Identifying key governance actors and their roles in the transition to AVs in the UK

Many Government organisations do work related to autonomous vehicle guidance and research:

- Department for Transport (DfT);
- Centre for Connected and Autonomous Vehicles (CCAV);
- Department for Business, Energy & Industrial Strategy (BEIS);
- Department for International Trade (DIT);
- Driver & Vehicle Standards Agency;
- Driver & Vehicle Licensing Agency;
- Government Office for Science;
- Office for Zero Emission Vehicles;
- UK Atomic Energy Authority;
- Innovate UK;
- Innovate UK Knowledge Transfer Network (KTN);
- Highways England;
- UK Space Agency

The highlighted departments and organisations have a direct recognisable role in shaping the AVs transition, as outlined below:

Department for Transport. DfT has a significant role in governance processes. DfT set up CCAV to further the CAV agenda in the UK. DfT as a government department (in the context of AVs transitions) is responsible for investing in and maintaining road networks and establishing digital infrastructure requirements for CAV deployment. DfT also developed the first guidance for CAV testing and trialling with the goal to ensure high standards of safety and security, including cybersecurity.

Centre for Connected and Autonomous Vehicles. CCAV was established by DfT and BEIS with the aim to promote and establish UK's position in AVs development, production, testing, and deployment. CCAV work with industry, academia, and regulators and are involved in AVs policy development and R&D funding.

Department for Business, Energy & industrial Strategy (BEIS) and ***Department for International Trade*** (DIT). Both departments work towards ensuring and promoting business growth in the UK. DIT specifically works on bringing overseas investors and supporting UK export. BEIS published the Industrial Strategy that set out the Government's ambition "to see fully self-driving cars on the UK roads by 2021" in the Industrial Strategy (2017).

Innovate UK is a government agency (non-departmental public body) that aims to support innovation. It is also part of the UK Research and Innovation and funds business-led innovation in all sectors, including connected and autonomous vehicles. ***Innovate UK KTN***[23] is a nation-wide network that works to create connections between innovators to form new partnerships and accelerate innovation.

Other organisations that have links with the UK governance actors and have a role in AV:

Zenzic (formerly Meridian) is a government-backed and industry-led organisation created to accelerate what the Government calls the "self-driving revolution". Zenzic has produced a CAV Roadmap – a tool that tracks the developments of CAV in the UK. Zenzic also coordinates CAM Testbed – a network of six facilities for modelling, simulation, testing, and trials of CAV.

6.3.1.2 Industrial Strategy in context

The "Industrial Strategy: building a Britain fit for the future" (HM Government, 2017) was a long-term plan to boost productivity and economic

[23] KTN was joined with Innovate UK following the action plan that Innovate UK set out in November 2021.

growth across the UK. This aligned with earlier policy statements by the Coalition government – the Plan for Growth (HM Treasury and BEIS, 2011) that set out key objectives to achieve economic growth – and 2015 White Paper "Fixing the Foundations" (HM Treasury, 2015). The Industrial Strategy focused on four "grand challenges" that the UK faces: AI and data, clean growth, future of mobility, and aging society. It aimed to address these challenges by investing in research and development, upgrading infrastructure, and supporting businesses.

The Industrial Strategy is a key white paper[24] that set out UK's vision for AVs on roads by 2021. Under the future of mobility challenge, the Industrial Strategy outlines the Government's goal to become a world leader in the development and deployment of connected and autonomous vehicles. It highlights the need to invest in the necessary infrastructure, such as 5G networks and charging points, and to create a regulatory framework that supports innovation and safety. The Industrial Strategy also includes sector deals, which are agreements between government and industry to boost productivity and competitiveness in specific sectors. The Automotive Sector Deal, for example, aims to secure the UK's position as a global leader in the development and manufacture of low-carbon vehicles.

Significantly, self-driving cars was singled out as one of the four "early priorities" in the Industrial Strategy and specific areas of focus were identified in the Industrial Strategy:

> *"We will establish a flexible regulatory framework to encourage new modes of transport and new business models Mobility has always depended on standards. Our regulatory environment must evolve with the times to support the emergence of new technologies and new business models. We will ensure we*

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[24] White papers are policy documents produced by the Government that set out their proposals for future legislation.

continue to have one of the most open environments in the world for transport innovation and new services by undertaking a thorough regulatory review of all relevant legislation. The Government wants to see fully self-driving cars, without a human operator, on UK roads by 2021. We will therefore make world-leading changes to the regulatory framework, including updating our code of practice for testing automated vehicles to allow developers to apply to test their vehicles nationwide without a human safety operator and carrying out a project with the Law Commission to set out proposals for a long-term regulatory framework for self-driving vehicles." (HM Government, 2017:50)

And

"We will prepare for a future of new mobility services, increased autonomy, journey- sharing and a blurring of the distinctions between private and public transport." (HM Government, 2017:51)

And

We will explore ways to use data to accelerate development of new mobility services and enable the more effective operation of our transport system We will continue to invest in R&D and testbed infrastructure for connected and autonomous vehicles. We will explore how simulated digital environments can support and accelerate development of self-driving technology through an R&D competition to be launched by the Centre for Connected and Autonomous Vehicles, the first R&D competition of its kind in Europe. (HM Government, 2017:51)

The Industrial Strategy also links the potential of CAV with another 'grand challenge' identified that is the ageing society. As demonstrated, the Government set the ambition for fully-self driving cars and identified the need for an updated regulatory framework, R&D investment, and testing infrastructure as key priorities for achieving that ambition from the Government's perspective.

Another significant part of the Industrial Strategy is the long-term objective to raise total R&D investment to 2.4% of GDP by 2027 (in 2019 it was 1.74%). Alongside the Industrial Strategy, the Business Secretary launched a new fund – Industrial Strategy Challenge Fund – aimed at addressing "the big societal challenges being faced by UK businesses today" (ukri.org, n.d.). It named six key areas of funding, self-driving vehicles being one of them (BEIS et al., 2017).

6.3.1.3 AV R&D funding landscape in the UK

Department for Transport together with Department for Business, Energy & Industrial Strategy established Centre for Connected Autonomous Vehicles (CCAV) in 2015 to deliver on the Government's ambition in autonomous mobility sector, namely in three key areas (Centre for Connected & Autonomous Vehicles, 2018):

- Regulation
- Research and development
- Testing infrastructure.

Since 2014 the Government has invested £120m in AVs projects, with additional £68m funding coming from industry (Centre for Connected & Autonomous Vehicles, 2018). Initial AVs trials were launched in four towns, which have since been followed by over 80 collaborative R&D projects in multiple funding rounds and streams (Innovate UK and UK Research and Innovation, 2020), involving major globally significant research and manufacturing bodies in the UK.

CAV funding has been targeted to support the delivery of CAV that aligns with policy strategy. CAV funding has been allocated in alignment with policy delivery in stages with each aiming at a specific step in CAV development. The funding rounds are summarised in Table 6-1.

Table 6-1 List of CAV R&D funding rounds and number of funded projects (by author, data source: UKRI (2022))

2014: Four Cities Trials
GATEway
UK Autodrive
VENTURER
2015: Connected and Autonomous Vehicles 1 (encourage development of CAV)
8 collaborative R&D projects
12 feasibility studies
2016: Connected and Autonomous Vehicles 2 (technical solutions for CAV features that will provide real-world benefits to users)
15 collaborative R&D projects
12 feasibility studies
2017: Connected and Autonomous Vehicles 3 (business opportunities or real customer problems, with a clear commercial benefit)
10 collaborative R&D projects
11 feasibility studies
2018: Connected and Autonomous Vehicles: simulation and modelling solutions
6 projects
2018: Connected and AVs 4: piloting passenger services
3 projects
2018: Meridian 3, autonomous highway, rural and parking test facilities
3 projects
2019: Connected and Autonomous Vehicle Cyber-Security Feasibility Studies
7 projects

Across the over 90 funded projects a total of 223 organisations have participated in at least one project. Some participants have participated at a number of projects. Table 6-2 shows participants on these project show have been involved in at least three projects. The list is colour-coded by industry/sector. It shows that the majority of participants are not from the automotive sector. Noticeably while CAV projects in the UK have been industry-led, there is a large representation of academic institutions. Academic institutions participating in AVs R&D projects are listed in Table 6-3. Table 6-4 summarises ten R&D participants who have been classified as 'large industry participants'. From those, only two are automotive manufacturers -Jaguar Land Rover and Arrival, while most others are large technology, IT, and engineering companies.

Table 6-2 Participants who have worked on 3 projects or more, colour-coded by sector/industry (by author, data source: UKRI (2022)*)*

Participant	Industry/sector	Number of projects
University Of Warwick	academic	17
Horiba Mira Limited	manufacturer of precision instruments for measurement and analysis	12
Jaguar Land Rover Limited	Vehicle manufacturer	10
Transport Systems Catapult	Government's innovation agency	10
Trl Limited	Transport research and consultancy	10
Oxfordshire County Council	County council	7
Oxbotica Limited	Autonomous vehicle software company	7
Aimsun Limited	Transport simulation software	6
United Kingdom Atomic Energy Authority (Ukaea)	Government organisation	6
Coventry University	academic	6
University Of Bristol	academic	5
Westfield Sports Cars Limited	Manufacture of motor vehicles	5
Cranfield University	academic	5
Dg Cities Limited	Tech consultancy	4
Fusion Processing Ltd	Autonomous driving systems	4
Immense Simulations Limited	Mobility simulations	4
Avl Powertrain Uk Limited	Engineering consultancy (development, testing simulation in the automotive sector)	4
Transport For London	Local government body	4
Heathrow Enterprises Limited	Holding company - airports	4
Cisco International Limited	IT, networking, cybersecurity	3
Thales Uk Limited	Electrical systems; defence	3
Idiada Automotive Technology Uk Ltd.	Design, engineering, testing and homologation services for the automotive industry	3
Arrival Limited	Electric vehicle manufacturer	3
Sbd Automotive Limited	Automotive technology and security consultancy	3

Amey Ow Limited	Engineering consultancy	3
University Of The West Of England	academic	3
South Gloucestershire Council	Local authority	3
University Of Oxford	academic	3
West Midlands Combined Authority	Local authority	3
Myrtle Software Limited	Machine learning optimisation	3
University Of Nottingham	academic	3
University Of Leeds	academic	3
Richmond Design & Marketing Limited	Automotive OEM	3
Conigital Ltd	Driverless vehicle IT consultancy	3
The University Of Surrey	academic	3
Loughborough University	academic	3
Imperial College London	academic	3

Table 6-3 Academic participants and number of projects participated in (by author, data source: UKRI (2022))

Academic Participant	**Number of projects**	**Academic Participant**	**Number of projects**
University Of Warwick	17	Imperial College Of Science, Technology And Medicine	2
Coventry University	6	University Of Southampton	1
University Of Bristol	5	University Of Sheffield	1
Cranfield University	5	University Of Salford	1
University Of The West Of England	5	University Of Portsmouth	1
University Of Oxford	3	University Of Bath	1
University Of Nottingham	3	University College London	1
University Of Leeds	3	Manchester Metropolitan University	1
The University Of Surrey	3	Harper Adams University	1
Loughborough University	3	Euratom/CCFE	1
Imperial College London	3	Edinburgh Napier University	1
University Of Liverpool	2	Durham University	1
University Of Birmingham	2	Cardiff University	1
United Kingdom Atomic Energy Authority (Ukaea)	2	Birmingham City University	1

Table 6-4 Large industry participants and number of projects (ten with most projects) (by author, data source: UKRI (2022))

Participant	Industry/sector	Number of projects
HORIBA MIRA LIMITED	manufacturer of precision instruments for measurement and analysis	12
JAGUAR LAND ROVER LIMITED	Vehicle manufacturer	10
AVL POWERTRAIN UK LIMITED	Engineering consultancy (development, testing simulation in the automotive sector)	4
CISCO INTERNATIONAL LIMITED	IT, networking, cybersecurity	3
THALES UK LIMITED	Electrical systems; defence	3
IDIADA AUTOMOTIVE TECHNOLOGY UK LTD.	Design, engineering, testing and homologation services for the automotive industry	3
ARRIVAL LIMITED	Electric vehicle manufacturer	3
TRL LIMITED	Transport research and consultancy	3
Amey OW Limited	Engineering consultancy	3
HEATHROW ENTERPRISES LIMITED	Holding company - airports	3

Most of the funded projects so far have been demonstrators, providing glimpses into futures envisioned by industry; however, we can expect significant changes to still take place before we see fully AVs on roads. Demonstrators take place in highly controlled environments and therefore do not need to account for uncertainties and risks associated with real-life driving situations, such as unexpected behaviours of other road users, confusing or lacking signage, and even poor-quality road markings.

6.3.1.4 Regulation

The Government can intervene in technological innovation and deployment processes through regulation. Driving behaviour is one such aspect. For example, a law requiring all drivers to wear seatbelts came into force in 1983, and subsequently in 1993 a requirement for all adults in car to wear seatbelts was introduced. This is an example of how the Government responded to increasing car use, driving speeds and associated safety risks by directly regulating driver behaviour. The prospect of a vehicle not having an identifiable driver poses questions about liability in case of an accident.

For AVs to be deployed on public roads at scale, there needs to be a clear regulatory framework that sets out provisions for areas such as liability, insurance, safety, testing, vehicle and infrastructure standards, and others.

International agreements

There are international agreements in place to facilitate road and vehicle safety. Geneva Convention (1958) (known also as “1958 Agreement”) sets out a legal framework for a set of common technical requirements for vehicles and parts. Vienna Convention on Road Traffic (1968) is an international treaty designed to facilitate international road safety by establishing standard traffic rules amongst the contracting parties. Both conventions set out that the driver can at all times control the vehicle. Vienna Convention was amended in 2016 to allow some autonomous driving systems as long as they comply with international regulations and can be overridden or deactivated, if necessary. The UK has ratified both conventions.

Insurance and liability

The Automated and Electric Vehicle Act 2018 set out insurance compensation routes for autonomous vehicles. This provides a legal framework for testing AVs on roads and clarifies that if the autonomous vehicle causes damage to another party, the compensation route is within the motor insurance settlement framework, not through product liability against manufacturer. This Act is one of very few examples where the legislation significantly predates the technology (Atkinson, 2020).

AV testing

In the initial legislative review by DfT, it found that there are no legal barriers for AVs testing, as long as a suitable safety driver is provided. With automated driving technology reaching stages where vehicles are capable of performing driving tasks without human intervention, there is a need for regulation that sets out how to assess the safety of these tests and who is liable in case of an accident. To further this issue, the Law Commission has launched an extensive review process on AVs of the legal framework for automated vehicles with focus on their use as part of public transport networks and on-demand passenger services in the future (Law Commission, 2020). The review findings were published in 2022 (Law Commission, 2022) and set out recommendations for legal reform that set out "initial approval and authorisation of self-driving vehicles, ongoing monitoring of their performance while they are on the road, misleading marketing, and both criminal and civil liability" (Law Commission, 2022:online).

In contrast with other countries, the UK is adapting a Code of Practice rather than a regulatory approach to AVs testing. DfT expects this to be a key factor in capturing the AVs testing and piloting market.

6.3.2 Industry

The Automotive sector Deal in Industrial Strategy anticipates that AVs will bring significant changes to how vehicles are manufactured, powered, used, and driven, and it sets out that the industry "must continue to adapt to maintain its position as a global leader" and it must also "take decisions now to ensure it remains both attractive to invest in and central to the UK economy" (BEIS, 2018:online).

UK automotive industry

The UK is one of the biggest car manufacturers in the world, ranking 16th globally and 5th in Europe (Table 6-5). 17 of the world's 20 biggest automotive suppliers have a UK base (SMMT, 2019c). Having a strong automotive industry is an indication of the technological capability to design, develop, and test new technologies.

Table 6-5 Global vehicles manufactured by country in 2020 (source: oica.net)

	country	**2020**
1	CHINA	25,225,242
2	USA	8,822,399
3	JAPAN	8,067,557
4	GERMANY	3,742,454
5	SOUTH KOREA	3,506,774
6	INDIA	3,394,446
7	MEXICO	3,176,600
8	SPAIN	2,268,185
9	BRAZIL	2,014,055
10	RUSSIA	1,435,335
11	THAILAND	1,427,074
12	CANADA	1,376,623
13	FRANCE	1,316,371
14	TURKEY	1,297,878
15	CZECH REPUBLIC	1,159,151
16	**UNITED KINGDOM**	**987,044**

Figure 6-7 Jaguar Land Rover concept vehicle (source: jaguarlandrover.com)

Because of the permissive policy and regulatory approach and automotive sector having a strong lobby position, the futures that the industry actions envision (for example, visions developed by two leading vehicle manufacturers in the UK Nissan and Jaguar Land Rover in Figure **6-7** and Figure **6-8**)can have a significant importance on how the transition takes place and what the outcomes are.

Figure 6-8 Nissan future of mobility vision developed together with Foster + Partners (source: nissannews.com)

SMMT

The Society of Motor Manufacturers and Traders (SMMT) is the largest automotive trade association in the UK. It aims to support and promote its members interests through voicing members' views, guiding strategies and developing relationships with the Government and regulatory bodies. They represent more than 800 automotive companies in the UK (SMMT, n.d.).

SMMT is "heavily involved in political lobbying on behalf of the industry to ensure this vital sector of the economy is effectively represented to government" (SMMT, n.d.) . SMMT is involved in the All-party Parliamentary Motor Group (APPMG) in the parliament where it can directly promote members' interests in the parliament. The APPMG describes its purpose as "to debate current and future issues of strategic importance to the UK's automotive industry, motorsport industry and vehicle users, focusing on the role of the motor vehicle, including the environmental impact; and to promote dialogue between politicians, these industries, users and other stakeholders” (parliament.uk, 2020).

SMMT have previously voiced criticisms from the automotive industry’s perspective about government measures aimed at lowering transport emissions. As an automotive lobby group, SMMT have objected to a number of government policies and proposals related to transportation, mainly to do with measures aimed towards zero emission futures citing negative impacts it would have on the industry. For instance, SMMT CEO Mike Hawes in 2020 argued that low-emission zones that proposed to ban diesel cars were causing confusion and reducing consumer confidence (Heaphy, 2020). SMMT together with major carmakers – BMW, Ford, Honda, Jaguar Land Rover and McLaren – have also argued that ban on sales on new petrol and diesel cars should be delayed because otherwise it would affect the industry’s commercial viability (Jolly, 2020).

In AVs context specifically, so far SMMT has been supportive of the Government’s approach, especially regarding the permissive regulatory approach (SMMT, 2017). From transitions perspective, this is a significant actor that represents incumbents and can use its powers to delay disruptive shifts. Simultaneously, if such actor is supportive of particular policies, it can play a significant role in achieving the desired outcomes.

6.3.3 Science

In the science sub-system there are multiple strands that are relevant to the case study.

Firstly, the technological development. Autonomous driving is still at an early stage and therefore research and innovation are critical aspects of technology to make it road and market ready. This chapter has evidenced in other categories the R&D activities that are happening in the AVs development domain, and the also relate to the science sub-category of this socio-technical system, including R&D funding, technological advances, education programmes, and partnership building.

Secondly, DfT has developed a DfT Science Plan: the vision for science in DfT (DfT, 2021b), which sets out the departmental strategy of engaging with science through three pillars: people, partnerships, and purpose. These are aligned with the broader Strategic Priorities of DfT, which are to improve connectivity across the UK to support economic growth; to improve user experiences with transport by ensuring safe, reliable, and inclusive transport networks; decarbonising transport; innovative outward-facing industry to maximise global trade; internally well-functioning department. The People pillar is aligned with "capability building in the wider transportation sector" (DfT, 2011:14) through supporting new skills development and establishing a 'talent pipeline'. Partnership aspect prioritises R&D activities and developing partnerships between businesses and industry, and government departments. Third pillar – Purpose – sets out to engage with science in policy and decision-making.

The strategic pillars encourage engagement with the transportation research in academia. At a strategic and planning level there are contributions from researchers on transport governance and climate change (Marsden and Rye, 2010), smart mobility (Docherty et al., 2018), and also AVs specifically (Stilgoe, 2018; Cohen and Cavoli, 2019). Engagement between the governance and the social sciences is also evident in Autonomous Vehicles: What can Social Science offer? report that evidences a dialogue between governance actors and social researchers and sets out potential avenues for contribution and collaboration between the two. Additionally, government commissioned research shows evidence of the governance actors seeking specific knowledge from academic experts, providing avenues for academic research to contribute to governance processes.

6.3.4 Culture

In socio-technical transitions context, culture represents the “cognitive” rules that are present in a socio-technical system. Cognitive rules refer to beliefs, knowledge, and agendas. In the system of automobility and driverless mobility transitions the cultural beliefs can impact the transition process.

Attitudes towards autonomous vehicles

Because AVs is not yet an established innovation, single events can change the discourse, especially the public opinion more than established technologies. For example, the widely reported Uber’s self-driving vehicle crash that killed a pedestrian caused a widespread media coverage and concern, and resulted in temporary suspension of self-driving car testing in Arizona, US. Because AVs is a novel technology that disrupts the accepted norms and behaviour, and trust around the practice of driving, such events can dramatically shift the public opinion more than similar accidents happening with human-driven vehicles.

Societal acceptance is pivotal for successful advance of any innovation. The Government appears to recognise this and has taken proactive steps by commissioning research on how to improve public perception on AVs to ensure and accelerate AVs deployment (Kantar Public, 2018). Public attitudes can also influence how and when a technology is introduced by making a choice as consumers and also by supporting or opposing policies and political parties based on their perceptions and desires (Litman, 2014; Fagnant and Kockelman, 2015; Hohenberger et al., 2017; Penmetsa et al., 2019). DfT has commissioned research into public awareness of and attitudes to current and emerging transport technologies, which includes AV.

The public opinion tracker is published approximately every six months and allows to assess public opinion and awareness over time. Currently (2017-2019), it shows little change over time for awareness and knowledge on AVs (Figure 6-9), however, the tracker was launched in 2017 and therefore does not yet provide long-term trends. From the existing data, it can be concluded that over 80% of the population are aware of the AVs technology, and over half (51%-62%) claim to have some knowledge about AVs (Kantar, 2020). Public opinion trackers reveal that majority of people are aware of the AV, however, most are able to name more disadvantages than advantages of AVs (Kantar Public, 2019).

Another aspect to consider in cultural and societal attitudes towards new technology is the impact of singular negative events. When Elaine Herzberg was fatally hit by a vehicle in self-driving mode, it elevated questions about safety and trust in autonomous driving in the society through increased press coverage and debate. While it is impossible to estimate what the impacts of such accidents are on innovation trajectories due to it still being an ongoing process, it seems likely that single events can impact the public attitudes towards new technologies more than they do with established technologies and systems.

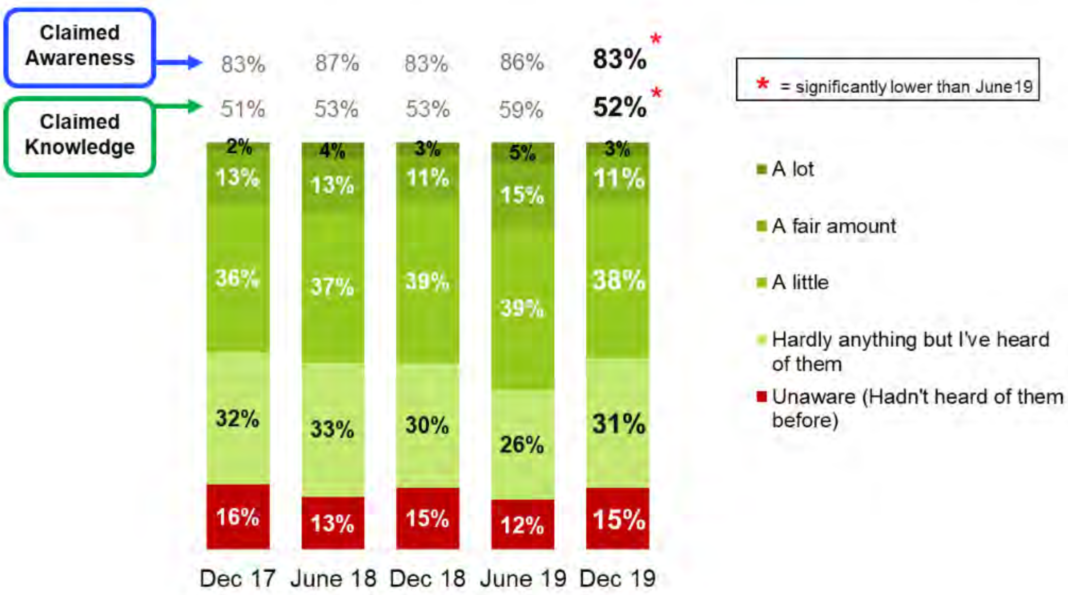

Figure 6-9 Awareness and knowledge of AVs (source: Kantar (2020:5))

Finally, landscape changes can impact public attitudes and change them at a system level. People are increasingly more concerned about the climate change (ONS, 2021). It does not reflect in observable consumer attitude and behaviour changes around automobility yet, but it can lead to shifts in the future.

6.3.5 Markets; user preferences

Markets

A move to autonomous driving systems will see a shift in jobs associated with the industry. While in traditional sense of automobility developments the innovation related directly to the vehicles and their components – powertrains, drivetrains, chassis, materials, the development, deployment and maintenance of connected and AVs will involve skills that do not have the traditional automotive engineering backgrounds – electrical and software engineering, machine learning, artificial intelligence, data science (SMMT, 2017). The anticipation of the market change is observable in other actors too: governance actors seeking to understand and predict the market change (DfT, 2015, 2016) and educational institutes developing and introducing education programmes specific to AVs (Table 6-6). The institutions that have developed these programmes are the institutions that have participated in the R&D projects (see above), demonstrating a link between R&D activities and addressing the market needs.

Table 6-6 Examples of UK universities offering CAV related courses (by author)

University	Programme
University of Warwick	MSc Smart, Connected and Autonomous Vehicles (SCAV)
Coventry University	Connected Autonomous Vehicle Systems MSc
Cranfield University	Connected and Autonomous Vehicle Engineering (Automotive) MSc

User preferences

While the fully-AV future might seem distant, they might dominate the roads a couple decades after the first fully autonomous car reaches market.

Currently, the average age of the car on the UK roads is 8 years (SMMT, 2019a).On average, in the UK car users upgrade their personal car every 4 years, while a vehicle stays on road for an average of 15 years (Aucock, 2011). This number is decreasing, especially as people and companies favour leasing instead of buying. The change to leasing is also indicating the societal shift of personal association with the car; however, it is too early to speculate on how this trend will affect the personal vehicle and AVs market. The broader societal attitudes to vehicles (see landscape section above) and public attitudes towards AVs (see previous section)

6.3.6 Infrastructure

Autonomous vehicles require specific infrastructure provision to operate on roads:

- Physical infrastructure
  - High quality and standardized road signs and marking
  - Fuel/charging access
  - Quality of road surfaces
- Digital infrastructure
  - Up-to date mapping information (including roadworks, road closures etc)
  - Roadside communication and connectivity
  - Cybersecurity.

DfT is the Government department responsible for infrastructure. DfT are responsible for the following areas of infrastructure that relate to AV:

- provide policy, funding and guidance to local authorities to support road infrastructure functionality and development;
- invest in and maintain motorway network;
- promote low carbon and active travel;
- are responsible for safe and secure transport.

An important step in preparing vehicles, roads, and users for driverless cars, is testing infrastructure that allows to narrow the gap between concepts, visions, and simulations and real-world deployment. A network of testing sites has been created in the UK to provide a comprehensive testing environment for connected and autonomous vehicles.

6.4 Niche innovations

Many of the features seen on new vehicles in the market can already be associated with automation. With increasing digital technology presence, software and automation component market are establishing their presence in transport and mobility sector. AVs sensors and ADAS (Advanced Driver Assistance Systems) components are already one of the biggest areas of mobility investments globally, having grown from 0.6bn to 5.6bn (2010 to 2019) (Holland-Letz et al., 2019), indicating that technological megatrends are impacting mobility (McKinsey&Company, 2019). While fully AVs do not exist on roads yet, ADAS features such as assisted parking, ABS, adaptive cruise control, lane detection, automatic emergency braking, blind spot assistance, and others are common and can be considered as incremental technological evolution steps towards full automation. Traditional automobility markets are being disrupted by new self-reinforcing disruptors, that have been summarised as ACES (autonomous; connected; electric; shared) (Holland-Letz et al., 2019).

Specifically to autonomous vehicles, there are technologies and innovations that are required to perform the self-driving functionality. These range from physical devices – sensors, radars, cameras – to data and software solutions – mapping, navigation, data processing, situational awareness, decision-making algorithms, communication, machine learning, AI. In contrast to traditional vehicles, which offers some of the driver assistance features, self-driving vehicles will rely solely on the hardware and software of the vehicle to fulfil the driving function. This shift has led to new actors appearing in the automobility industry. Some of these actors are established technology giants, such as Google and Apple, while others enter as start-ups offering AVs solutions previously unknown or unrecognised in the automobility markets. This is also reflected in mobility investments. McKinsey Center for Future Mobility have estimated that “95 percent of disclosed

investments in companies focusing on any of the four disruptive trends come from nonautomotive players—over 50 percent of which are tech players" (Heineke et al., 2017) ('four disruptive trends' refer to ACES).
The trend is reflected in the automobility sector in the UK.

Table 6-7 summarises all companies launched in the UK that have launched in the automotive sector and specifically self-driving vehicle industry. Aligning with the emergent global trends, in the automotive sector in the UK the vast majority of

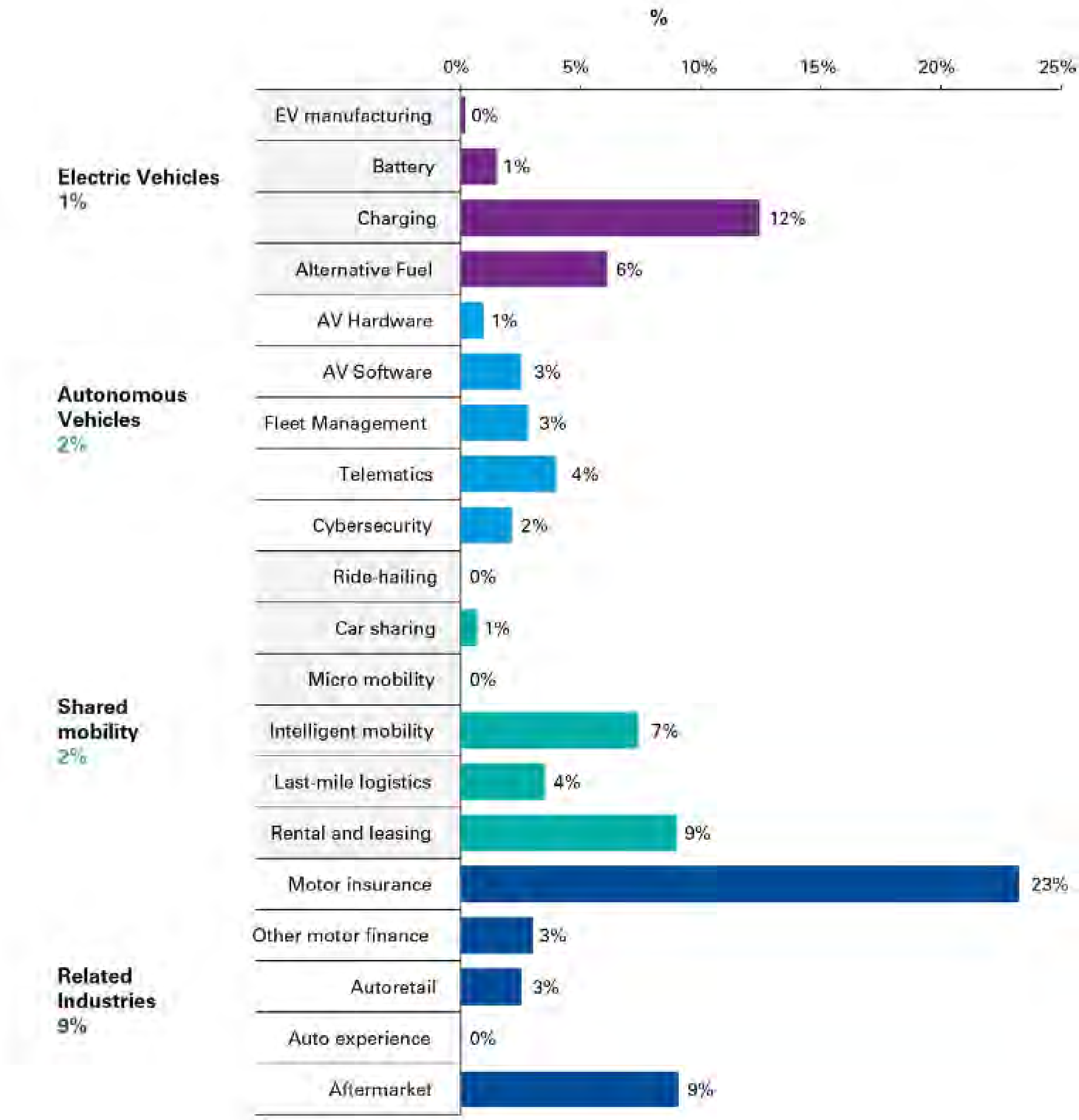

Figure 6-10 UK proportion of capital invested across key mobility sectors (2015-19) (source: KPMG (2020:12))

companies are software-based companies developing solutions for autonomous driving (Figure 6-11).

Table 6-7 UK AVs start-ups (by author)

Company	Year founded	Industry/description	notes
Academy of Robotics	2016	Autonomous delivery vehicle development focused on last mile local delivery	
Arrival	2015	Lightweight electric commercial vehicles	Arrival is a lead participant in the Government-funded Robopilot autonomous vehicle project, as well as a consortium member of the OmniCAV and MultiCAV projects.
Autopia	2018	AV software to optimise network performance	
Baro Vehicles	2015	autonomous vehicle platforms	
Blue Vision Labs	2016	augmented reality technology	acquired by Lyft for $72m in 2018
Cube Intelligence	2017	Car network security	
dRISK	2019	autonomous vehicle software for edge cases testing	
Eatron	2017	Control systems, software	
ECAVIA	2016	Web portal for connectivity	
Five; five.ai	2015	Cloud based development and assurance platform	
Humanising Autonomy	2017	AI-enabled software for autonomous vehicles; solutions based on pedestrian intent	
Imperium Drive	2019 (in Berlin)	Remote driving technologies for AV	Founded in Berlin, but moved to UK because they found that testing and development was easier and more streamlined
LGN	2019	AI-enabled perception system for AV	

Machines With Vision	2015	Low-cost localisation & dynamic positioning solutions for autonomous driving, railways, robotics	
neurobotX	2019	Neural networks for smart navigation of drones	
ODIGA	2015	Neuromorphic vision systems for driver safety & security	
Oxbotica	2014	AV driving software using computer vision and machine learning	
Roborace	2015	Organises racing leagues for AV	
Small.	2014	Design/technology group	
StreetDrone	2017	AV software and technology	Has partnered with Renault and Nissan to test vehicles
Synaptiv	2017	Data analytics platform focusing on generating value from car/sensor data	Backed by InMotion Ventures (Jaguar Land Rover subsidiary)
The Floow	2012	Auto telematics; learn about drivers behaviours to price cover appropriately	
Waywe	2017	Deep learning AI technology for AVs driving	
Zenzic	2019	Public-private collaboration aiming to bring together industry, academia, government and channel investments	

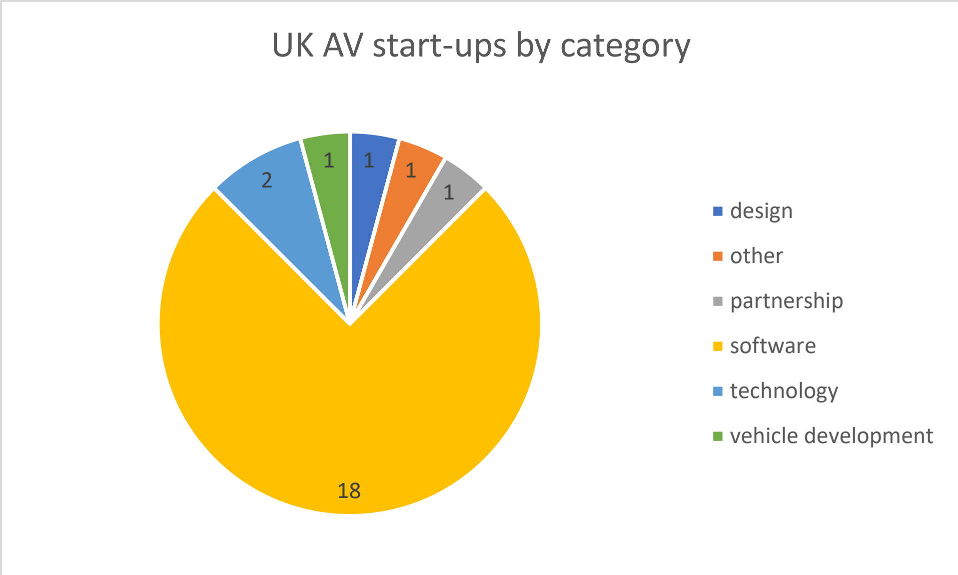

Figure 6-11 UK AV start-ups by category (by author)

Another observation is that the system actors are engaging with niche actors through forming partnerships. For instance, in 2017 StreetDrone partnered with Renault – a traditional automotive manufacturer – to develop a self-driving vehicle. There is also evidence of similar partnerships that do not involve automotive actors, for example, Wilko – a homewares and household goods retail chain – becoming a lead investor in StreetDrone with the ambition to develop “car-sized robotic delivery units” (Nott, 2021). Another start-up Blue Vision Labs, who develop augmented reality, have been acquired by Lyft – a mobility services provider.

6.5 Chapter summary

This chapter has presented analysis and findings for the first step of the SRPM framework (identification of entities and interpretation of observations based on MLP theoretical framework). This chapter has developed the case study by contextualising the ongoing transition to AVs in the UK. The use of the MLP theoretical lens enables categorisation of distinct, but inter-related areas of AV. The landscape developments position the AVs discourse in the broader discourse of the climate change and the decarbonisation discourse.

The system-level analysis reveals a significant interest in the AVs technology by the incumbents, including the governance actors who see societal, environmental, and economic benefit in AV. Regulatory, funding, and infrastructural development are enabling furthering of the technology.

At the niche level there are no distinct innovations that directly compete with incumbents. The innovations in autonomous mobility are part of broader shifts in the transportation sector and can be summarised as furthering specific aspects of automobility, rather than developing a competing alternative innovation. In the UK context, there are examples that demonstrate behaviours that characterise niche-system interactions. Those can be characterised as coalition formation, knowledge building, and strategic reorientation.

Coalition formation is a process in which actors with different interests and resources come together to achieve a shared goal. In the context of socio-technical transitions literature, coalition formation refers to the process of forming a collective action among stakeholders to bring about a sustainable and transformative change in the socio-technical system (Fischer-kowalski and Rotmans, 2009). In the socio-technical transitions literature, it is recognized that transitions to more sustainable and equitable systems often require the involvement of diverse actors, such as businesses, government, civil society organizations, and communities. These actors may have different perspectives, interests, and resources, and forming a coalition allows them to leverage their complementary strengths and overcome barriers to change (Geels, 2014b; Geels et al., 2018). In the context of this thesis, the coalition formation can be seen in the collaboration between incumbent and emergent actors.

Knowledge building involves the development of new knowledge and the integration of existing knowledge across different fields and domains. The process of knowledge building can be seen as essential for driving socio-technical transitions because it enables stakeholders to identify and address the complex challenges that arise during a transition. This includes understanding the technical, economic, social, and political dimensions of the system, as well as the trade-offs and synergies that exist between different pathways for change. Knowledge building can take place through various mechanisms, such as research programs, networks, and partnerships, as identified earlier in this chapter in this transition. These mechanisms can facilitate the exchange of ideas and information among different actors, leading to the creation of new knowledge, the refinement of existing knowledge, and the identification of new research directions.

Strategic reorientation is understood as a “change in the directionality” (Geels, 2014a) of innovation in transitions literature. This can involve questioning and challenging dominant narratives and power relations, and identifying new opportunities for innovation and collaboration. Strategic reorientation can occur at different levels, such as individual, organizational, and institutional levels. It can involve changes in the governance and regulation of the system, the development of new technologies and business models, and the engagement of civil society and other stakeholders in the decision-making process. The process of strategic reorientation is often facilitated by the formation of coalitions and networks of actors who share a common vision for change. Because the AVs transition is yet at its beginning, the strategic reorientation here is expressed through the positioning of priorities, which are closely aligned with investment and with overall transport policy direction.

7 Sub-systems and shaping of the internal structure: regulative, normative, and cognitive rules and the morphogenetic cycle

This chapter looks at the internal dynamics of the socio-technical system in relation to the ongoing transition process through the notion of rules and morphogenetic cycle.

7.1 Rules

Chapter 3 identified that MLP literature distinguishes three types of rules: regulative; normative; cognitive. The rules are identified as “three institutional pillars” by Scott (1995, 2001), by which they act together to strengthen and reinforce structures. Rules are categorised as:

- Regulative – obedience; laws and sanctions
- Normative – social obligation; certification and credibility
- Cognitive – accepted as true; predominance and diffusion.

Actors’ agency – capacity to act – is guided and shaped by rules (Geels, 2011). Simultaneously, rules are outcomes and results from actors’ actions and interactions. To maintain system stability actors continuously use, interpret, implement, transform, reform and reproduce rules (Geels, 2004). The notion of rules provides a way to look at the internal structure of the socio-technical system.

In this section, the identified rules are summarised following the categorisation of system parts in previous chapter, which are governance, technology, science, infrastructure, culture, markets. These six categories come directly from socio-technical transitions theoretical framework and together constitute the socio-technical system of automobility. The rules were identified through the grey literature analysis. NVivo software was used to code and store the identified rules and for linking the rules with the relevant actors. Those relationships are demonstrated diagrammatically to identify how the rules are shaped by and shaping the other entities. Four types of relationship were identified during the analysis, which are demonstrated diagrammatically and in text in the following sections:

1. Actor influences rules.
2. Rules influence actors.
3. Actors and rules influence each other.
4. Indirect influence (a link has been identified but there is no directionality of influence).

Table 7-1 shows summary of the identified rules in each of the system components and categorised by regulative, normative, and cognitive rules. While some rules can be identified in most categories, some observation can be drawn about internal alignments within the rules. From the analysis it can be observed that governance, technology, science, and infrastructure actors are more aligned with regulative and normative rules, while culture and markets align more with normative and cognitive rules.

Following sections addresses each category of rules more closely and identifies not only the alignment between observations, but also the dynamics between system components and identified rules. By doing so, this analysis seeks to further identify internal dynamics of the socio-technical systems to theorise about causal powers and mechanisms. The identification of directionality between rules and entities further sheds some light on causal powers within the system.

Table 7-1 Summary of rules in each of the sub-systems (by author)

SYSTEM COMPONENT	REGULATIVE	NORMATIVE	COGNITIVE
GOVERNANCE	Industrial Strategy (Automotive deal); zero emission vehicle targets; government grants; CAV testing guidance; AVs Bill (for insurance); traffic law	Interaction between the industry and the Government: matched funding, AVs pilot schemes, collaborative R&D; 'light-touch' approach to AVs governance	Techno-optimism; sustainability agendas; roadmaps
TECHNOLOGY	Vehicle standards and specifications (emission targets etc); insurance	Agenda setting by incumbents and representative/lobby groups (such as SMMT and Zenzic); funding	problem formulation around technological solutions
SCIENCE	R&D funding; DfT guidance on CAV testing and trials	Partnership forming	agendas
INFRASTRUCTURE	Need for specific standards, quality, connectivity;	accessibility	Testing infrastructure
CULTURE		Car dependency; expectations	Symbolic associations with car ownership, accessibility etc; attitudes towards car ownership and driving;
MARKETS	insurance and liability; testing	New partnerships forming; (user) perceptions and expectations	User preferences

7.1.1 Regulative rules

Regulative rules are the legally sanctioned rules that the actors within the system must abide by. Those are policies, laws, regulations, sanctions. In system of automobility such rules are primarily governed by governance actors through passing legislation, setting vehicle and emission standards, developing policy, and supporting innovation through R&D funding.

Figure 1-1 identifies the regulative rules identified through the grey literature analysis. The links between the rules and actors identify the inner dynamics of how these rules are shaped. Figure 1-2 shows those links in separate diagrams by type. As demonstrated, governance actors play a pivotal role in shaping regulative rules by establishing policies, strategies, and laws that subsequently affect the operations of actors within the system. Notably, a significant Governance -> Rules -> Technology linkage has been identified in the context of this transition, indicating that the development of technology is affected by regulatory measures. For example, the targeted R&D funding (CCAV streams 1 to 4) have supported R&D activities setting out specific objectives and priorities (such as CAV integration with other mode son transport, accessibility, data security) together with DfT guidance on testing and trials have led technology actors towards developing AVs and technologies that align with these objectives. One such example is the Westfield pods that have been used in various CAV trials and deployments across the UK (Heathrow Airport where the pods operated on a dedicated track and provided a frequent and reliable service for passengers; London Olympic Park where the pods provided visitors with a guided tour of the park; Coventry where the pods were used to transport passengers between Coventry's main train station and the city's transport interchange forming a part of an integrated public transport system; London Greenwich where the pods were used to transport passengers between the North Greenwich tube station and the O2 arena).

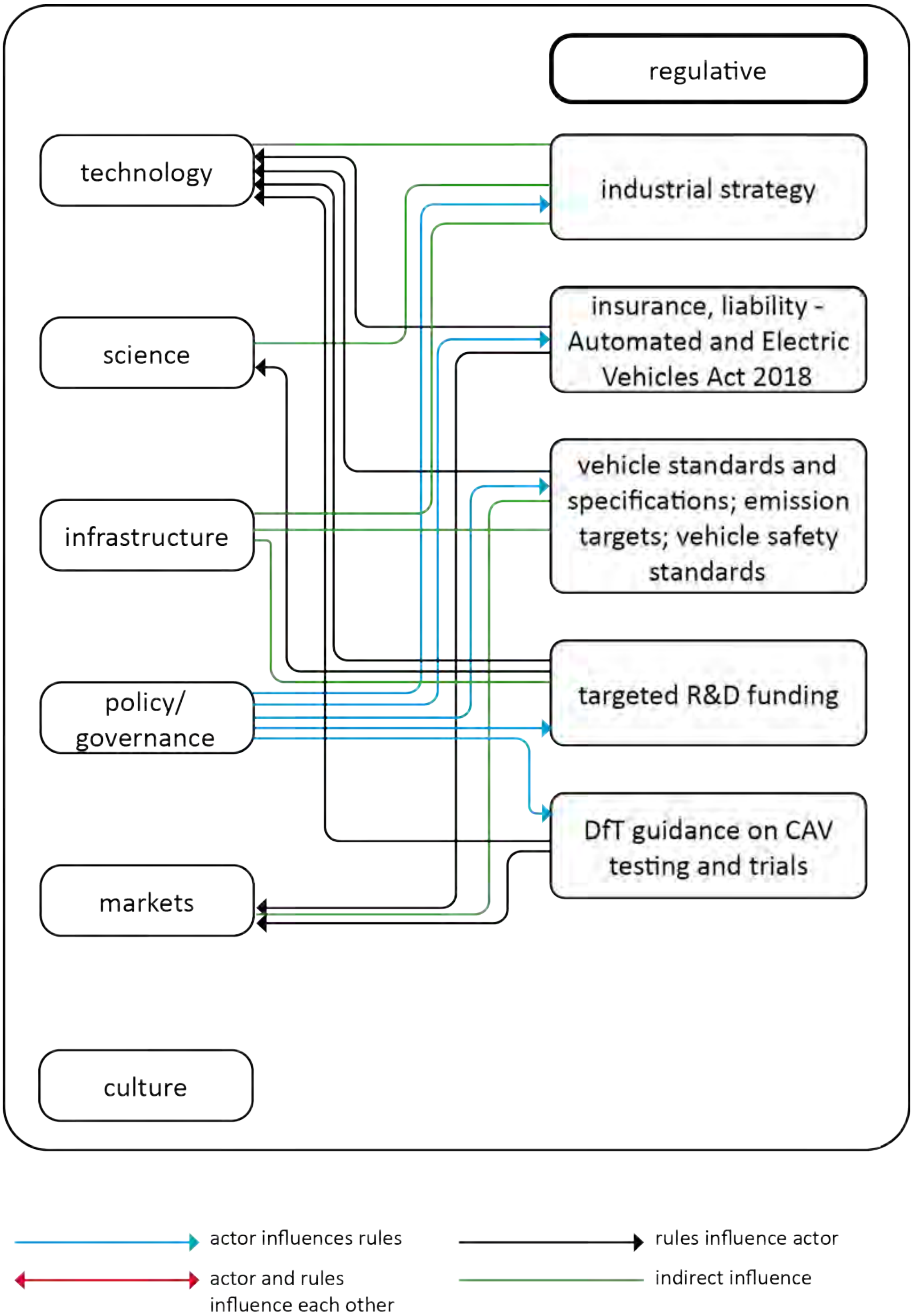

Figure 7-1 Influences between sub-systems and regulative rules of the socio-technical system (by author)

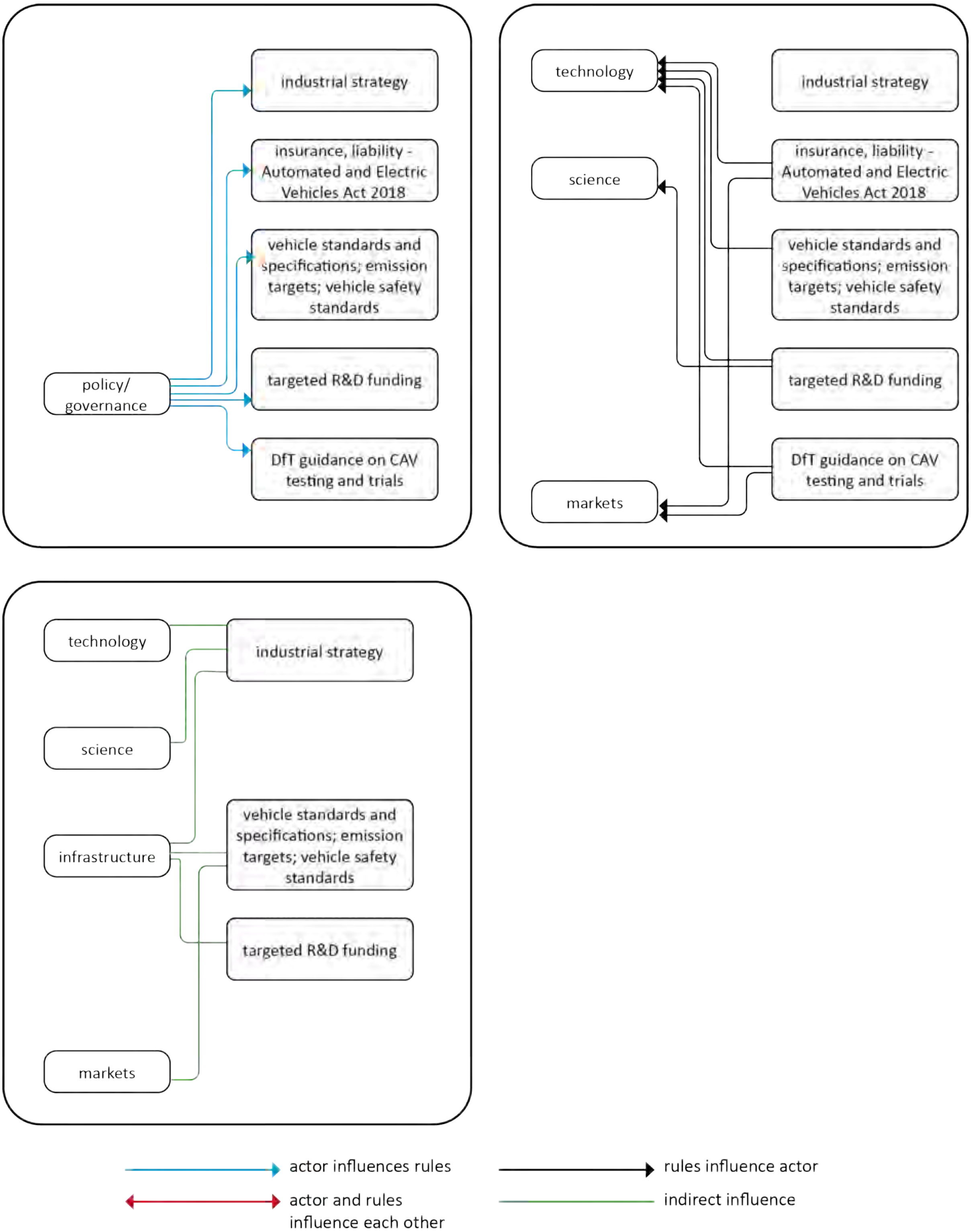

Figure 7-2 Influences between sub-systems and regulative rules of the socio-technical system by type of linkage (by author)

7.1.2 Normative rules

Normative rules are the ‘unwritten’ rules that actors follow in certain settings. Those can be habits, work norms, guidelines and common practices, which are enacted and enforced through approval and disapproval by other individuals within that “norm cycle” (Sorrell, 2018). Figure 7-3 illustrates how normative rules are established and implemented by all entities within the subsystems of a given transition, while Figure 7-4 presents each type of linkage separately.

The technology industry plays a crucial role in shaping the normative rules, with industry actors engaging in agenda setting, automotive lobbying, and R&D activities. For example, members of the industry participate in consultation processes concerning self-driving cars, and the automotive industry holds a powerful lobbying position in the parliament. Governance actors also contribute to the establishment of normative rules by providing matching funding for R&D activities in AV development and adopting a "light touch" approach to AVs governance, thereby granting more influence over the transition process to industry actors.

These normative rules, in turn, exert causal effects on other entities within the system. User perceptions and expectations, which are shaped by normative rules, have an impact on markets and technology. For instance, industry actors recognize the need for public support and activities, such as pilot demonstrations, aimed at building trust and generating further interest in new technologies. Cultural associations with cars and their current usage also contribute to shaping normative rules.

The dynamics evidenced here explain the locked-in status of the automobility system, car-dependency, and how technology’s role is dominant in the path dependent trajectory of the system of automobility.

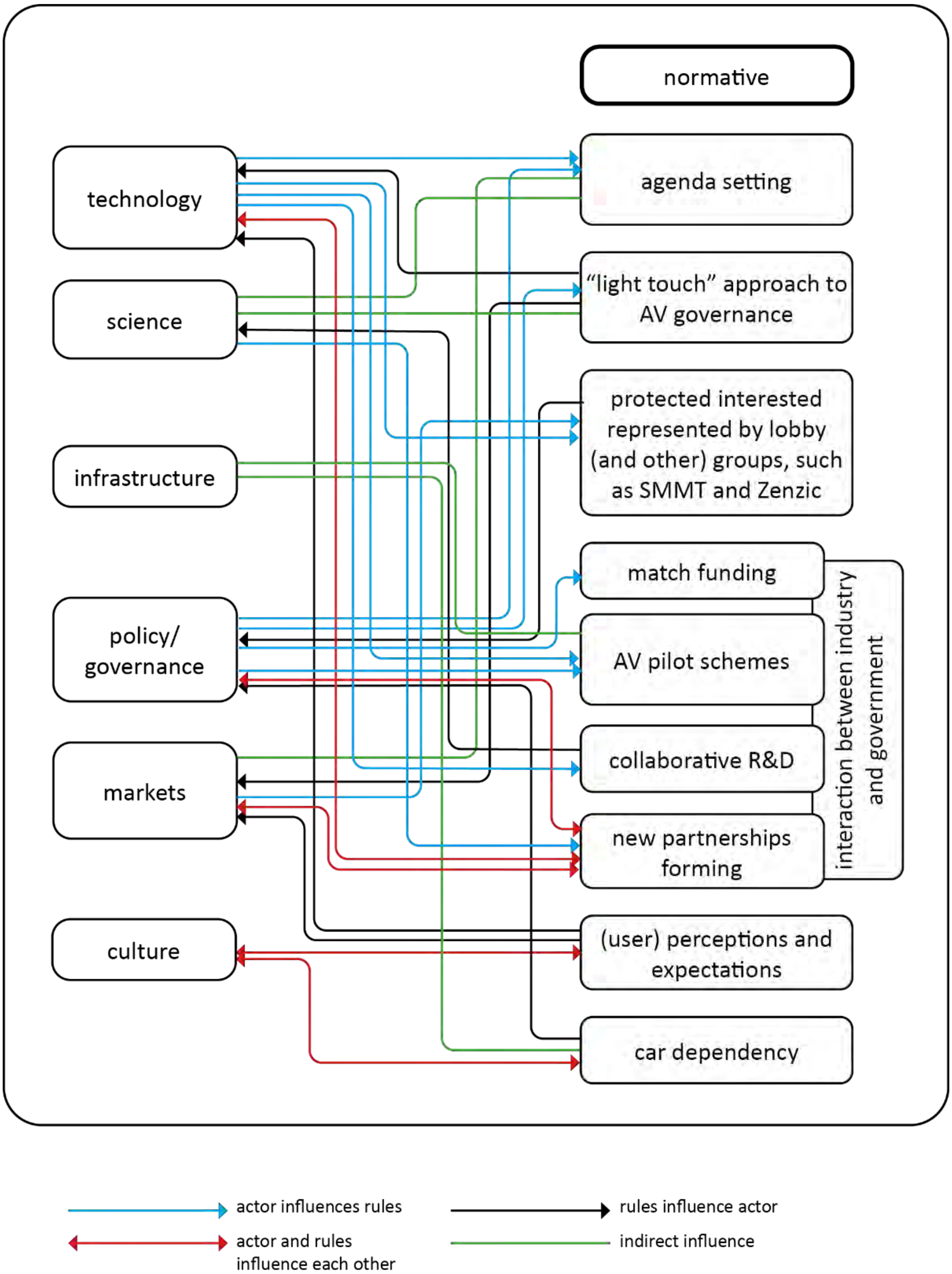

Figure 7-3 Influences between sub-systems and normative rules of the socio-technical system (by author)

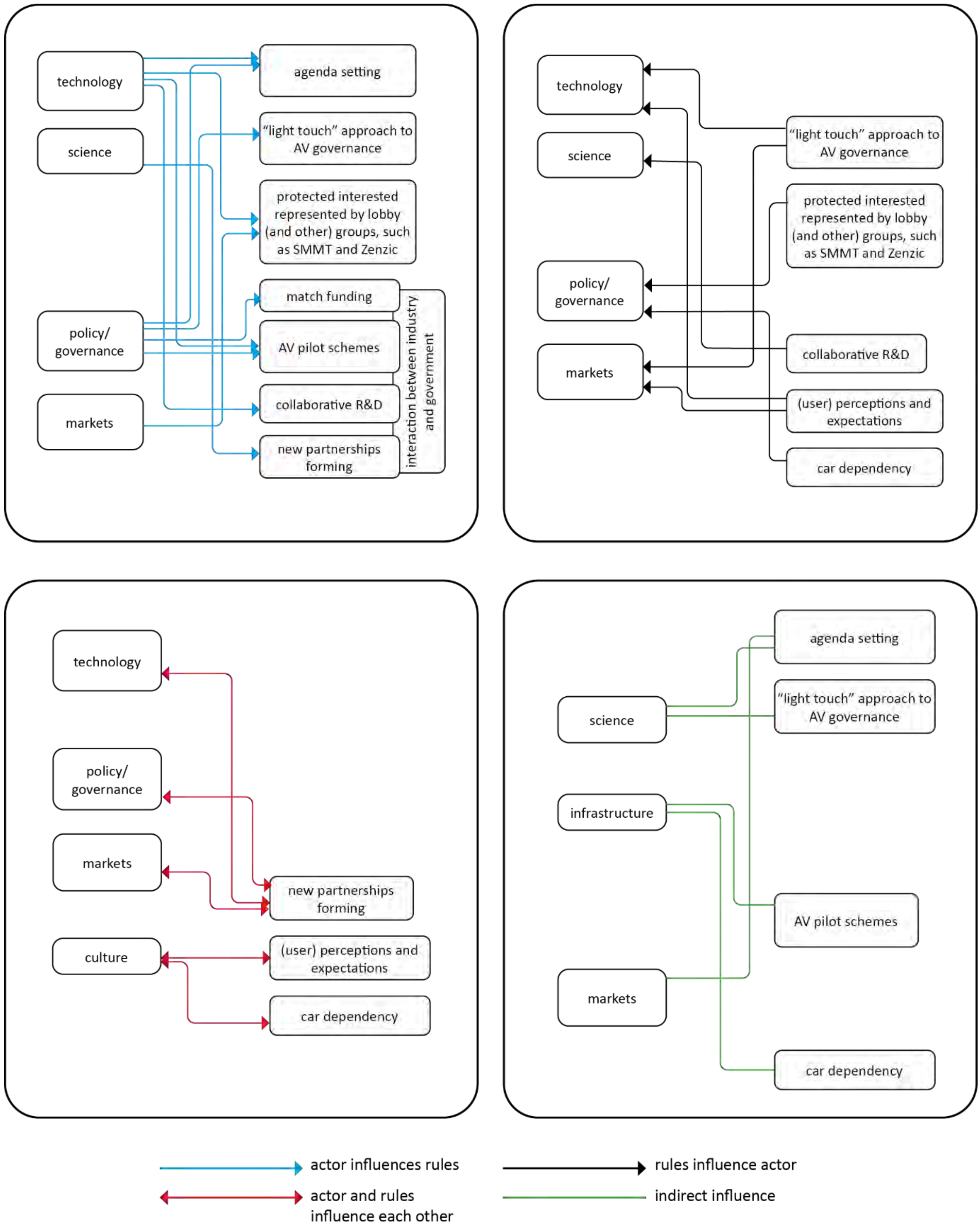

Figure 7-4 Influences between sub-systems and normative rules of the socio-technical system by type of linkage (by author)

7.1.3 Cognitive rules

Cognitive rules pertain to actors' beliefs and values that influence their actions. Although less tangible than the other types of rules, cognitive rules describe how actors shape their social reality and make decisions based on their values and beliefs.

In the context of AVs transitions and the system of automobility, cognitive rules refer to general attitudes towards car ownership and its role in society, as well as external influences such as the sustainability agenda. Figure 7-5 and Figure 7-6 show these relationships. The industry and governance actors' framing of AVs as a solution to current transportation challenges significantly shapes actors' beliefs in technological solutions. Cultural associations with car ownership and preferences towards new mobility technologies also reflect deeply rooted cognitive norms surrounding the current system of automobility.

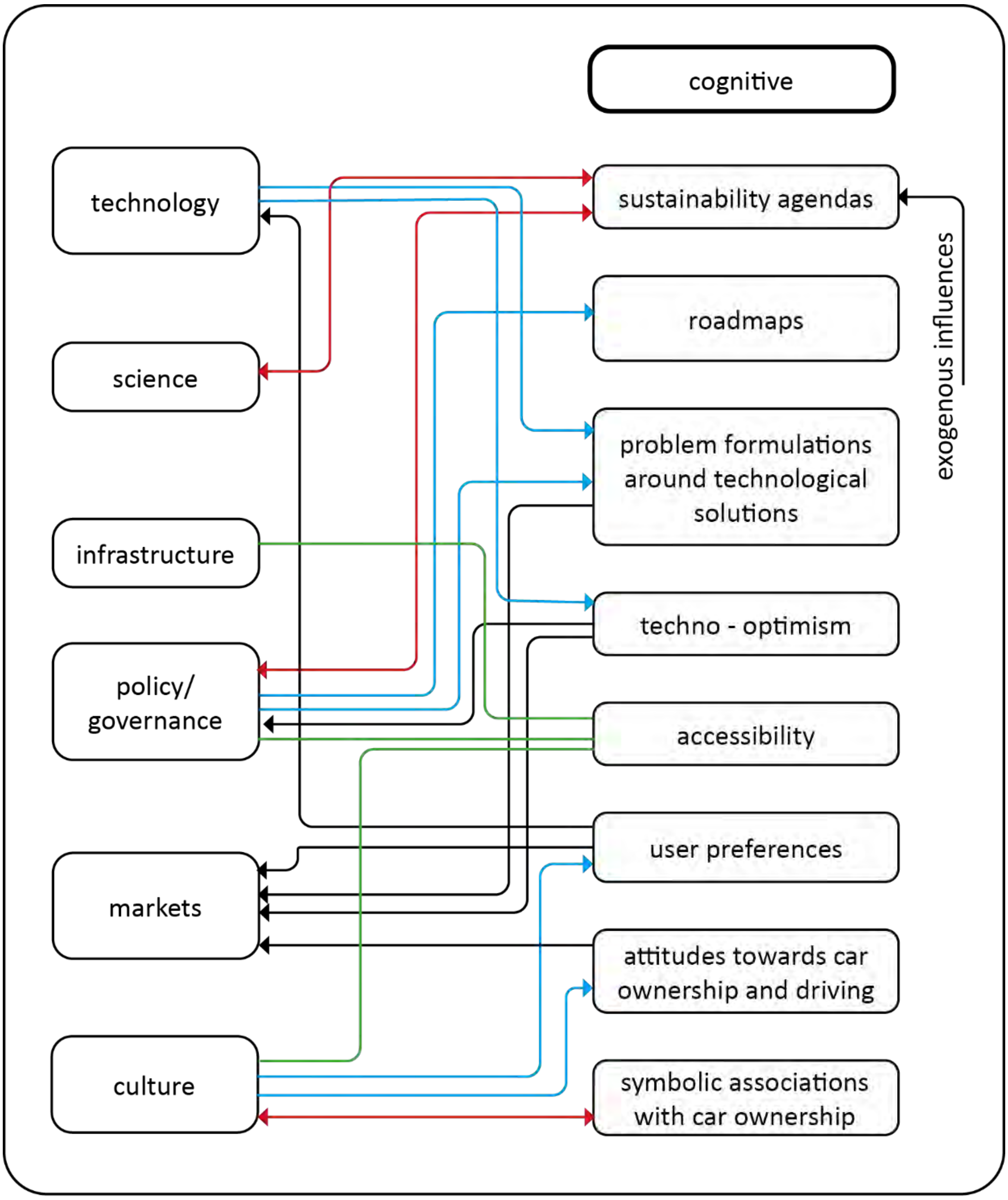

Figure 7-5 Influences between sub-systems and cognitive rules of the socio-technical system (by author)

influence each other

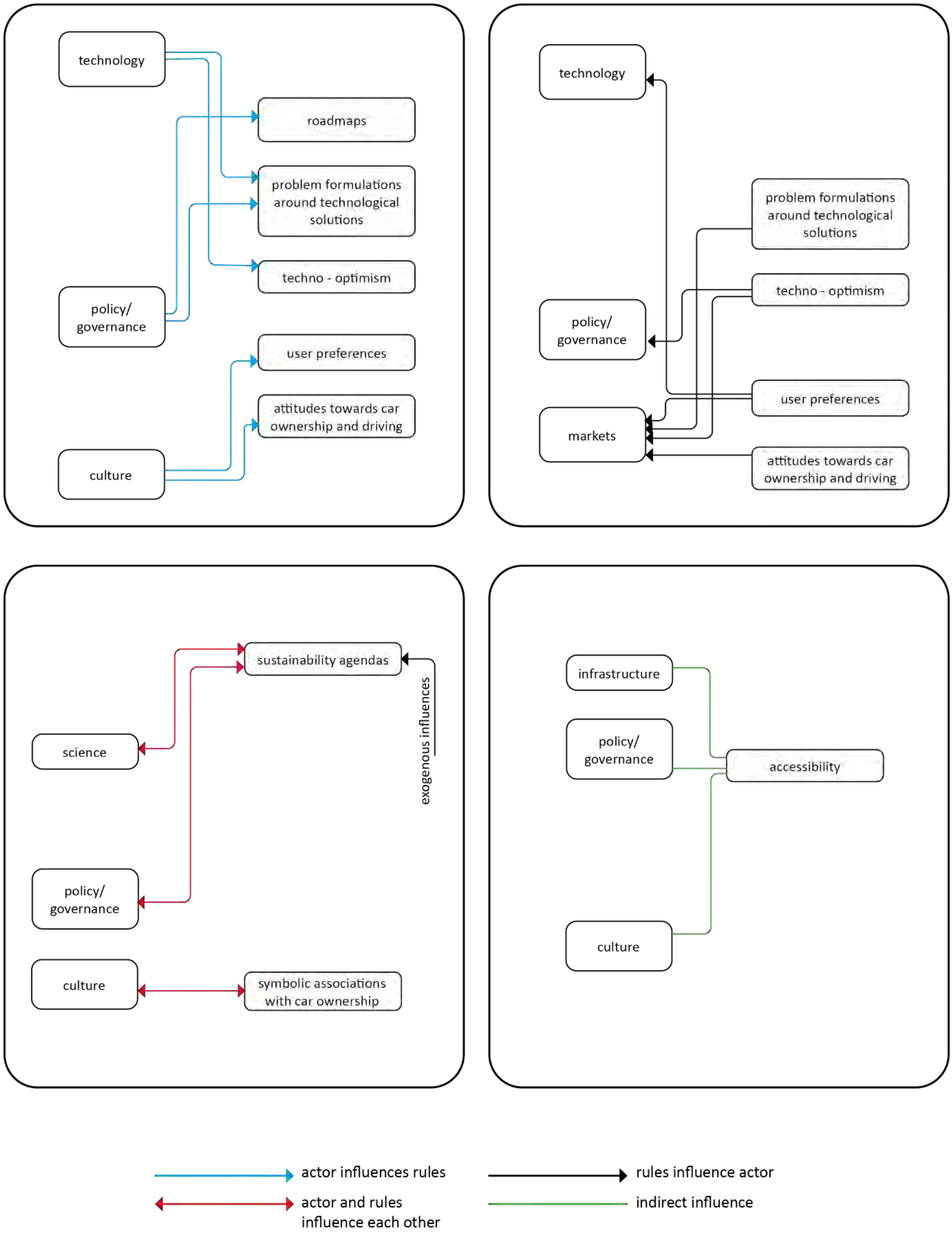

Figure 7-6 Influences between sub-systems and cognitive rules of the socio-technical system by type of linkage (by author)

7.2 Morphogenetic cycle

Table 7-2 shows the morphogenetic cycle analysis of findings. Events, actions, and conditions (column A) combines findings from chapter 6 and this chapter, and the identified mechanisms from chapter 9[25]. They are also classified in landscape/system/niche categories to reflect the level at which these items are observed.

Column B – structural conditioning - assesses whether the observation from column A can be conceptualised as internal or external (or both) structural condition. Structural conditioning is a term used in morphogenetic cycle to describe events and actions that predate observed phenomena but have a role in shaping the behaviour and actions of entities in the observed process. Internal or external distinguishes between whether the observed item affects the socio-technical system and the transition as an internal influence or as an exogenous condition.

Column C identifies whether the observed entity is involved in the structural elaboration – the current ongoing transition process. Column D places the observation in either structural elaboration or structural reproduction outcome. This is based on the interpretation of the tendencies that the observed action has shown. This can be transferred knowledge (if a similar pattern has been observed previously in a different case study), theoretical interpretation (tendencies of specific actions that have been identified in transitions literature), or speculative based on assessment of data and evidence collected.

Some areas cannot yet be determined or fall into both – elaboration and reproduction outcomes. For example, strong automotive base suggests a tendency towards system stabilisation, but it is also beneficial for innovation activities, and therefore it can point towards either outcome.

[25] The identified mechanisms were added iteratively throghout the research process to test the alignmnet with the morphogenetic cycle.

For example, climate concerns fall into the external structural condition category because they are more ‘global’ than the transition context, but they must be acknowledged as they will have an impact on the direction of the transition. They are further categorised as leading towards structural elaboration outcome. This is because there is evidence that the climate concerns are affecting and changing the legislative and innovation directions with more emphasis being placed on low-emission transportation and modal shifts, which, as already illustrated in this thesis, is influencing AVs developments.

From the system category, examples such as R&D funding, AEV Act 2018, investments, talent building, and formation of new partnerships can be categorised as internal system elaboration meaning that they are internally challenging and changing how the system of automobility is evolving during this transition. This therefore also places there items as leading to structural elaboration.

Other items – such as lobby, standards, existing standards, regulations, and accepted norms and behaviours – are signalling towards structural reproduction direction meaning that the system steers towards preserving the status quo.

As presented in the table, items have been identified that suggest different potential direction of the transition from the structural elaborations vs structural reproduction perspective indicating that there are competing objectives in this transition and the direction of the transition swill be affected by both sides.

Table 7-2 Alignment of findings to the morphogenetic cycle (by author)

Column A	**Column B**		**Column C**	**Column D**	
	Structural conditioning		(Internal) system elaboration	outcomes	
	External	internal		Structural elaboration	Structural reproduction
	method of interference				
Events; actions; conditions	observation		observation	speculative; comparative; theoretical interpretation	
landscape					
Climate concerns	X			X	
climate-oriented legislation and policies	X	X	X	yet unknown	
Technology advances	X	X	X	X	
promotion of owning and driving a car in the 80s		X			X
Societal attitudes towards AV, driving, car ownership	X	X	X	Yet unknown	
system					
R&D funding			X	X	
AEV Act 2018			X	X	
investments			X	X	
talent building			X	X	
Formations of new partnerships			X	X	
strong automotive base		X	X	X	X
lobby		X	X		X
Light touch non-regulatory approach		X	X		X
Traffic laws; vehicle standards		X	X		X
Existing infrastructure		X	X		X
Problem formulation around technology solutions		X	X		X
Visioning		X	X		X
self-fulfilling prophecy		X	X		X
techno-optimism		X	X		X
niche					
New types of actors emerging			X	X	
formation of new partnerships outside of the existing system			X	X	

7.3 Chapter summary

This chapter presents the results of the second step of the SRPM analytical framework, which is the analysis of rules and structures. Alongside the identification and classification of observed events into rules, the chapter also provides theoretical insight into the internal dynamics of these rules. By mapping these dynamics, the analysis uncovers the ways in which rules shape actors and how actors shape rules. The notion of the morphogenetic cycle is used to balance and contextualize these processes. The empirical application reveals that both approaches can be used in parallel to theorize about the internal dynamics of socio-technical systems and the structural factors that shape ongoing transitions.

The findings of this chapter suggest both structural elaboration and structural reproduction in the ongoing transition to AV. While some areas indicate a tendency towards transformative outcomes, others indicate a tendency towards reproduction. Though it is not possible to speculate on the final outcomes, the analysis provides clarity on the internal dynamics of the system, which can be further explored through the notions of pathways and mechanisms in subsequent chapters.

This novel methodological approach, which combines the morphogenetic cycle and the internal rules approach, offers a more nuanced and complex understanding of the socio-technical transition process. It highlights the contextual, conditioned, and constantly evolving nature of the internal structure of the system. The adoption of this approach can expand the theoretical framework of socio-technical transitions research and enhance its applicability to a wider range of systems and contexts.

8 Transition Pathways

This chapter aligns findings with transition pathways (part 3 of the SRPM analytical framework).

Transition pathways allow to theorise about the type of transition that is being observed based on characteristics set out in literature. In chapter 2 the pathways were introduced. This section theorises about the transition pathways that can be identified in the transition to AVs in the UK based on the identified processes (in chapters 6 and 7) relevant to this transition. An overview of the pathways is summarised in Table 8-1. Transition pathways usually describe aggregate patterns over time (Geels et al., 2016).

Table 8-1 Transition pathways and descriptions (by author, based on Geels and Schot (2007))

pathway	reproduction	transformation	de/re alignment
pathway description	On-going incremental processes of change within the socio-technical regime without external disruptions	If there is a moderate landscape pressure, incumbent actors will respond by modifying the direction of development paths and innovation activities	sudden landscape changes resulting in a number of other competing options emerging from niches, eventually establishing a new configuration of the socio-technical system
pathway	**substitution**	**reconfiguration**	**fusion**[26]
pathway description	Replacement of one dominant technology within the socio-technical regime by another as a consequence of interaction between all three levels	Replacement of a set of technologies by an alternative array of inter-related technologies which fulfil same or comparable functions	Socio-technical system merges with or is absorbed by another socio-technical system (or a prominent actor from another sociotechnical system) due to technological 'overlaps'

[26] System fusion is a new typology of a transition pathway identified in this chapter.

Each pathway is briefly introduced and illustrated, then evidence that aligns with the pathway from the case study is demonstrated (if present). Detailed breakdown also allows to ensure the focus remains on AVs transition rather than broader transportation and mobility transitions. If broader contextualisation is required, its relevance to AVs is further explained. Finally, potential implications of each pathway are identified.

8.1 Reproduction pathway

The ***reproduction pathway*** shares perception that the regime has sufficient problem-solving potential to deal with them (Geels and Schot, 2007). Innovation and development are present as small step-by-step incremental improvements in technology to boost efficiency and productivity.

Evidence

The UK government's position on AVs transition is to take "a step-by-step approach, and regulate in waves of reform" (Centre for Connected & Autonomous Vehicles, 2017), which is consistent with the reproduction pathway from transitions literature. The ambition demonstrated by the Government and leading industry bodies appears to be in line with this pathway. The AVs roadmap set out by SMMT and Zenzic sees AVs development as a process of introducing automation levels as an incremental process. This aligns with the wider international framework of levels of automation and the approach to introduce driverless technology in step-by-step increments.

Most major car manufacturers are working on AVs developments either within their capacity or by joining new partnerships both, globally and in the UK context. Such moves suggest that the automotive sector is anticipating the changes and the actors are building their adaptive capacity to navigate the transition.

In this transition pathway the regulative rules play a particularly key role in the transition process, because the incremental changes of this pathway favour the direction set by incumbents through regulative and normative rules. Regulative rules, such as policy and regulation, in this pathway are expected to evolve and provide sufficient problem solving within the regime, ensuring resilience and adaptability of the existing regime. An initial review by DfT found that the existing regulatory landscape was "permissive" and that there were no legal barriers to AVs testing provided an identifiable safety driver is present. Later, Automatic and Electric Vehicles Act 2018 was passed and set out "liability of insurers etc where accident caused by automated vehicle", which accounts for liability of insurer or owner in an event of an accident where no driver is present allowing car insurers to offer insurance to owners of fully autonomous or driverless vehicles.

Implications

Reproduction pathway is the preferred development model of incumbent actors because it avoids disruptive 'outside innovation' and further cements the incumbent status of dominant system actors. For governance structures this scenario allows a level of control and preparation regarding technological trajectories.

8.2 De-alignment and Re-alignment pathway

De-alignment and re-alignment pathway happen when a sudden divergent landscape events cause regime to collapse. Simultaneously, there are no well-developed niches to take over the regime, resulting in a new regime emerging from a number of competing options.

Evidence

Despite the many issues associated with the car-dominant regime, the automobility system is deeply embedded and locked-in into societies, making this pathway less plausible. Nevertheless, there is a risk associated with AV, which could cause a regime disruption due to the unpredictability and uncertainty associated with AV. If the technology is allowed to 'take its own path' , it can lead to unexpected and/or undesired outcomes, such as increased urban sprawl and increased dependence on personal transport (Duarte and Ratti, 2018).

Implications

The evidence is, however, not consistent with this pathway at this stage, and therefore it has little analytical relevance to the ongoing processes.

8.3 Technological substitution pathway

Technological substitution is a similar pathway to de-alignment and re-alignment pathway, however, in this scenario there is an alternative niche innovation developed sufficiently to break through and replace the existing regime. Technological substitution process can at first behave as a reproduction process, but the change happens when a sudden landscape pressure or shock increases pressure on the incumbents and thus provide a window of opportunity for a niche-innovation. This has been demonstrated in historic studies, such as transition from sail ships to steam ships (see Geels (2002)).

Evidence and implications

When aligning transition to AVs to the substitution pathway, it is important to assess the radicality of innovation. With historic examples, where a novel technology was a niche innovation in a sense that it provided an alternative competing innovation, a substitution pathway is fitting. For example, when cars replaced horse-drawn carriages there was a clear distinction of the technology that replaced the existing.

Here I argue that driverless cars are not a radical niche innovation. AVs are not currently juxtaposed with traditional cars, they are instead treated as an improvement or 'next generation' of vehicles, rather than a direct alternative competition.

While there is a question of the speed and rate of innovation and change, there is no evidence of driverless cars 'competing' for a market share. Furthermore, in automobility context, the system is so 'locked in' that a complete sudden regime overhaul and replacement by a new set of technologies is an unlikely scenario, and therefore the substitution pathway does not align with processes of this transition.

8.4 Transformation pathway

If there are evolving external landscape pressures that cause the regime actors to modify the regulatory and innovation activities in order to cope with the pressures, it is categorised as *a* ***transformation pathway***. In this pathway, the niches have not yet developed to provide a viable alternative.

<u>Evidence</u>

Environmental issues are being vocalised and reflected in regulatory changes concerning energy and transport, which is an example of landscape developments affecting the direction of regime developments. Compared to historic transitions in transport (such as transition from horse drawn carriages to cars (Geels, 2005d)), which were primarily driven by technological advances, transition to AVs (and other processes that can be described as transitions in transport) will need to address the environmental concerns. This has, for instance, created a favourable environment for hybrid and electric vehicle development. There are currently no landscape pressures to which AVs would be see as a viable solution or direction on its own, but there is evidence of actors framing AVs as a solution to specific environmental concerns, usually as a combination of AVs being electric, reducing congestion due to automated driving controls, and reducing number of vehicles on roads in scenarios where there is a modal shift where users switch from personal vehicles to shared on-demand autonomous vehicles.

In transformation scenario, established regime actors, such as car manufacturers, use their adaptive capacity to reorient their development to comply with the rules. A factor here, specifically in the UK context, is the strong lobby position that the SMMT holds (see previous chapter). There is evidence of SMMT lobbying against measures on emissions to support the industry they represent. Their position on AVs is supportive of the permissive regulatory stance (SMMT, 2017).

Implications

The most significant landscape pressure is the climate concerns. As the automotive sector is responsible for a large proportion of greenhouse gas and pollution, there is direct pressure on the system actors to respond. Here the AVs innovation discourse conflates with EV because of the assumption that battery electric vehicles are on trajectory to replace fossil fuel vehicles in the future, and AVs are therefore also perceived as being mostly electric.

8.5 Reconfiguration pathway

Reconfiguration pathway contains niche innovations that work as improvements or add-ons to specific locations, actors or technologies within the dominant system. This allows incumbent actors to explore the innovations and replace specific technologies within the system that fulfil the same function. Sequences of technology development are common in this pathway. In contrast with reproduction pathway, the reconfiguration pathway leads to substantial changes within the structure and rules caused by the adaptation and absorption of the niche innovations into the dominant socio-technical system.

Evidence

This kind of experimentation can be observed in the AVs associated activities in the UK, with certain actors pursuing and demonstrating specific incremental solutions towards AV, such as lidar technology, advanced cameras and sensors, pattern recognition, and others. Government support coming through funding channels is building a portfolio of case studies and use cases that can be revisited and used as learning tools when the technology reaches road-readiness.

Another aspect that is relevant to this pathway is the projected adaptation of AVs through the levels of automation. Such incremental step-by step technology advancement can be seen as sequences of directed innovations, which traditionally benefit the dominant actors.

Implications

The significant implication of the reconfiguration pathway is that the function of the system does not change through the transition. Instead, changes occur primarily in the configuration of technology itself, rather than the overall structure and functionality of the system.

8.6 A new transition pathway typology: system fusion

During the case study analysis, a new transition pathway was identified that does not fully align with the existing definitions of pathways introduced in MLP literature. Observations reveal a new type of a socio-technical pathway – system fusion (named by author) – in which technological innovation leads to fusion with another socio-technical system or domain, and in which dominant actors from the other domain or sector become incumbent by overtaking, merging with or developing an alternative technology.

While fusion pathway is in some ways similar to substitution pathway, in this study it is useful to distinguish the two. Substitution pathway identifies that radical innovations can be developed by ‘outsiders’ and the transition happens as a result of landscape changes that impact markets and institutions. Geels et a. (2016) identify that such change can also come from incumbents in other sectors as they diversify, such as internet companies moving into renewable energy market. Such moves are motivated by actors’ desire to capture emergent markets, technology trends, and to react to landscape pressures. In contrast, in fusion pathway the change arises from significant reconfiguration within the technology as a result of technological innovation and socio-cultural shifts.

Evidence

In broader mobility context, we can already see this pathway manifesting in servitisation of mobility where service rather than the physical artefact is sold to customers to provide (in the case of mobility) a way of traveling from A to B. While the socio-technical system remains largely unchanged in terms of how it functions (car-centric mobility), the technology advancements have resulted in a shift in actors and markets. For instance, the largest taxi company globally with over 12% market share – Uber – does not own any vehicles and is instead a tech company.

In context of AV, a significant component of the technology is novel to traditional notion of a car. Especially in the UK, where focus is on connected and autonomous vehicles, the connected aspect of the technology has a potential to disrupt the incumbent actors and practices. By adding the sensors, computers, communication devices and data to vehicles, the car becomes an IoT (Internet of Things) device that inherently becomes part of a ‘bigger’ system with associated characteristics and structures. Globally, the ICT is one of the largest industries in the world and it therefore has the capacity to enter another market – or in this case another socio-technical system.

Some examples of these activities were observed in the case study:

- Largest tech companies globally are developing AV:

    - Apple
    - Amazon
    - Microsoft
    - Alphabet (Google)
    - Meta Platforms (formerly Facebook).
- Cisco – a technology conglomerate company – has partnered with companies (globally and in the UK) to develop AVs related IoT technology, such as sensors, data sharing, connectivity, which play a key role in successful AVs deployment.
- Companies that are relatively new to transportation sector and do not operate as traditional business models, such as Uber are developing and testing AVs technology.
- The vast majority of UK based start-ups that identify in the AVs sector are software companies.
- Analysis of UK government's R&D projects shows that amongst the 30 companies with highest participation in those projects, only 3 are vehicle manufacturers, whereas 15 are non-automotive technology and software companies.

Implications

While it is too early to assess such shifts in the make-up of the sociotechnical system and its potential fusion with others, increasingly more 'smart' devices, for example, at homes ranging from personal devices such as smartphones and watches to IoT enabled home assistants (Google Nest, Amazon Echo etc) and appliances are appearing in everyday lives with already noticeable impacts on everyday practices.

The increasing value of IoT components and data for mobility services have a potential to change the make-up of the system of automobility by shifting the prominent role of the physical artefact – the vehicles and the infrastructure – to a system where the key technology is the digital and data-based hardware and software and the vehicle is the secondary 'shell' carrying the technology. With the shift to the cloud' mobility, this opens up a question – what (or who) will dominate the system of automobility and what policy and regulatory interventions will be required to 'manage' and govern such system.

8.7 Transition pathways: summary

This chapter presents findings and analysis for the third step of the SRPM analytical framework. Transition pathways is a way of theorising about a possible type of change in a transition. Aligning real-world processes with theoretical indicators offers a structured way of further analysing transition processes. While each of the pathways identified in theoretical literature has its own distinct characteristics, in a real-world scenario transitions can occur as a sequence of pathways with elements from different pathways emerging over time and affecting the transition process. In situations where the transitions pathways are applied as an analytical tool (such as this thesis), rather than a policy development instrument, it is especially likely to identify processes aligning with multiple pathways.

Although the outcome of this transition cannot be predicted, analysing the dynamic between the identified processes can provide a useful way to explore potential implications for transition trajectories and their associated impacts on the socio-technical system of automobility.

Assuming that road-ready AVs will not emerge as a radical niche innovation, given that the regime actors are aware of and working on the technology themselves, niche disruption can still emerge from adjacent technology and innovation fields. Moreover, regime destabilization can result from socio-cultural shifts and landscape developments. Thus, the regime actors should consider potential instabilities to ensure not only the delivery of the transition but also its benefits for the economy, the environment, and society, as well as resilient capacity to deal with emerging external processes that will arise outside of the governance perspective that currently dominates.

The analysis shows that the ongoing transition to AVs in the UK has the characteristics of multiple pathways, indicating multiple possible trajectories in terms of transition outcome. Specifically, this chapter has identified that the ongoing transition to AVs in the UK aligns with theoretical trajectories of transformation, reconfiguration, and system fusion pathways. System fusion, a new transition pathway identified through analysis, adds a new set of transition dynamics classifications to transition pathways discourse.

Both transformation and reconfiguration pathways can be characterized as incumbent-led and incumbent-centric transition pathways. The presence of the existing infrastructure and a strong automotive base in the UK provide incumbents with a foundation to test and experiment with new technologies while maintaining their roles within the system. Therefore, these pathways do not align with the anticipated radical disruption effect that AVs are believed to cause in some of the literature.

In contrast, the fusion pathway can lead to a whole new socio-technical configuration with altered roles of incumbent actors. The strong and unprecedented presence and involvement of ICT and tech companies in the transportation sector indicate a potential systematic change affecting the roles of incumbents. The fusion pathway offers a more transformative trajectory because it involves new actors with their own visions and preferred trajectories. Transformation and reconfiguration pathways, while also describing a socio-technical transition process, would potentially lead to less disruptive developments and outcomes at the system level.

Observations also align with the reproduction pathway, which describes a technological change that does not imply a drastic change in the socio-technical system. The morphogenetic analysis in the previous chapter also identified that some processes observed in this transition are more consistent with "structural reproduction" than "structural elaboration," aligning with the findings of this chapter that the autonomous vehicle transition is currently contained within the internal structure of the socio-technical system without observable significant transformative trajectories.

9 Causal mechanisms in the ongoing transition: identification of demi-regularities and development of mechanism schemata

This chapters identifies mechanisms in the ongoing transition process. Mechanisms are theorised about through the identification of demi-regularities. Demi-regularities can be understood as empirical manifestation of mechanisms. Those are then combined in mechanism schemata and sketches.

9.1 Identified mechanisms

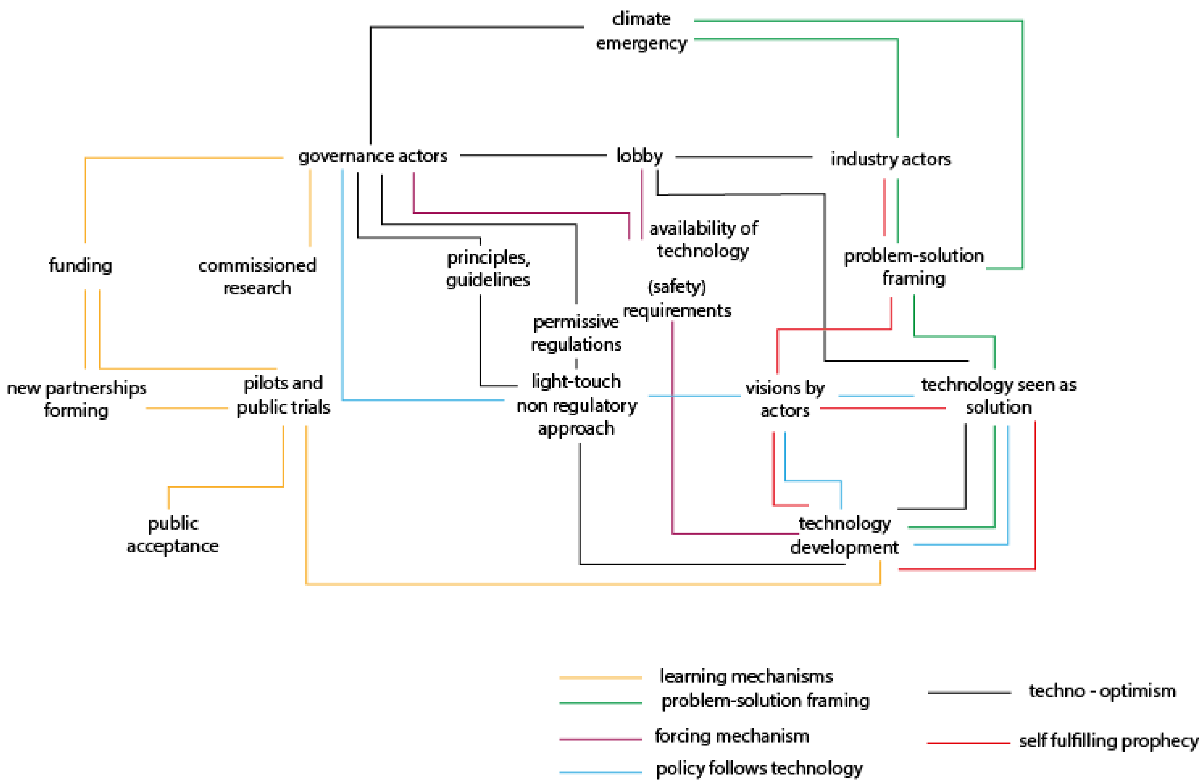

Figure 9-1 map of all identified mechanisms (by author)

Through case study and data analysis six mechanisms were identified. Figure 9-1 shows mapping of them with key system components, actors, and actions. Further sections provide more context, evidence, and implications for each of the identified mechanisms.

9.1.1 Learning mechanisms

9.1.1.1 Mechanism description

Learning mechanisms describe a set of mechanisms that actors routinely engage in in a socio-technical system. They are associated with finding incremental technology solutions to improve price-performance and forming new partnerships for technology development and innovation purposes. Learning mechanisms in literature are described as processes where experiences and knowledge from local projects, pilots, and testing is translated into general knowledge. In such process "knowledge flows" are created, which involve interactions among actors and "dedicated knowledge aggregation activities by intermediary actors" (Smith and Raven, 2012). Learning processes relate to evolutionary economics theoretical notions of variation and selection (Geels, 2002), where variation can be interpreted as learning and experimenting within organisations and systems, and selection describes the success of a technology through user acceptance and position in markets.

9.1.1.2 Mechanism evidence

Autonomous driving technology is being developed and tested globally and nationally by all major vehicle manufacturers. Additionally, non-traditional actors to the automotive sector are contributing to learning and experimentation processes.

In order to tackle some of the uncertainty and barriers to AVs implementation, the Government has commissioned research institutions and other organisations to conduct studies on a number of AVs related questions. Through these actions the governance actors are building a knowledge base to understand, support, and anticipate markets in which AVs will need to operate.

The UK government has also funded and match-funded R&D since the launch of CCAV and publication of the "Pathway to Driverless Cars". The Government pledged £250m match funding towards development and testing of AVs technology. Previous chapter identified that funding opportunities by the Government have resulted in formation of partnerships, which also facilitate learning.

9.1.1.3 Implications of this mechanism

Figure 9-2 maps the identified learning activities by governance and industry actors based on their comparative innovative capacity. These actions traditionally focus on price-performance improvements and incremental innovation, which has limited capacity to deliver transformative or radical innovations.

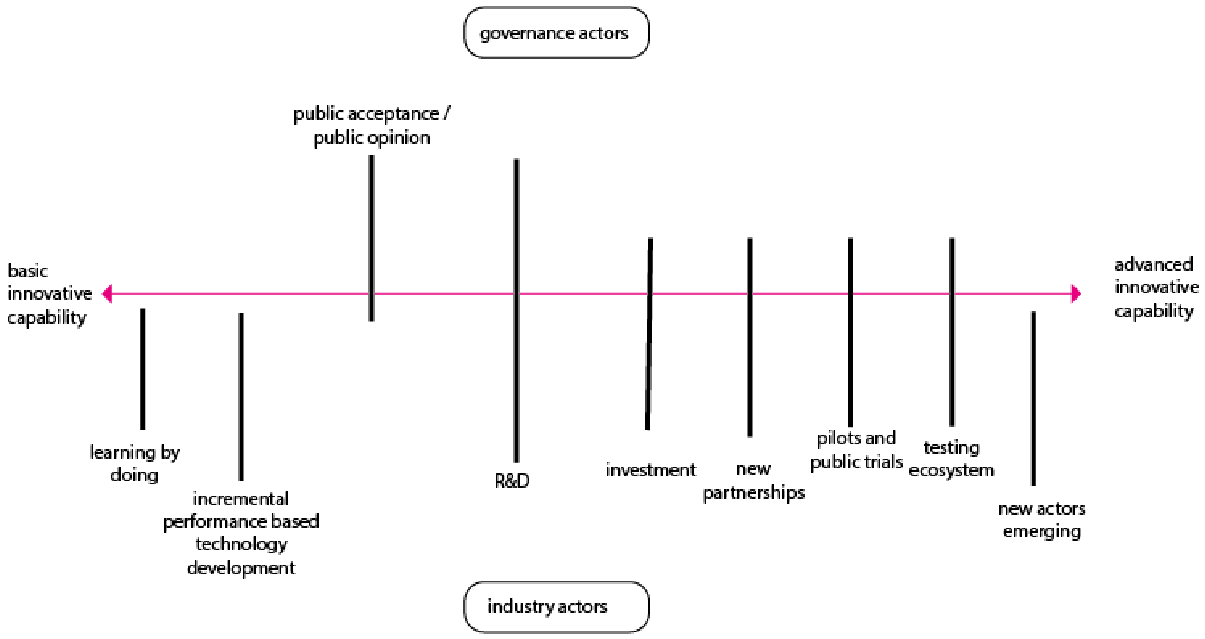

Figure 9-2 Industry and governance learning activities on innovative capacity scale (by author)

On the other side of the scale, linking to the "system fusion" pathway identified in previous chapter, there is evidence of non-automotive actors actively participating in R&D, which has a more advanced innovative capacity because it brings in technologies and visions from a different point of knowledge, which can lead to more radical shifts. Also at that end of the scale is the testing and experimentation ecosystem. This enables bridging the gap between conceptual technologies and real-world applications. Public trialling and demonstrations can also lead to increased public acceptance, because it allows the potential future users to learn and anticipate new technologies. This leads to another aspect of learning mechanisms - the integration within user's practices. When vehicles reach levels 3 and 4 there will need to be a period of learning and adjustment for users to fully trust and embrace the technology. The pathway to AVs is currently envisioned as a step-by-step process by involved actors with SAE levels of automation used as the progression markers, however, there is currently little evidence on how users would actually behave when offered the option to allow the vehicle to perform some of or the entire task of driving.

Provision of funds for experimentation, stimulation of network-building and vision-building are all conditions that optimise learning and thus promote a transition process (Elzen et al., 2004), and there is evidence of the governance actors engaging in all of them, albeit the vision-building is currently limited.

9.1.2 Self-fulfilling prophecy mechanism

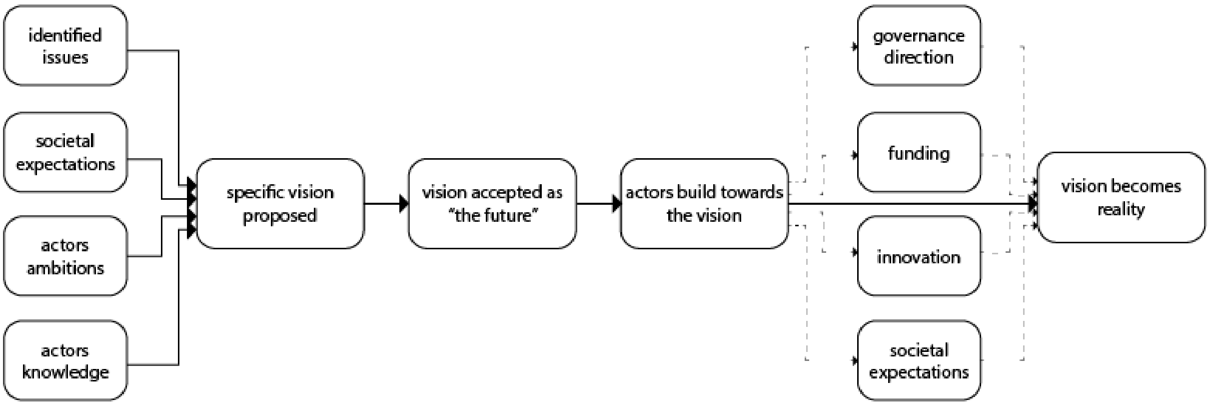

Figure 9-3 self-fulfilling prophecy sketch (by author)

9.1.2.1 Mechanism description

Self-fulfilling prophecies can be created by anticipating certain events (Figure 9-4). They can be created by creating a false or misleading description of a situation (or scenario), which in turn evokes behaviour that eventually make the initial false assessment come true (Merton, 1948). As evidenced by many issues concerning transportation and planning, decisions aimed at reducing congestion and improving traffic are short-sighted and can have the opposite consequences. For instance, transport planning decisions to increase lanes on motorways and provide additional parking have resulted in increased traffic and failed to address the challenges.

Traffic Inducing Traffic

Figure 9-4 example of self-fulfilling prophecy in transportation context (source: https://www.planetizen.com/node/56017)

9.1.2.2 Mechanism evidence

From analysed material, AVs are framed as "the solution" or an improvement to congestion and other issues concerned with traffic. Furthermore, another strong discourse is the "next automotive revolution" with the driverless car being the main disruptor. McKinsey(2019) have named autonomous mobility and connectivity amongst four key trends that show "disruptive potential".

In AVs context in the UK, similar assessments have been made. National Infrastructure Assessment 2018 set out *that "By 2050, road transport will be unrecognizable from today. Cars and vans will be electric, and increasingly autonomous. Electric, connected and AVs will change the nature of the transport debate in the UK."* (p.10) and it describes in more detail the potential changes as *"In the longer term, connected and AVs will bring even greater changes to the UK's roads. They will improve safety, and could allow more people to use personal transport and free up driving time for work or leisure. They may even encourage a* *shift towards increased vehicle sharing and reduced car ownership. Traffic lights and stop signs may become unnecessary, speed limits could be higher, and the use of road space could be automatically and constantly changing according to need." (p.11)*

Future of mobility: urban strategy *claims that "Much of the change in travel will happen first and fastest in urban areas, where transport is busiest, economic opportunities greatest, and space most restricted." (p.6) and it argues that "The window of opportunity to shape some of these changes is currently open but will not stay open forever" (p.37), which sets out how the transition to AVs would happen (in cities) and adds a sense of urgency. This could lead to AVs being first introduced in urban areas and geared towards the necessities of urban dwellers. While such outcome cannot yet be assessed as desirable or not, it sets up a trajectory, which can potentially exclude other use cases.*

Less direct actions setting up this mechanism are the R&D funding directions and commissioned research. By deciding on what type of innovation and research the actors should focus on, they inherently align themselves with those trajectories. By setting out such scenarios, the actors are already starting to work towards achieving them.

9.1.2.3 Implications of this mechanism

Self-fulfilling prophecy mechanism allows system actors to keep some level of control over the trajectories of innovation. However, by setting out a specific vision the actors potentially risk following an undesirable trajectory and/or missing out on an alternative pathway.

Setting of trajectories and scenarios is not fundamentally problematic. Arguably, with growing climate concerns the majority of scholarly authors argue for more robust and radical decision making to shift socio-technical systems towards sustainable trajectories. Furthermore, the “decide and provide” discourse has been identified as a better alternative approach in transport planning to the demand-led “predict and provide” approach (Lyons and Davidson, 2016). Despite evidence that “predict and provide” approach is not sufficient for complex todays and future transport challenges, the Government is indicating an approach where “where we can foresee issues, we plan to implement solutions” (Centre for Connected & Autonomous Vehicles, 2017:7).

The decision makers should consider the broader implications of statements that single out specific directions and assess whether or not the ‘prophecies’ align with desired future outcomes. *Autonomous Vehicles: What can Social Science offer?* Report also puts emphasis on “appropriate governance” (p.9) without which AVs might fail to achieve some objectives when reaching the market.

In the research question context, this links to the next identified mechanism – techno-optimism. Governance actor’s position to employ a ‘hands off’ approach on AVs governance enables industry actors to put forward visions and choose a trajectory towards which to steer the transition.

9.1.3 *Technology bias/techno-optimism*

9.1.3.1 Mechanism description

Techno-optimism in literature is described as "(an exaggerated) belief in human technological abilities to solve problems of unsustainability while minimizing or denying the need for large-scale social, economic and political transformation" (Barry, 2016). It is driven by belief that negative issues caused by current practices – such as societal issues and environmental challenges – can be solved and even eradicated through technological innovation.

Azar and Sanden (2011) highlight the challenge with so-called 'technology neutral' policies and identify that, while at higher level policies can avoid 'pushing' a specific technology, when it comes to lower level and action agenda, "technology-specific policies are (often) implemented" (Azar and Sanden (2011:138)). Boon and Bakker (2016) arrived at a similar conclusion that "the further one goes down the staircase in providing protection, the closer one gets to interference in industries and markets and the further one is removed from the 'level playing field' which is regarded as a beneficial consequence of innovation policy" (2016:196).

9.1.3.2 Mechanism evidence

Connected and AVs being named as one of the four Grand Challenges that the Industrial Strategy 2017 identified together with the statement that the Government wants to see fully self-driving cars on UK roads by 2021 singles out self-driving vehicles as a technological priority.

The permissive regulative approach that the Government has adapted allocates strong causal powers to the actors invested in autonomous vehicles.

As identified in coding results earlier, the focal promises/benefits associated with AVs are primarily concentrated around the potential of novel technologies, for example:

- Reduced stopping distances;
- Reduced need for parking;
- Freed-up travel time;
- Reduced accidents;
- Reduce accident-induced delays;
- Improved connectivity;
- Reduced pollution.

"We are on the cusp of profound changes in the ways people and goods move around, changes driven by extraordinary innovations in engineering, technology and business models. The introduction of CAVs presents us with exciting and potentially transformational opportunities" (CCAV, 2018). This position frames the substantial changes in the automotive sector around innovations in engineering and technology.

This evidence aligns with the mechanism definition suggesting that there is focus on technology's ability to solve specific issues related to transportation. Simultaneously, there is lack of evidence suggesting broader strategic approach. Furthermore, the visions about future roads presented in visualisation format (Figure 9-5, Figure 9-6, Figure 9-7) also appear technology-heavy showing extrapolated technology potential, and apart from the design and technology of vehicles shown in the visualisations very little appears to have changed in broader urban environments. Another visualisation (Figure 9-8) appears to consider potential negative effects of mismanagement of this transition, however, also in this image the negative effect appears to be technology-specific as it shows a congested street with futuristic looking personal vehicles.

Figure 9-5 visualisation from "UK Transport Vision 2050" report (source: UKRI (2021:22))


4. An opportunity to improve urban mobility dramatically

New technology and business models could deliver substantial benefits for society, the environment and the economy.

Figure 9-6 Visualisation from Future of Mobility: Urban Strategy report (source: DfT(2019:24)). Visualisation shows an urban street with people using active modes of travel, electric bus, and electric autonomous individual and shared vehicles.

Figure 9-7 Visualisation from Future of Mobility: Urban Strategy report (source: DfT(2019:25)). Visualisation depicts an urban mobility hub with people using active modes of travel and self-driving shared vehicles.

5. The risks from failing to manage change effectively

Failure to shape the implementation of emerging technologies and services could mean that we miss out on the opportunities presented above. Unintended consequences could lead to worse outcomes for society, the environment and the economy.

Figure 9-8 Visualisation from Future of Mobility: Urban Strategy report (source: DfT(2019:34)). Visualisation aims to warn about potential adverse effects from future mobility technology.

9.1.3.3 Implications of this mechanism

The techno-optimism can lead to unintended negative consequences because "framing issues in largely technological terms obscures both our understanding of the social and political complexities that might accompany any technological benefits, and the consideration of alternative mobility trajectories" (Cohen et al., 2020).

Because of the techno-optimism set-up, the rules – the regulative, normative, and cognitive conditions – are not scrutinised and the overall system lacks self-reflection leaving status quo remains unchallenged. This might work against achieving normative sustainability goals.

From a systems perspective, techno-optimism addresses macro problems at a micro (or sometimes meso) scale. Contextualising this back into the theoretical framing of this thesis, such micro-scale approach to macro-scale challenge is problematic. Firstly, this can be acknowledged through the notion of emergent causal powers. The causal powers of a locked-in system of automobility are complex and non-reducible to lower-level powers (such as those of individual technologies). Following this logic, causal powers of a technological innovation – the self-driving vehicle - might not be sufficient for a system-level change. Secondly, from a socio-technical transitions perspective, the existence of a technology alone is not sufficient to trigger a system-level transition. For this to happen, all analytical levels need to align in a specific configuration to enable a transition process.

Another aspect of the techno-optimism is the hype-disappointment cycle, where actors strategically inflate expectations (Ruef and Markard, 2010) to attract attention, which is followed by other actors to benefit from the available resources (Bergman, 2017). However, there is usually a decline in attention when the technology does not fulfil the expectations, or another new technology emerges. Because of the incumbent status of actors developing AV, it is unlikely that the idea of a self-driving car would be abandoned entirely, however, if the expectations of the speed of the transition and adaptation are not met, the expectations about the ‘radicality’ of AVs might change.

9.1.4 *Technology diffusion mechanism: "policy follows technology"*

9.1.4.1 Mechanism description

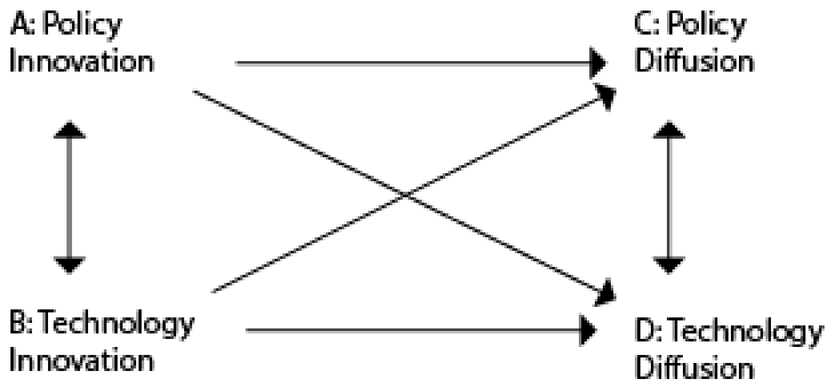

Figure 9-9 Diffusion patterns of innovation (source: Janicke (2000))

AV is an innovation that has attracted governance attention in the UK, and therefore it can be assumed that the manner and sped of technology diffusion will depend on the relationship and process that the innovation develops with policy.

The technology diffusion patterns model (Figure 9-9) conceptualises possible patterns of technological innovation in relation to policy innovation measures. Originally developed for environmental policy (Jänicke, 2000), it is applicable to other types of technological innovation and policy relations, where there is significant involvement from governance actors, such as the ongoing transition to AV. Patterns can describe the dynamics of innovation, such as technology forcing (ABCD), technological initiative or priming (BACD), political initiative or dominance (ABDC), independent technological development (BD) (Jänicke and Jacob, 2004).

9.1.4.2 Mechanism evidence

Based on this model, the AVs innovation in the UK can be characterised as BACD trajectory. The AVs technology has reached a stage where it can be tested and deployed in real-world environments, to which regulators have responded by anticipating and embracing the technology through regulatory review, strategy development, commissioned research, and R&D funding, signifying a trajectory where technology triggers a policy change. Policy response thus uses the promise of the technology to contribute towards policy goals (hence the BA sequence), such as emission or safety targets. Simultaneously, because AVs diffusion has been set as a government ambition and is further supported by investment and partnership development (AC trajectory), it indicates policy push towards technology development and diffusion (CD).

House of Commons briefing paper stated that “a central focus for government and automotive industry has been on creating the conditions in which the UK can capture a significant proportion of the global CAV R&D and manufacturing markets, and the potentially substantial economic benefits this could bring”(Clarke and Butcher, 2017:8). The same briefing paper further identifies a ‘pathway to driverless cars’ (Figure 9-10), which evidences a responsive governance strategy (step 2 – responding to market and steps 3 and 4 – agile regulation), which aligns with the BA diffusion pattern,

9.1.4.3 Implications of this mechanism

The position that the governance actors have taken enables industry actors to shape its direction. The diffusion mechanism identified here sheds light on internal dynamics of the transition trajectory.

Technology actors are driven by their set of priorities, which from transitions theory can be summarised as desire to stay in incumbent positions. Their actions are usually geared towards incremental technological advances focusing on price-performance improvements, market attraction and user satisfaction, which are trajectories of transformation and reconfiguration pathways identified before.

‘Leaving AVs decisions’ to those actors might lead to their preferred scenarios where innovation is managed towards their individual agendas. This, in turn, can limit potential systemic changes that are needed for societal and environmental benefits.

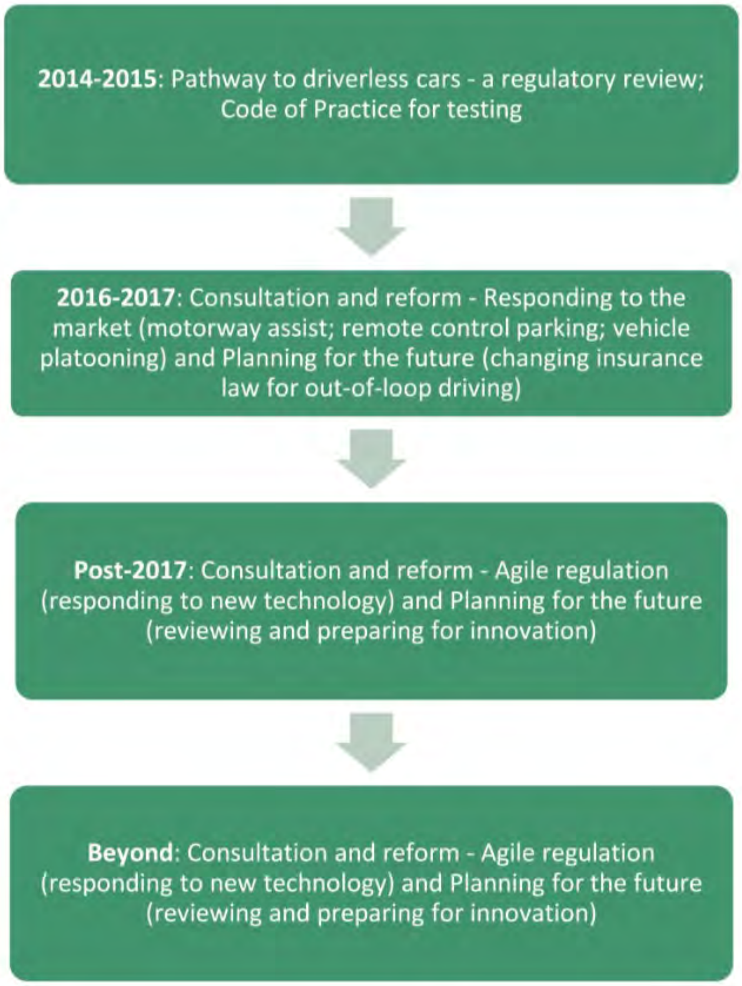

Figure 9-10 UK government's "pathway to driverless cars" approach (source: Clarke and Butcher (2017))

9.1.5 *Innovation framing mechanism*

9.1.5.1 Mechanism description

Innovation framing mechanism relates to the techno-optimism mechanism identified previously. This mechanism is enacted when actors frame the innovation to suit a particular objective. This can be done to attract user approval, funding, or other support. This mechanism can enact together with closure mechanisms from SCOT (section 3.1.1), which identified two types of closure mechanisms:

a. a rhetorical closure mechanism: a declaration is made that no additional design work is necessary; or
b. a redefinition closure mechanism: unresolved problems are redefined so that they no longer concern the social groups.

In a scenario with normative goals, innovation framing can be aligned with goals so that a "solution" is agreed among actors and accepted by regulators and users.

9.1.5.2 Mechanism evidence

Many strategies and policies in transport and related areas include within themselves normative goals, for example:

- 100% reduction of greenhouse gas emissions (compared to 1990 levels) (The Climate Change Act 2008 (2050 Target Amendment) Order 2019)
- Ban on sale of new petrol and diesel cars and vans by 2030 (HM Government, 2020).

UKRI have proposed a UK Transport Vision 2050 that identifies the investment strategy and is based on policy strategies (which are set out in the Industrial Strategy, Industrial Strategy Grand Challenges, and the Future of mobility: urban strategy) and is summarised in five target areas:

- Meeting societal and transport user needs
- Seamless transition of people and goods
- Net zero emissions

- Safe, secure, and resilient
- (UKRI, 2021).

The regulatory and legislative measures place pressures and direction on policy and industry[27]. To which the industry actors respond by adjusting innovation trajectories.

In the socio-technical analysis it was identified that the discourse of AVs (globally) is framed around safety, accessibility, improved traffic, and economic benefits. For example, Connected and AVs briefing paper[28] (2021) lists that the key potential benefits of CAV are:

- Convenience
- Safety
- (reducing) congestion
- Increased mobility for young, old, and disabled people
- Economic and productivity benefits.

As shown in Figure 9-11, the areas of perceived CAV benefits map against the strategic investment areas, suggesting that there is a causal link between the two.

[27] This links to the forcing mechanism addressed in the following section.

[28] Research briefings are research and analysis papers produced by the House of Commons Library to provide impartial analysis and research on topics that affect current policy discourse in the UK – economy, transport, energy, safety, health etc.

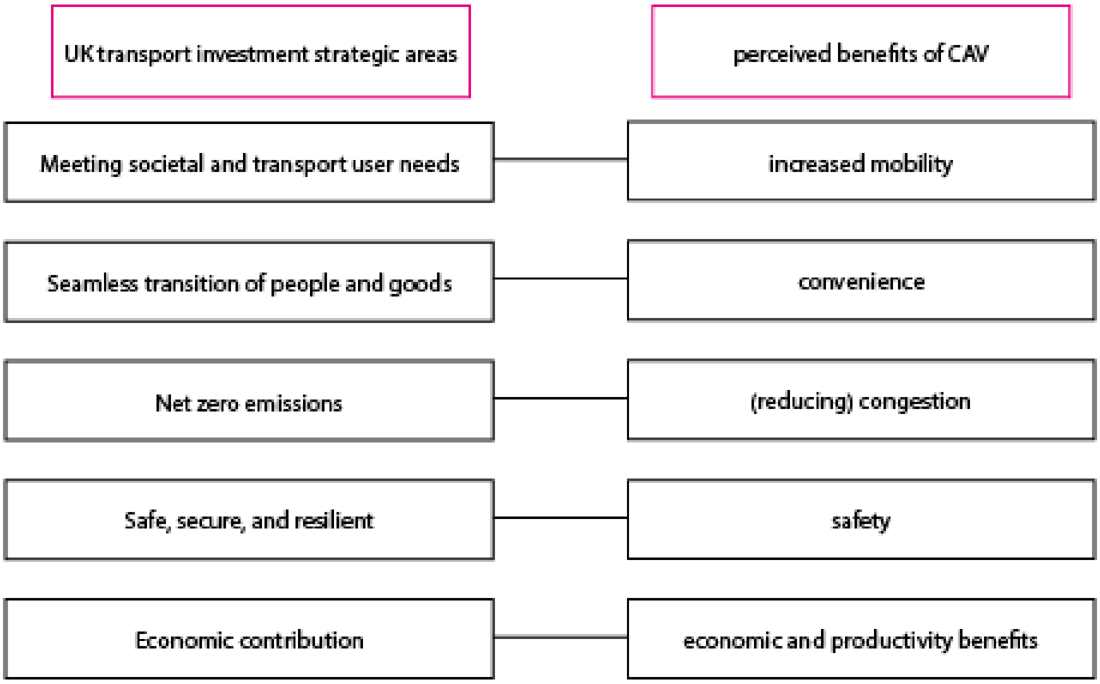

Figure 9-11 Mapping of UK transport investment strategic areas mapped against perceived benefits of CAV (by author)

9.1.5.3 Implications of this mechanism

Framing self-driving cars around strategic areas can have both, societally positive and negative outcomes. If the framing targets and achieves a specific goal, it can lead to societally beneficial outcomes. On the other hand, targets through framing can be set in a way that frames the technology as a solution, but either underdelivers or misses out on other aspects and implications of the technology.

This mechanism links to the next mechanism – innovation forcing mechanism.

9.1.7 *Forcing mechanism*

9.1.7.1 Mechanism description

Schot et al (1994) demonstrated implications of technology forcing in different contexts comparing the US and the Netherlands approaches to EV. As demonstrated in their California example, a technology forcing mandate triggered innovative activity both from incumbents and emergent actors.

This is similar to the framing mechanism above, but here the causality goes from governance actors to technology, meaning that through regulatory and policy instruments specific innovation outcomes can be achieved.

9.1.7.2 Mechanism evidence

In AVs context specifically a common statistical claim is that over 90% of all car accidents are caused by human error[29]. One of the major promises of AVs is reduction and potential elimination of this factor in car accidents. Advances in technology have enabled developments of safety features that the cars can be equipped with, such as blind spot assist, lane keeping and following, forward collision avoidance systems, and others. At the moment, the features are at the Levels 1 and 2 automation based on SAE classification, but more advances are expected to happen. The UK is looking at regulation allowing autonomous driving in specific situations – such as during congestion on motorways (DfT et al., 2021).

DfT was part of the working group that set out EU safety requirements (General Safety Regulations) for new cars. Those requirements are:

- Intelligent speed assistance

[29] The number ranges between 94% and 98% depending on source/region

- Alcohol interlock installation facilitation
- Driver drowsiness and attention warning systems
- Advanced driver distraction warning systems
- Emergency stop signals
- Reversing detection systems
- Event data recorders
- Accurate tyre pressure monitoring.

However, because of Brexit, these standards do not apply to the UK. As of beginning of 2022, the UK government has not announced its position on this matter. While some are campaigning for the regulations calling them “the biggest leap forward for road safety this century - perhaps even since the introduction of the seat belt” (Stone, 2022:online), others suggest the UK should “capitalise on our regulatory freedoms” (ibid). This is an example of regulatory powers directly impacting technology.

Another evidence of the forcing mechanism is the R&D funding. While it does not explicitly ‘force’ a specific technological trajectory, the available funding can incentivize actors to develop and prioritise the specific technologies. Figure 9-12 shows themes of R&D projects so far that have been part of the Government’s match-funding rounds.

Simultaneously, the role of the industry actors and their lobby position must be acknowledged. SMMT in their position paper on CAV (SMMT, 2017) have called for the Government to work closely with the industry.

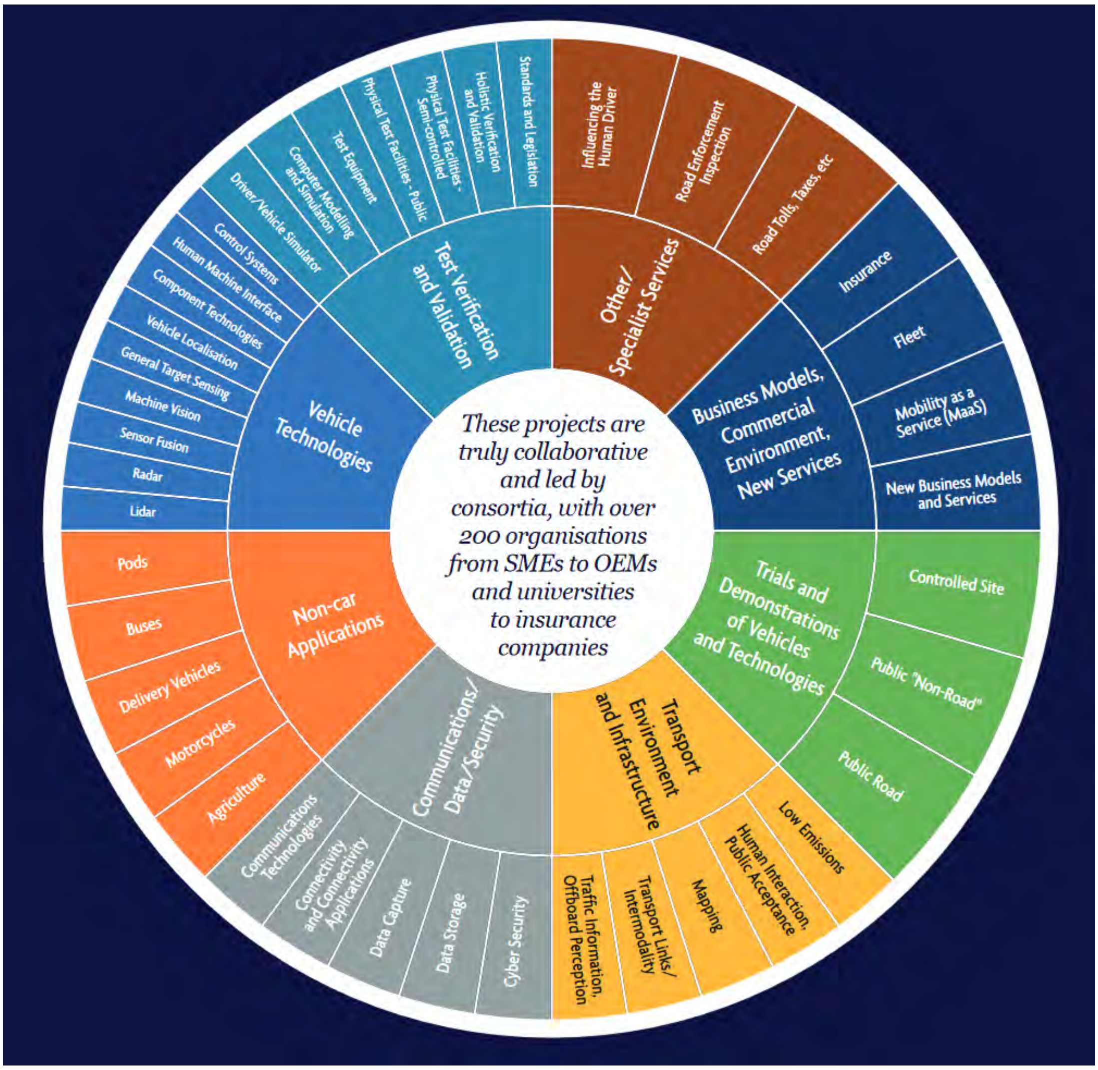

Figure 9-12 Areas of CAV R&D projects so far (source: CCAV (2020:6))

9.1.7.3 Implications of this mechanism

This mechanism puts the governance actors in a more leading role for the transition trajectory, and it shows that emerging technology can potentially be governed through strategic funding and regulatory changes. This mechanism is currently at a stage where it can be enacted – the structures and powers are there, however, it is not yet observable how and if the actors will choose to deploy the causal powers to impact the transition from a top-down position.

9.2 Chapter summary

The focus of this chapter is on the identification and analysis of demi-regularities and mechanisms in the context of the ongoing transition to AVs (AVs). Using directed coding, grey literature sources were analyzed to identify demi-regularities, which then led to the theorization of six causal mechanisms. These mechanisms were then matched with relevant discussions in both theoretical and empirical literature.

While some of the identified mechanisms, such as learning mechanisms and techno-optimism, have been established in transitions literature for some time, others, such as the technology diffusion mechanism, have not been explicitly discussed as mechanisms before. Nonetheless, they can be linked to literature and historical examples.

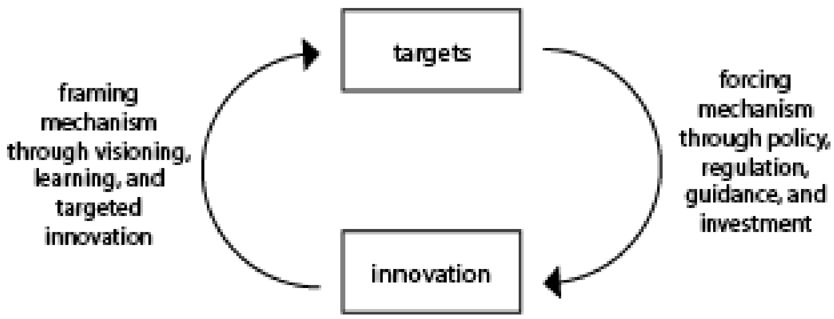

Figure 9-13 Relationship between innovation framing and innovation forcing mechanisms (by author)

Two new mechanisms were introduced in this chapter - innovation framing and innovation forcing - which share similar characteristics. Innovation framing occurs when technology actors frame the innovation activity around desired governance trajectories, while innovation forcing involves the top-down direction of innovation through regulatory measures (Figure 9-13). It is currently difficult to determine which direction is more significant in the ongoing transition to AVs, partly due to the strong lobby position of the industry in the UK's governance, which provides them with causal influence on some strategic directions.

Observed mechanisms at this stage are not isolated sequences but rather a combination of events that demonstrate some causalities, tendencies and trajectories that allow speculation about potential directions and outcomes.

Overall, this chapter provides valuable insights into the mechanisms driving the ongoing transition to AVs, and highlights the complex interplay between industry actors, regulators, and governance trajectories. By understanding these mechanisms, policymakers and stakeholders can better navigate the transition and shape its trajectory towards more sustainable and socially beneficial outcomes.

10 Discussion: Contextualisation of empirical findings and the significance of the application of the SRPM analytical framework

This chapter discusses the findings of this thesis. It outlines the key findings and relates them to the current research in transportation and sustainability transitions. It then outlines how the specific analytical framework – SRPM - designed and employed in this thesis provides a unique perspective and findings that offer new insights compared to the other methods outlined previously. Finally, this chapter contextualises the findings and contribution of this thesis within the current literature.

10.1 Summary and significance of empirical findings on the ongoing transition

Summary of findings using SRPM analytical framework

Table 10-1 summarises key findings from each of the analytical steps. The four-step process enabled a guided theorisation about the ongoing transition process to AVs in the UK. The insights provide a unique outlook on socio-technical transition inner dynamics that go beyond the traditional approaches of theory-testing or theory-matching. Here, through a theory-building mechanism-based approach the research develops a novel perspective on the ongoing transition process, and it builds an explanation of ***how*** the transition process is happening.

Table 10-1 Summary of findings

Analytical step	Findings
Socio-technical system (Chapter 6)	Landscape: • Technological developments nearing road-readiness • Transport decarbonisation • Mild shifts in travel behaviours; ageing population; road traffic forecasted to grow System:

	• light-touch non regulatory approach to AVs governance in the UK • targeted AVs development funding • testing ecosystem • R&D participation mostly by non-automotive industry • UK automotive sector supportive of the current governance direction • Public opinion in the UK unsure about advantages of CAV Niche: • Emergent firms working in AVs sector are not automotive companies • New types of partnerships forming across incumbents and other systems, and niche actors
Rules and the morphogenetic cycle (Chapter 7)	Internal dynamics reveal how the socio-technical system of automobility is stabilised and which aspects of the identified developments are pointing towards a structural change. It found that regulative rules shape the technology actors, while the technology actors shape the normative rules, which in turn affect other entities. These findings shed some light on how the system maintains the locked-in status and how it stays on a path-dependent trajectory.
Transition pathways (Chapter 8)	A new transition pathway typology was identified – system fusion. Findings demonstrate alignment with theoretical trajectories of the transformation, reconfiguration, and fusion pathways. The fusion pathway indicates a potentially disruptive change, while the other two point toward a less disruptive outcome.
Causal mechanisms (Chapter 9)	Identified processes were abstracted into a mechanism sketch, from which 6 distinct mechanisms were identified. The findings allow contextualising ***how*** the current AVs trajectories are being shaped.

Aligning pathways and mechanisms

Table 10-2 maps findings from chapters 8 (pathways) and 9 (mechanisms). This mapping allows interpretation of how mechanisms identified in the final step of analysis align with earlier findings on transition pathways that have been identified in the analysis. The mechanisms provide insight on how or through precisely which entities and actions the observed outcomes are brought about.

Table 10-2 Mapping of identified transition pathways and mechanisms (by author)

mechanism	**pathway**			
	Reproduction	**Transformation**	**Reconfiguration**	**Fusion**
Learning		X	X	X
Self-fulfilling prophecy	X			
Techno-bias		X	X	
Innovation framing			X	
Technology diffusion / policy follows technology			X	X
forcing		X		X

The following sub-sections identify areas of findings that previously have not been addressed in AVs literature, but they bear relevance to the ongoing discussion and discourse about AVs transition.

10.1.1 Understanding the non-regulatory approach and its implications in the UK from a socio-technical transitions perspective

The analysis identified that the UK government has developed an agenda to "be at the forefront of the AVs testing and development", and it has set out to support the development and deployment of AVs because it sees economic and other potential in this technology. The Government is actively exploring opportunities for testing and enabling AVs development through encouraging regulatory standpoint and investment in innovation and R&D projects. The reasoning behind the non-regulatory approach is to enable more rapid development and testing, with the ambition to deliver a 'world leading' AVs products and ecosystem. This approach is currently supported by the automotive sector. Simultaneously, the Government is taking a non-regulatory approach, meaning that the incumbent industry actors are given powers to steer this transition. Instead of regulation, to facilitate safe testing and deployment, DfT has published a best practice guide for AVs testing.

From a socio-technical transitions theoretical perspective, incumbent actors seek to maintain stability within the system and prefer incremental technological advances. This is in contrast with some of the claims about the disruptive potential of autonomous vehicles. While there are pressing environmental and societal issues within the system of automobility, there is a question about the ambitions of incumbent actors concerning these goals. In the case of AVs in the UK, there is currently no clear strategic vision at the governance level about the expected outcomes of AVs deployment, which again allows industry actors to envision and direct the technology and its applications, which could lead to undesirable societal and environmental outcomes.

10.1.2 AV is not a niche innovation

This thesis set out to understand the transition to AVs as a socio-technical transition. Often AVs is seen as a niche innovation in literature together with EV, MaaS and other innovations in transportation when basing the studies in transitions (and MLP specifically) literature (Geels, 2012a; Nykvist and Nilsson, 2015; Moradi and Vagnoni, 2018; Meelen et al., 2019). As a niche innovation, it is assigned some 'radicality' (coming from the idea of radical niche innovations) and associated socio-technical change. Radical change can happen when the dominant socio-technical system destabilises (due to landscape or internal pressures) allowing the niche interruption to overtake and thus change the socio-technical system.

However, regarding AV, the evidence presented in this thesis points to transition pathways that are consistent with theoretical descriptions of transformation and reconfiguration pathways. This implies a change of the socio-technical system that is driven from within the system and therefore seeks to further stabilise the system and drive innovation through incremental change and reduce the risk of destabilising the positions of incumbents.

Thus, framing the arrival of the AVs as a revolution in transportation is misleading because it lacks the ‘characteristics’ of a niche innovation. AVs is not the only innovation treated as a niche innovation in the transportation sector. Studies have looked at other innovations, such as e-scooters (Gössling, 2020) and electric vehicles (Dijk et al., 2013). Niche innovations are radical technologies that offer to take over the existing one by offering a ‘better’ alternative to the existing dominant technology. In complex systems, such as automobility, there is an added challenge of identifying the boundaries of the supposed niche innovations. For instance, Boon and Bakker (2016) also question the boundaries of the niche in sustainable mobility and clean car transition and characterise it as nested hierarchies of technological niches.

Characterised as a radical innovation and novelty, the technology is susceptible to misinterpretation of its transformative powers. Also in academic literature, Cohen et al. (2020), for instance, warn that the “potentially disruptive technology” needs to be addressed.

The ‘disruptive’ innovation narrative about AVs is mostly positioned as a positive in government and industry publications, suggesting that the disruptive nature of AVs technology can provide a ‘solution’ to some of the key challenges in the sector. On the other side, the academic literature warns about potential negative impacts due to a lack of assessment of potential impacts. It is important, however, to acknowledge that the transition to AVs is normatively directional, meaning that it is guided by normative visions and aspirations of what a desirable future should look like, with the current discourse acknowledging unsustainable practices and directions in the domain of transportation and the need for a change.

While there is not yet sufficient evidence to evaluate how AVs will affect the trajectory of this change, the research presented in this thesis suggests that the impact of AVs innovation could be less 'radical' than often argued in academic and other literature – the technology might change practices associated with how vehicles are made, maintained and driven but there is no evidence to link this with inherently positive or negative broader environmental and societal impacts. It is important to note thought that, as presented here, treating VA as a niche innovation in the sustainability transitions context specifically needs a further consideration to avoid misleading assessment about the potential of the technology and its impacts. Of course, continuing the 'business as usual' trajectory even with the presence of self-driving cars would continue and even amplify the unsustainable trajectories that the transportation system is currently on, but it can be argued that it would be due to inertia rather than disruption.

This does not, however, suggest that AVs have no place in shaping transportation in a more equitable and sustainable direction. It is unlikely though that they will deliver the overhaul of the automobility system that is sometimes promised if the current trajectories are followed.

10.1.3 Role of local authorities

In chapter 6, it was demonstrated that local and combined authorities possess a degree of autonomy when it comes to formulating strategies for AV. Despite their involvement in AVs research and development initiatives, however, no strategic publications have been produced by these authorities thus far. This lack of strategic action may represent a missed opportunity, as authorities are typically well positioned to devise transport strategies that are tailored to the unique geographic, economic, and social factors of their respective areas. This is especially relevant given that some of these authorities have published transportation strategies extending as far as 2040, which make no mention of AVs whatsoever. Although there is no guarantee that AVs technology will ultimately be deemed road-ready or make significant contributions to the transportation sector, neglecting to address this emerging technology could result in these authorities failing to capitalize on potential benefits that could be uniquely relevant to their contexts.

10.1.4 Identification of a new pathway: system fusion

Chapter 8 identified that there are aspects of this transition that do not fully fit in the existing characterisation of transition pathways. The new pathway – system fusion (named by author) – characterises a socio-technical transition in which the technology development in one system reaches a point where key components of the new technology are incorporated from another established system. It is evident that in the mobility sector the current and future developments are increasingly more reliant on technologies that traditionally have not played a significant role in the configuration of vehicles and the system of automobility itself. Trends such as automation, MaaS, and demand-responsive transport all rely on and are enabled by data, which until recently has not been a prominent part of transportation, especially private vehicles. Autonomous vehicles, however, introduce new actors in the system. Self-driving cars require technology – sensors, radars, computers – that previously have not been crucial for vehicle design and deployment. As seen in previous chapters, those tools and services are developed and provided by actors who, while new to transportation, are incumbent in other socio-technical systems. Figure 10-1 shows a simplified example of this pathway typology.

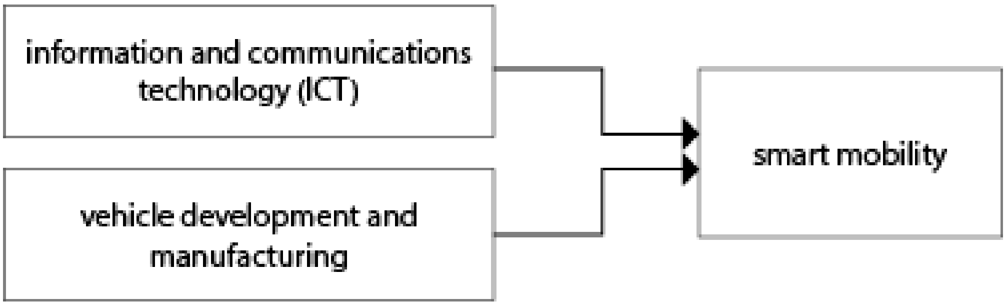

Figure 10-1 Simplified example of system fusion pathway (by author)

The implications of this pathway are that there newly introduced actors can rapidly change the dynamics of the system because of their inherent established powers in other systems. Currently, socio-technical transitions literature does not consider such configuration. With increasing globalisation and data-driven technology solutions, this typology provides a previously unidentified transition dynamic.

Compared to other findings, the fusion pathway can lead to more disruptive outcomes because the identified new actors are not ‘niche’ in the sense that they have established positions in their respective markets, and they might have enough causal power to change the structure of the system of automobility with more disruptive outcomes.

10.2 Using a mechanism-based approach to reveal new perspectives on ongoing transition processes: evidence of new findings through SRPM framework compared to traditional MLP approach

This section demonstrates how findings presented in this thesis differ from typical MLP analysis findings and highlights the significance of using the SRPM framework in accessing these findings.

Conceptually MLP can be summarised as focused on theory testing, while the SRPM approach shifts the focus on theory building. Because MLP is a theory-guided process, the findings of these studies identify processes that fit within the theoretical framework and mechanisms identified within. These mechanisms are, for example, learning mechanisms, coalition forming, and re-enforcing mechanisms that create and strengthen path dependence. When addressing historic or 'finished' transition processes, this approach produces an explanation that identifies relevant, mechanisms, actors and how their actions produced the observed outcome. Application to historic case studies leads to the findings being of descriptive nature. Within historic studies, the narrative does not require testing, because the observed outcomes have already occurred. In contrast, when investigating an ongoing process, the outcomes are not always observable and therefore conclusive findings are more challenging to prove by using the traditional MLP approach, and therefore a new re-focused analytical framework was developed in this thesis.

Table 10-3 demonstrates three distinct examples of how the SRPM approach has enabled new types of discovery, compared to the traditional MLP approach. Each difference is further discussed below.

Table 10-3 Comparison of key differences between MLP and SRPM that demonstrate how SRPM enables the identification of different and new findings (by author)

MLP approach	SRPM approach
Approach towards known mechanisms	
MLP names mechanisms (usually known mechanisms from theory and previous studies). Mechanisms are used to align narrative with theoretical conceptualisation.	SRPM approach identifies and explains mechanisms and explicitly presents evidence (or parts of evidence) through mechanism sketches/schemata.
Addressing an innovation that is not a niche innovation	
MLP conceptualises radical new innovations as niches. Some 'internal' innovations are identified through transition pathways, but the framework lacks capacity to address innovations that fall outside of the pre-defined scope of niche innovations.	SRPM allows contextualisation and conceptualisation innovations through morphogenetic cycle and mechanisms, which looks at both, external conditions and internal causation. There is no preconception of where or how innovation occurs allowing to build new theories about

	the nature of technological innovations, while still using a theory-driven approach for contextualisation and abstraction.
Morphogenetic approach to better interpret internal and external relations	
MLP prioritises the internal relations (regimes) for causal and explanatory powers, which can under-represent external influences.	SRPM applies the morphogenetic cycle parallel to investigation of internal rules to enable a more balanced representation of spatio-temporal contexts and causality. The notion of regimes is changed to system to account for a broader and more balanced range of entities, processes, and causal powers.

Approach toward known mechanisms

While the notion of mechanisms is not new to socio-technical transitions research, the difference lies in the explanatory powers of those mechanisms. For example, learning mechanisms are frequently found in MLP case studies and are often mentioned in core principles of socio-technical transition dynamics and pathways. Nevertheless, researchers often do not deliberate on these mechanisms beyond identification. In historic case studies this approach is appropriate, as the outcomes of those mechanisms and interactions are evident. In an ongoing process, however, shedding some light on the dynamics of such processes, provide further insight that not only identifies a process, but seeks to explain how specific outcomes are generated through those mechanisms.

For example, the learning mechanisms identified in this thesis demonstrate how government actors seek knowledge to further or fulfil a specific policy agenda. Learning mechanisms here serve as an enforcement instrument to primarily advance and explore a pre-set agenda, rather than gather broad knowledge on an emergent innovation, which is how learning has previously been conceptualised in transitions literature.

Such findings are accessible and distinguishable through the mechanism-focused framework applied in the empirical study in this thesis. In summary, MLP approach names mechanisms, while mechanism-based approach seeks to explain and demonstrate the mechanisms.

Addressing an innovation that is not a niche innovation

One of the criticisms of MLP is the overemphasis on internal rules (Sorrell, 2018), which can result in an analysis that develops a very internally focused view on transitions. This results in the exogenous context (landscapes and niches) seen as 'triggers' that cause system actors to respond, adapt, ad adjust trajectories. Adding the morphogenetic cycle approach to this allows having a view of transitions that not only identifies external conditions but also explains how they are affecting the dynamic of the transitions.

Another discovery of this thesis – technological innovations enabling autonomous cars is not a niche innovation – has been identified through a retroductive mechanisms-based approach. Other MLP studies that have looked at transitions in transport treat new sets of technologies as niche innovations. This is because in those cases researchers directly apply the MLP framework through abductive reasoning. Such perspective leads to a different formulation and interpretation of transition processes. In contrast, this thesis offers a view of the ongoing transition that investigates the transition beyond the concept of 'emergent niche innovation'. The discovery is enabled by two key positions that are directly adapted from critical realism: causal emergent properties of entities and the morphogenetic cycle.

- Causal emergent properties. A central concept of critical realism is emergence and emergent causal powers, which dictates that social actors and structures possess causal powers that cannot be reduced to individuals that make up those entities. This understanding requires a closer examination of which entities working towards specific agendas and whether they have the causal powers to account for those actions. From this, it led to the understanding that the key proponents of AVs are incumbent actors, rather than niche entities.

- Morphogenetic cycle offers a view on transition dynamics that considers structural condition, which is the structural implications of events and actions that predate and condition the observed phenomenon. These can be both, properties of the socio-technical system and exogenous influences (landscape). This way, the observed transition is placed in a spatio-temporal context that accounts for more than just the internal dynamics of the system, which is the case with the MLP approach. This further allows theorising about how and why the innovation has come about without the requirement to place it inside specific analytical or theoretical bounds.

Morphogenetic approach to better interpret internal and external relations

As identified previously, MLP seeks to theory-test and has developed a conceptualisation of how transitions occur. This however offers the limited capacity to theorise about trajectories of processes that cannot be sufficiently explained with the existing theory.

The previously discussed example of an innovation that is not a niche innovation – AVs - is an outcome of a configuration of mostly contingent relation – decades of technology developments enabling the self-driving technology to be near road readiness and application at scale. The developments are bounded by other contingent factors – climate pressures and population trends. The morphogenetic approach allows the conceptualisation of this as a structural condition. If the technology had been introduced a couple of decades ago – when the personal car was presented as a symbol of status and freedom – it is less likely that manufacturers would have developed low-emission self-driving vehicles focusing on on-demand and shared mobility, which characterises the AVs paradigm today. Therefore, these external/contingent conditions are not only important as a 'trigger' or 'pressure' but also as the specific spatio-temporal context that affects the behaviour of the actors and system as a whole.

Furthermore, the finding that AVs is not a niche innovation, or something that is external or alternative to the existing system, configuration directed the study further to investigate how and why it is framed, which was analytically enabled through theorising about mechanisms.

10.3 Addressing uncertainty

Socio-technical transitions research involves the study of complex, multi-level processes of socio-technical change, and uncertainty is often an inherent part of this research. Uncertainty can arise due to various factors such as subjective interpretation, incomplete data, unexpected events, and the complexity of the socio-technical phenomena under investigation. Uncertainty in social science qualitative research when analysing a real-world ongoing process needs to be addressed in the context of the analytical framework and the research findings.

The study aimed to identify the underlying structures and mechanisms that drive the socio-technical transitions associated with AVs in the UK context, while acknowledging the role of contingency and context-specific factors that may shape the direction of these transitions. However, it is important to note that the process of socio-technical transitions is inherently complex and uncertain, and the analysis can be limited to providing a partial and temporal understanding of this process. Furthermore, the analysis is based on a snapshot of the socio-technical system over a specified time period, and ongoing developments and changes in the system may modify and advance the findings in the future. Furthermore, as identified in the meta-analysis of the analysed literature (section 5.7), phrases such as “if channelled effectively”; “these benefits are not inevitable”; “the solutions for the distant future might not work now” suggest uncertainty about the transition process from the involved actors themselves. Therefore, this area of socio-technical transitions requires investigation from multiple perspectives across multiple time and scope scales to provide insights about the direction of the transition and potential points of intervention.

While the findings of the present study provide valuable insights into the potential socio-technical transitions associated with AVs in the UK, a degree of epistemological consideration is necessary when interpreting and contextualising the results, recognizing that the understanding of the underlying structures and mechanisms is temporal and can change when new data or interpretations come into existence.

To address some of these challenges, a novel analytical framework SRPM was developed to guide the study. This framework enabled a structured and systematic analysis of the complex and dynamic interplay between the technological, social, economic, and institutional factors that shape the socio-technical transitions associated with AVs in the UK.

In the context of uncertainty, the framework enables:

- Clarifications of concepts and definitions: The development of the framework has drawn on MLP and CR theoretical frames and has identified specific terminology and how it has been applied to the framework reducing ambiguity that often accompanies real-old studies of socio-technical transitions studies 9as identified in chapters 3 and 4).
- Organizing data: the ‘ladder of abstraction approach’ provides a way of organising data in a structural way enabling traceability of findings and claims and helping to identify patterns and relationships that might otherwise be difficult to discern.
- Enhancing transparency and replicability: The SRPM framework provides a transparent and replicable methodology for research, which can improve the quality of the findings and enhance the credibility of the research. A transparent and rigorous data collection and methods with clear scope and boundaries minimise uncertainty by ensuring that the research process is systematic, replicable, and transparent.

Considering these uncertainties, the SRPM framework developed in this study enables developing a more adaptive and iterative approach, incorporating ongoing data collection and analysis to update and refine the understanding of the socio-technical transitions associated with AVs in the UK context and other socio-technical transitions studies. The framework can also be applied to replicate a study when more data becomes available, facilitating a more comprehensive and robust analysis of the ongoing socio-technical transitions.

10.4 Relating findings to relevant research and broader discourse

Methodological contribution: how can we study an ongoing transition

This thesis demonstrates the applicability of the MLP theoretical framework, which is used to develop an analytical framework to study ongoing transitions.

MLP is becoming an increasingly popular framework used for studying transitions in socio-technical systems, including water systems (Geels, 2005a), sanitation (Geels, 2006), food (Papachristos and Adamides, 2016), energy (McDowall, 2014; Geels, 2018), and transportation (Berkeley et al., 2017). Scholars have demonstrated its applicability to transitions at various scales – from studies zooming in on specific innovations (Daramy-Williams et al., 2019) to whole system changes (Markard, 2018). This thesis also demonstrates that as a theoretical perspective it is applicable to abstract and conceptualise complex phenomena.

On the other hand, there are fewer studies on ongoing transitions that apply MLP, and the theoretical contributions have not moved forward as much as the empirical applications in the literature. The development of the SRPM framework contributes to this gap by presenting an analytical framework that can be applied to study ongoing socio-technical transitions. In literature some emergent approaches have been introduced: application of MATISSE (agent-based traffic simulation system) model (Köhler et al., 2018), dynamic simulation based mechanisms (Papachristos, 2018), complexity-based approach (Vasileiadou and Safarzyńska, 2010) suggesting that there are applications for more robust and defined analytical frameworks. The SRPM framework presented in this thesis also offers an approach to studying a transition process more systematically, but in contrast to other approaches outlined above, it allows for more theoretical and methodological flexibility. Firstly, the framework allows the application of multiple methods and, secondly, the theoretical framework used to guide the initial stages of the research process can be chosen by a researcher depending on the study.

Other transitions studies on AV

Since starting the writing of this thesis, new studies have emerged on driverless cars that have both, demonstrated findings that align with those of this thesis and contributed to the growing discussion on how autonomous driving futures would and should look like (Legacy et al., 2018; Porter et al., 2018; Cohen and Cavoli, 2019; Cohen et al., 2020; Lindgren et al., 2021; Lyons, 2022). The growing literature body signifies increasing attention given to AVs in academic domains beyond the technological aspects of driverless cars, allowing to gain a broader perspective on the transition process, to which this thesis also contributes to. During the completion of this thesis, a number of other studies specifically addressing AVs from a socio-technical transitions perspective emerged. These studies are summarised and discussed below.

A study by Martin (2021) focused on sociotechnical imaginaries in the transition to AVs and identified how visual imaginary is and can be used as a tool to convey narratives and agendas from incumbent and niche actors. The findings relate to the techno-optimism and mechanisms identified in this thesis, supporting the conclusion that visual discourse can have an impact on the trajectory of the transition. Furthermore, this could be explored together with the 'decide and provide' paradigm introduced further in this section.

In a study on mobility trends, Turienzo et al. (2022) used MLP theoretical framework to identify emergent trajectories in mobility and how governance should support them. Their findings focus on the socio-psychological aspect of the transition, suggesting that governance actors should promote certain aspects of new mobility services to maximise the benefits of emergent technologies. Their findings are in line with some aspects of the recommendations of this thesis in that the governance actors have a role to play in governing the transition in a direction that is beneficial to society. Their findings, however, are presented as more general, compared to the findings of this thesis, meaning that they do not identify specific action points or areas because their approach follows a more traditional MLP framework.

Canıtez (2021) deployed MLP to identify three AVs adoption models across a number of countries. Their findings, similarly, to the abovementioned MLP studies, are also presented in a narrative form and present high-level observations of potential directions and policy considerations. In their findings, they suggest that the UK government is sending a clear message on AVs direction through AV-oriented policies and strategies. This claim is different from the findings presented in this thesis. While I also acknowledge that the Government is supportive of AVs development and deployment, the regulatory approach identified in this thesis is enabling industry actors to direct AVs development and deployment, which can lead to AVs futures dictated by those actors rather than following a 'clear message' from the Government.

These studies demonstrate that MLP as an analytical framework can be applied to a range of aspects, even when addressing the same socio-technical transition. In line with the critique of MLP demonstrated in this thesis, the findings presented in the studies above follow a narrative-based approach. The strength of this approach is that it enables a way of constructing and presenting the observed process through a theory-guided process. However, as the identified studies demonstrate, the insights and decision-making recommendations are limited. This thesis argues that, when addressing ongoing transitions, there is value in the re-focusing approach so that not only a narrative but also causal insights and corresponding decision-making recommendations should be made. The MLP theoretical framework provides a strong theoretical base for understanding transition processes, and the re-focus on causal mechanisms allows actioning of those theory-informed findings. At a time when climate change demands informed action, this approach allows the identification of theory-driven and empirical evidence-supported causal insights that can be applied to policy and decision-making.

Transitions and policy

Looking at transitions from a socio-technical perspective enables placing the societal aspects of innovation in the discussion. Innovation and policymaking do not occur in a vacuum, and it is, therefore, a nuanced co-evolution of multiple often contrasting and competing sub-systems.

Hall (1993) assessed that “Without denying the impact of material interests on the policy process, we need to know much more than we now do about the role that ideas play in policymaking and in the process whereby policies change”. The research domain of powers and politics is vast, and it has crossed over into the transitions discourse as well (Smith et al., 2005; Kern and Smith, 2008; Johnstone and Newell, 2018; Noel et al., 2019).

While historically there have already been significant changes in the materialities associated with mobility in the city, the decision-making has not changed, leading to the same patterns of lock-in mechanisms. This amplifies the importance of the need to integrate decision making with policy and land use. A report by the Transport Systems Catapult (2018) discussed priorities for involving the social sciences in the move towards autonomous transport systems. This raises discussion towards transdisciplinarity to address complex problems such as transitions. The need for collaboration between government, local government, research, regulatory agencies, and private companies has been reflected in mobilities (Büscher et al., 2009) and transitions literature (Geels, 2012a), highlighting the importance of understanding the dynamics between industry, policymakers, consumers, and civil society in order to be able to contribute to transitions to sustainable (mobility) futures.

In contrast to earlier technological transition studies, such as the transition from sail ships to steamships, the ongoing transition to AVs is a more complex phenomenon that has impacts beyond the technological merits. As identified in previous chapters, currently the dominant discourse about AVs is that it is a technology-driven radical transformation of existing automobility systems. However, the transition exists in an automobility context that is facing significant environmental and socio-economic challenges. Furthermore, it is difficult to separate autonomous driving technology from other trends occurring simultaneously in transportation, such as MaaS, EVs, sharing, on-demand, and others. Therefore, AVs should be addressed not only as an innovation itself but also within the context of wider issues/developments.

Transport planning and sustainability

Transport does not develop in a linear fashion (see Gunn (2018) for a review of UK transport history) and Gunn also highlights that the transportation sector in the UK has seen “reversals and survivals” due to complex inter-related relationships between the various modes and systems. Historically, those relationships have been both, complimentary and detrimental, which is a cause for concern in regard to AV. The private car is already the dominant force in personal mobility and if its status were to be challenged, there should be a clear understanding of how the AVs can be of contribution to this, rather than being detrimental and furthering the lock-in of the private car. While some of the benefits of the technology might be welcomed, the impact of AVs on other modes, especially, active travel should be considered. The potential conflict and tension are also acknowledged in the Future of Mobility: Urban Strategy report, however, it lacks further guidance and evidence on how this should be approached.

Most recent literature on transport planning has indicated a recommendation to shift from the “plan and provide” to the “decide and provide” (P&P) model (Lyons, 2016; TRICS, 2021). The “decide and provide” (D&P) paradigm suggests deciding on the preferred future outcomes and provide the means necessary to achieve those outcomes. P&P is a forecast-led planning paradigm, while D&P is a vision-based paradigm. D&P also accounts for the increasingly noticed aspect of uncertainty in transportation planning (Marsden and Lyons, 2019) by enabling consideration of alternative visions and outcomes.

Furthermore, the paradigm shift towards D&P aligns with the position of sustainability transitions research. For sustainability transitions research, the research is directed toward achieving normative goals – which is broadly expressed as sustainability but can refer to specific policy objectives as well as broader system-level changes that would steer socio-technical systems in sustainable directions. This identifies a clear link between D&P and sustainability transitions because both can be seen as goal-oriented positions. This points towards a potential for further work aligning both domains that build on both, the theoretical grounding and emergent methodologies and frameworks from sustainability transitions and D&P policy and transport and land-use applications.

The findings of this thesis – the techno-optimism and lock-in mechanisms specifically – demonstrate through mechanisms identification how the 'plan and provide' paradigm is still embedded in the transition to humanless driving in the UK. In opposition to techno optimism that permeates the publications analysed in the technical part of this thesis, academic literature is more sceptical when it comes to assessing the potential changes AVs could bring about (Cohen et al., 2018; Legacy et al., 2018; Porter, 2018; Stilgoe, 2019). In wider literature, the issues that mobility is/will be facing have been discussed, and the general understanding is that the AVs is neither the cause nor the solution to any of the issues the transport sector is facing, which relates to wider discussions on transport planning and governance. Gruel and Stanford (2016) used scenario analysis to demonstrate that AVs on their own are unlikely to result in sustainable mobility. Elliot Fishman in Porter et al. (2018) calls driverless cars a "disappointing distraction" from the "real challenges" facing our cities. Pooley, Turnbull and Adams (2006) criticised the focus on technologies in transport innovation by arguing that a simple technological fix would not solve contemporary travel problems in cities. These findings align with the findings of this thesis that the trajectory that the AVs transition is heading towards mostly aligns with pathways that seek to stabilise the dominant socio-technical system, rather than radically disrupt it.

10.5 Summary

This chapter has identified and discussed the key empirical findings of this thesis. It has illustrated how the application of the SRPM framework has enabled the discovery of findings that would not be identified with the traditional MLP approach. Three specific areas of discovery were identified. This chapter has also contextualised the findings of this thesis within current literature, and it makes a comparison of the approach and findings of this thesis in comparison to new studies on AVs that have used socio-technical transitions approaches.

11 Conclusions

> *"If you always do what you've always done, you'll always get what you've always got"* Henry Ford

This chapter discusses how this study responds to the research questions set out at the beginning of the thesis and outlines the contributions to knowledge that this thesis makes. Then, recommendations identified in the thesis findings are presented. Finally, limitations of this thesis are discussed, and potential further areas of work are identified.

11.1 Answering the research question

This thesis set out to study the ongoing transition to AVs in the UK and set the following research questions:

WHAT ARE THE CAUSAL MECHANISMS SHAPING THE TRANSITION TO AVS IN THE UK? WHAT ARE THE IMPLICATIONS OF THESE FOR FUTURE MOBILITY IN THE CONTEXT OF THE SUSTAINABLE MOBILITY AGENDA?

WHAT ARE THE CAUSAL MECHANISMS SHAPING THE TRANSITION TO AVS IN THE UK?

To study the ongoing transition to AVs and to answer this research question, I first needed to establish the appropriate theoretical, analytical, and methodological frameworks. The investigation led to the identification and subsequent critique of the multi-level perspective. While it was identified as an appropriate framework to study transitions, it did not have sufficient analytical capacity to investigate ongoing transitions. This gap was addressed by the development of a novel tangible analytical framework to study ongoing transitions. The analytical framework enabled the discovery of causal processes and causal mechanisms in this transition, which are presented in chapters 6 to 9 and discussed and contextualised in chapter 10.

What are the implications of these for future mobility in the context of the sustainable mobility agenda?

Autonomous vehicles as a technological artefact are neither the cause nor the outcome of a broader debate on mobility and the future of mobility. They have however emerged in the automobility arena as a near-future possibility and therefore need to be considered concerning the broader context, which can be broadly summarised as sustainable mobility agenda. The sustainable mobility agenda encompasses a broad range of topics related to the promotion of transportation systems that balance social, economic, and environmental concerns. Researchers have identified a variety of challenges to achieving sustainable mobility, including the dominance of the automobile limited availability of sustainable transportation options, and entrenched institutional and policy structures that prioritize car-based transportation. The promotion of sustainable mobility has been framed as an important policy goal for addressing climate change, reducing air pollution, improving public health, and enhancing social equity.

To achieve these goals, research has emphasized the need for a range of interventions and policies that support mode shifting away from the car [REF]. Attention has also been given to the potential of emerging technologies, including autonomous vehicles, to transform the transportation system in ways that support sustainable mobility.

As identified in this thesis, AVs has been framed as an innovation that offers societal, environmental, and economic benefits. There is however insufficient evidence currently to evaluate whether those claims will result in real-life benefits. This thesis also identified that the governance actors have the capacity and powers to guide innovation, which in the context of normative environmental agendas could be used to ‘push’ the innovation towards more desirable trajectories. This has a direct implication for the sustainable mobility discourse. Much of the literature (both, academic literature and the grey literature reviewed in this thesis) often overlook the locked-in car dominated system of automobility and the incumbent actors’ ambition to maintain (or advance) their position, influence, and market share. Looking from a socio-technical transitions perspective, this thesis has identified that the observable developments in the field of AVs in the UK are currently more consistent with pathways, which, as described in theoretical literature, do not challenge the status quo (see section 10.1 for the list of findings).

11.2 Contribution to knowledge

This thesis makes a contribution to knowledge in two distinct areas: theoretical/ methodological contribution and empirical contribution.

Theoretical/methodological contribution

This thesis contributes to knowledge in socio-technical transitions studies and sustainability transitions studies by developing an analytical framework that can be applied to the study of socio-technical transitions. This contribution is significant to the field of transitions studies because it addresses a previously unaddressed gap in transitions research. The development of the SRPM framework provides a prescribed step-by-step analytical process for future studies on transitions. The framework is particularly relevant to the study of ongoing transitions because it provides tools to investigate processes in which outcomes are not yet observable. The re-focused approach to causal mechanisms enables theory-building (in contrast, existing studies typically employ theory-testing), which is particularly relevant and useful in studies that address processes that do not have historic precedents in literature.

Empirical contribution

In chapters 6 to 9 of this thesis, the application of the SRPM framework is demonstrated in the ongoing transition to AVs in the UK. The findings contribute to the domains of transitions research and mobility research. Autonomous mobility is still an emerging discourse with growing academic interest as evidenced in the previous chapter, and this thesis makes a unique contribution by taking a meso-level look at the ongoing process. The findings also provide insights and perspective on the ongoing transition process in the UK that can be of use to policy and decision makers.

11.3 Recommendations

This research concerns a real-world ongoing socio-technical transition process. When researching real-world phenomena there is an opportunity to relate research findings to the ongoing processes in a form of recommendations. In this case, I make three areas of recommendation, which are outlined further in this section.

11.3.1 Recommendation 1: addressing the gap in research areas

The UK government and other system actors are establishing a knowledge base by various means of learning mechanisms, including commissioned research on specific AVs areas. As identified in chapter 9, most studies commissioned by the Government have focused on technical aspects of autonomous vehicles. The other major area of research has been on governance – regulatory and policy framework research and development to enable AVs testing and deployment. On the other hand, fewer studies have been done addressing the social aspect of humanless driving. There is a particular gap (Figure 11-1) in the area between social and technical/industry research. From a socio-technical theories perspective, a key characterisation of a transition is the co-evolution of social and technical systems, and therefore further research in the area of human-technology interaction would be useful in ensuring societally beneficial technological innovation trajectories.

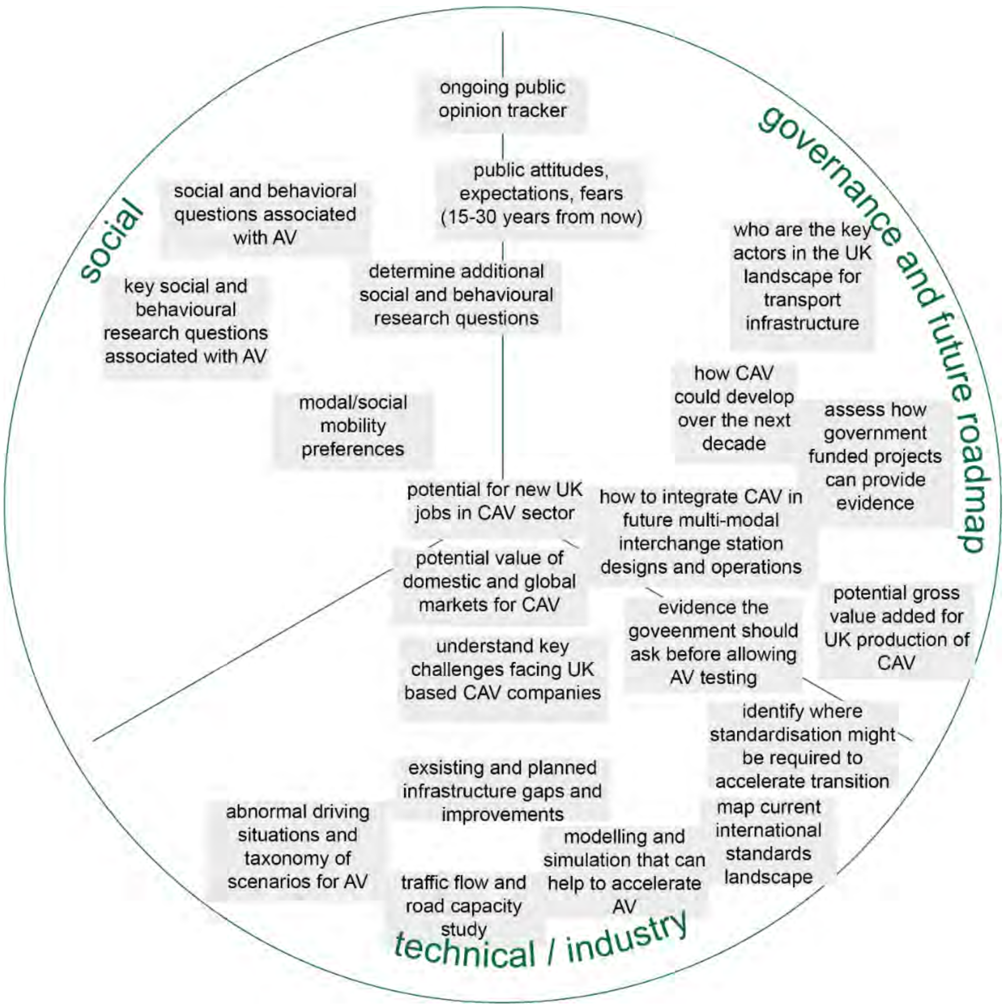

Figure 11-1 Thematic map of research commissioned by the Government (by author)

11.3.2 *Recommendation 2: a need for a multi-level understanding of transitions at a governance level*

One of the key roles of transport governance in the AVs transition is to balance the potential benefits of the technology with its potential negative impacts. This includes considering the impact of AVs on road safety, employment, and the environment. Transport governance also plays a role in creating a conducive environment for innovation and investment in AVs technology. This includes providing regulatory frameworks that support innovation while also ensuring public safety. In the UK, this thesis has evidenced that the Government has taken an active role in supporting AVs innovation through its Future of Mobility Grand Challenge and the Centre for Connected and Autonomous Vehicles. However, there are also challenges associated with transport governance in the AVs transition. For example, there is a need to coordinate and align policies across different levels of government (at the UK, devolved governments, combined authorities, and local authorities scales). There is also a need to ensure that the benefits of AVs technology are distributed fairly across different regions and social groups.

Both key theoretical frameworks used in this thesis – MLP and CR – acknowledge that transitions happen at different scales. In MLP, the idea of scale refers to systems, landscapes, and niches, each with its properties. From the CR perspective, the idea of scale can be associated with the concept of emergence. Causal properties of socio-technical systems are not reducible to causal properties of individual actors and entities.

These theoretical principles apply to real-world understanding and governance of transitions. To direct socio-technological transitions towards desirable trajectories, there should be an understanding of the processes at each analytical level. Furthermore, when making claims about the impacts of a specific innovation, its relevant 'level' and causal properties should be considered. For example, targeting funding towards a specific set of technologies might not lead to system-level changes because the innovation lacks causal properties of such scale.

This further links to the discussion about the causal mechanisms identified. The transition to humanless driving in the UK can be characterised as industry-driven and techno-focused. Claims have been made about the potential of AVs to significantly improve issues concerned with the transportation sector, however, often these claims are made about system-level changes but are based on lower-level entities. For instance, claims about AVs reducing congestion are made based on studies about platooning and efficiency of travel but do not consider wider causes of congestion that are to do with rising e-commerce, construction activity, population growth and other factors that place pressures on road space. While lower-level changes contribute to overall emergent properties of systems, when it comes to policy decisions, they should not be allocated causal powers that they do not possess.

11.3.3 Recommendation 3. Being explicit about how AVs will benefit the identified areas: can a mechanism-based approach help?

This study has identified how AVs have been framed in relation to environmental, societal and urban challenges. There is, however, a lack of research and understanding on ***how*** the technology is to achieve those ambitions. Furthermore, specific studies often deliver opposing claims on the same issue. For instance, there are studies claiming that AVs would reduce congestion (Fagnant and Kockelman, 2015), and studies that suggest that AVs would lead to increased traffic and congestion (ATKINS, 2016). Some reports claim that the advent of AVs would decrease the number of vehicles on road due to sharing and vehicles being able to self-park outside of dense urban areas. At the same time, other studies suggest that AVs would allow a more 'productive' commute time (Haboucha et al., 2017) and provide access to mobility to those users who cannot drive. These aspects would suggest that there might be an increased number of vehicles on the road when AVs are introduced on roads at scale. Currently, there is no uniform consensus on any impact area of self-driving cars. Nevertheless, those studies are useful to shed some light on potential scenarios and open a debate on desirable and disadvantageous outcomes. The challenge is, however, to understand those scenarios within existing complex multi-level real-world processes and systems.

This is where a mechanism-based approach can be useful. This thesis has developed an analytical framework allowing looking at:

- Mixed methods

    - The framework enables mixed methods research, which is especially relevant to policy that needs to consider complex multi-faceted issues
- Identify causality
    - Mechanism-based approach requires an explanation and validation of how X led to Y.
    - In order to identify appropriate requirements for policy and infrastructure, there needs to be more understanding of causality across multiple scales and domains to avoid undesirable consequences, which the framework addresses through the conceptualisation of observed phenomena at analytical levels.

11.4 Limitations and challenges of this research

No real-life study happens without its challenges. For this study, the limitations are mostly availability and the existence of available material that fit the criteria set out in the methodological framework. Because transitions to humanless driving are an ongoing phenomenon, information and discoveries have been and will be published outside and beyond the scope of this study. This would open an interesting opportunity for a comparative case study in a few years.

Another limitation is the complexity and breadth of the transportation domain. To develop the study, some boundaries had to be placed, however, it has to be done in a way that still leads to significant results. To address this limitation, in this thesis a theoretical perspective was used to bound and frame the empirical part of this thesis. Using a theoretical frame allowed abstracting the complex multi-layered system of automobility into simplified manageable sub-systems and entities. Such abstraction and focusing on a specific scale – the meso level – allowed managing this research. Another benefit of using a theoretical frame is that it allows the re-contextualisation of results and findings back to the relevant research domain. Another technique to set workable limitations was set in the analytical step 4 – identification of demi-regularities through a very specific limited dataset. Using this approach allows focusing on information at a very specific scale and context.

11.4.1 Defining the scope/setting analytical boundaries

Defining the scope for initial data collection was an easy-to-follow task. Later stages of the research, especially the coding step posed a scoping challenge. While the publications for analysis were selected based on their fitness for the pre-defined criteria, the content often covered more than the pre-defined scope. Therefore, for the coding exercise decisions had to be made to limit some information that was not directly related to the AVs transition. This was done to keep the study focused on the research question and limit contextual information to a minimum, which in a complex system such as automobility is a challenging task requiring informed judgement.

However, this limitation also provides an opportunity to study the ongoing transition from multiple perspectives. Studies 'zooming out' and looking at the transition from a global perspective as well as 'zoomed in' studies that address dynamics between parallel innovations or compare developments between different countries could also be useful.

11.4.2 Availability of empirical evidence

This thesis applied a theoretical framework to an ongoing real-life process. Therefore, not all aspects of the theoretical framework could be explored in depth due to the lack of available relevant publications.

This thesis presents and uses statistical and other data from secondary sources. While the data and sources were reviewed and considered, and, where possible, cross-referenced, it must be acknowledged that secondary sources can be biased and misleading. When analysing publications in this thesis, the Governmental (or other) body that commissioned the research has been identified and considered.

11.5 Future work

This section outlines potential future research that relates to this study.

Operationalisation of findings in the context of sustainable mobility agenda and the potential of combining SRPM with Transitions Management approach

This thesis has identified that the transition to AVs in the UK currently presents many characteristics that are consistent with a less 'radical' typologies of transition pathways, implying that despite the disruptive potential of AV, the current trajectories are consistent with less drastic change, which might consequentially result in a less desirable outcome from the sustainable mobility point of view. Because the transition is ongoing, the identification of those actors and processes can be used for directed intervention. This thesis employed the MLP framework with the aim to understand and to explain the ongoing transition process. Transitions management is an analytical approach in sustainability transitions that involves a structured process of analysis, planning, and implementation aimed at facilitating systemic change in a socio-technical system. Transitions management is a process of guiding and facilitating a transition from one state to another, usually towards more sustainable and desirable outcomes. It involves understanding the current state of a system, identifying the desired state, and developing strategies and actions to facilitate the transition. Applying transition management framework to the ongoing AVs transition would enable operationalisation of the findings of this thesis towards tangible policy interventions that could shift the transition towards desirable future trajectories. By adopting a transitions management approach, policymakers and stakeholders can work together to guide and facilitate the transition to AVs in a way that is consistent with the sustainable mobility agenda.

Defining the niche and transition dynamics

This thesis identified that AVs is not a traditional niche innovation and is, in fact, brought about by mostly internal processes. Simultaneously, other new innovations are emerging in the transportation sector and, because of the complexity of the socio-technical system of automobility they might be challenging to identify and understand. It is however crucial to correctly identify those actors and their powers in order to provide evidence for policy and decision-making. Further explorations in this area would be a useful contribution to the transitions dynamics discourse. One such approach could be the application of the SRPM framework to those transport innovations because it moves away from the notion of 'true niches' and instead focused on causality and dynamics of transitions.

Applications of the SRPM framework

This thesis has developed an analytical framework that can be applied to study socio-technical transition processes. Transitions research is a vast and increasingly expanding research area, however, as identified in this thesis, so far very few contributions have been made to establish an analytical process. This thesis has contributed to that gap by designing a process that offers structure to research design but also enables flexibility to be applicable to different socio-technical systems at different scales. The potential application areas of the framework are:

1. Application of the framework to other countries and contexts where the AVs transition is happening. The SRPM framework could be used to analyse the AVs transition in other countries and identify the dynamics there and potentially compare them to the transition mechanisms and dynamics to the findings of this thesis. This would be useful both, in advancing the academic field of sustainable transitions research and in informing policymakers and other stakeholders about the insights across the borders. Countries where this could be applied are:

a. United States. Many relevant companies are based in the US that are heavily involved in the AVs development, such as Waymo, Tesla, Uber, General Motors, and others. Some US states have also allowed self-driving car testing in urban environments, providing a different context for a SRPM study.
b. Japan and South Korea also have a strong automotive base and innovative potential with a different regulatory structure and cultural contexts, which again would make an interesting case study for comparison with the UK.
c. Insights could also be gained from counties like Israel, which are home to companies like Mobileye, which are developing advance driving assistance systems and other AVs technology, which is already used by global manufacturers.

2. Other socio-technical transitions can also be studied using the SRPM framework. The framework is most suitable for transitions of a similar scale to that presented in this thesis because it operates at a socio-technical system level with a degree of abstraction. Alongside autonomous vehicles, other technological developments could also be addressed through this framework as either stand-alone or comparative studies. Transitions to electric vehicles, micro mobility, on-demand mobility, and shared mobility can all be conceptualised as socio-technical transitions and similar studies on these processes would provide insights into other socio-technical dynamics that are relevant to transportation systems. Studies on transition to electric and/or hydrogen vehicles would offer an interesting comparison to the traditional case studies in these areas. As demonstrated in this thesis, the traditional MLP approach can mischaracterise innovation as 'niche' and consecutively assign it radical disruptive powers without fully investigating the internal dynamics of the system in which the innovation operates. Whereas the SRPM framework employs an approach that balances the innovation with its context

and with the application of the morphogenetic cycle and mechanisms demonstrates the mechanisms of how the transition is shaping.

3. Because the SRPM framework is designed to investigate the transition process through a mechanisms – based approach, it leads to identification of specific actions and consequences. For example, in this study, while the transition is still ongoing, there is evidence suggesting that there is a link between targeted governance actions and technology developments. At the same time, the governance actors are not fully engaging with the desired outcomes of the transition by letting the industry actors lead some of the innovation process. This could be more explored in the context of sustainability transitions with stakeholders using the framework and the findings to develop more targeted strategies and policies towards sustainable directions.

11.6 Summary

In 2017 the UK government set out to see self-driving cars on roads by 2021. At the time of writing up this thesis – in early 2022 – the 'mobility revolution' remains yet to be seen. The advent of self-driving cars is an ongoing process, and as the transition evolves there are opportunities for informed intervention and action to steer the process towards desirable sustainable trajectories. As this thesis (and other research in this area) identifies, the technology by itself is neither the cause, nor the solution to the societal challenges of today, but it is a result of complex co-evolutionary processes of multiple entities, which need suitable understanding and management.

Bibliography

Acheampong, R. A., Cugurullo, F., Gueriau, M. and Dusparic, I. (2021) 'Can autonomous vehicles enable sustainable mobility in future cities? Insights and policy challenges from user preferences over different urban transport options.' *Cities*. Elsevier Ltd, 112, May.

Alessandrini, A., Campagna, A., Site, P. D., Filippi, F. and Persia, L. (2015) 'Automated vehicles and the rethinking of mobility and cities.' *Transportation Research Procedia*. Elsevier B.V., 5 pp. 145–160.

Aljoufie, M., Zuidgeest, M., Brussel, M. and Van Maarseveen, & M. (2011) 'Urban growth and transport: understanding the spatial temporal relationship.' *Transactions on The Built Environment*, 116 pp. 1743–3509.

Araujo, L., Mason, K. and Spring, M. (2012) *Self-driving cars A case study in making new markets*.

Archer, M. (1995) *Realist social theory: the morphogenetic approach*.

Archer, M., Bhaskar, R., Collier, A., Lawson, T. and Norrie, A. (2013) 'Critical realism: Essential readings.' *Critical Realism: Essential Readings*. Taylor and Francis, June, pp. 1–756.

Archer, M. S. (2020) 'The Morphogenetic Approach; Critical Realism's Explanatory Framework Approach.' *In*, pp. 137–150.

Archer, M. S. and Archer, M. S. (1982) 'London School of Economics Morphogenesis versus Structuration : On Combining Structure and Action Published by : Wiley on behalf of The London School of Economics and Political Science Stable URL : http://www.jstor.org/stable/589357 Linked references are.' *The British Journal of Sociology*, 33(4) pp. 455–483.

Astbury, B. and Leeuw, F. L. (2010) 'Unpacking Black Boxes: Mechanisms and Theory Building in Evaluation.' *American Journal of Evaluation*, 31(3) pp. 363–381.

ATKINS (2016) *Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow*.

Atkinson, K. (2020) 'Autonomous cars : A driving force for change in motor liability and insurance,' 17(1) pp. 125–151.

Aucock, R. (2011) *Why Drivers Are Holding on to older cars*. [Online] [Accessed on

28th February 2020] https://www.rac.co.uk/drive/news/motoring-news/the-rise-of-the-middle-aged-motor/.
Avelino, F. (2017) 'Power in Sustainability Transitions: Analysing power and (dis)empowerment in transformative change towards sustainability.' *Environmental Policy and Governance*. John Wiley & Sons, Ltd, 27(6) pp. 505–520.
Avelino, F. and Rotmans, J. (2009) 'Power in transition: An interdisciplinary framework to study power in relation to structural change.' *European Journal of Social Theory*, 12(4) pp. 543–569.
Axsen, J. and Sovacool, B. K. (2019) 'The roles of users in electric, shared and automated mobility transitions.' *Transportation Research Part D: Transport and Environment*. Elsevier, 71(February) pp. 1–21.
Azar, C. and Sandén, B. A. (2011) 'The elusive quest for technology-neutral policies.' *Environmental Innovation and Societal Transitions*. Elsevier, 1(1) pp. 135–139.
Banister, D. (2008) 'The sustainable mobility paradigm.' *Transport Policy*. Elsevier, 15(2) pp. 73–80.
Banister, D. (2011a) 'Cities, mobility and climate change.' *Journal of Transport Geography*. Elsevier Ltd, 19(6) pp. 1538–1546.
Banister, D. (2011b) 'The trilogy of distance, speed and time.' *Journal of Transport Geography*. Elsevier Ltd, 19(4) pp. 950–959.
Barry, J. (2016) 'Bio-fuelling the Hummer? : Transdisciplinary thoughts on techno-optimism and innovation in the transition from unsustainability.' *Transdisciplinary Perspectives on Transitions to Sustainability*. Routledge, June, pp. 106–123.
Barton, M. S. and Gibbons, J. (2017) 'A stop too far: How does public transportation concentration influence neighbourhood median household income?' *Urban Studies*, 54(2) pp. 538–554.
Beach, D. (2016) 'It's all about mechanisms – what process-tracing case studies should be tracing.' *New Political Economy*. Taylor & Francis, 21(5) pp. 463–472.
Beach, D. and Pedersen, R. B. (2013) 'Process-tracing methods: Foundations and guidelines.' *Process-tracing Methods: Foundations and Guidelines* pp. 1–199.
Beach, D. and Pedersen, R. B. (2018) 'Process Tracing Methods - Foundation and Guidelines (Forthcoming).' *The University of Michigan Press*.
BEIS (2018) *Industrial Strategy: Automotive Sector Deal*. [Online] [Accessed on 27th

June 2022] https://www.gov.uk/government/publications/automotive-sector-deal/auto#fn:5.

BEIS, Innovate UK, Clark MP, G. and Hammond, P. (2017) *Business Secretary announces Industrial Strategy Challenge Fund investments - GOV.UK*. [Online] [Accessed on 15th June 2022] https://www.gov.uk/government/news/business-secretary-announces-industrial-strategy-challenge-fund-investments.

Bennett, R., Vijaygopal, R., practice, R. K. part A. policy and and 2019, undefined (n.d.) 'Attitudes towards autonomous vehicles among people with physical disabilities.' *Elsevier*.

Bergman, N. (2017) 'Stories of the future: Personal mobility innovation in the United Kingdom.' *Energy Research and Social Science*. Elsevier, 31(October 2016) pp. 184–193.

Bergman, N., Haxeltine, A., Whitmarsh, L., Kohler, J., Schilperoord, M. and Rotmans, J. (2008) 'Modelling socio technical transition patterns and pathways.' *Journal of artificial societies and social simulation*, 11(3) p. 7.

Berkeley, N., Bailey, D., Jones, A. and Jarvis, D. (2017) 'Assessing the transition towards Battery Electric Vehicles: A Multi-Level Perspective on drivers of, and barriers to, take up.' *Transportation Research Part A: Policy and Practice*. Elsevier, 106(June) pp. 320–332.

Bertolini, L. (2017) *Planning the mobile metropolis : transport for people, places and the planet*. Red Globe Press London.

Bhaskar, R. (2014) 'The possibility of naturalism: A philosophical critique of the contemporary human sciences.' *The Possibility of Naturalism: A philosophical critique of the contemporary human sciences*. Taylor and Francis, January, pp. 1–194.

BHASKAR, R. (1978) 'On the Possibility of Social Scientific Knowledge and the Limits of Naturalism.' *Journal for the Theory of Social Behaviour*, 8(1) pp. 1–28.

Bhaskar, R., Frank, C., Høyer, K., Parker, J. and Naess, P. (2010) *Interdisciplinarity and climate change: Transforming knowledge and practice for our global future*.

Biesbroek, R., Dupuis, J. and Wellstead, A. (2017) 'Explaining through causal mechanisms: resilience and governance of social–ecological systems.' *Current Opinion in Environmental Sustainability*. Elsevier B.V., 28 pp. 64–70.

Bijker, W. E. (1997) *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change*. MIT Press (Inside technology).

Blaikie, N. (2009) 'Designing Social Research' p. 352.

Blanco, M., Atwood, J., Vasquez, H. M., Trimble, T. E., Fitchett, V. L., Radlbeck, J., Fitch, G. M., Russell, S. M., Green, C. A., Cullinane, B., Morgan, J. F., Marinik, A., Bishop, R., Fitchett, V. L., Morgan, J. F., Trimble, T. E. and Blanco, M. (2015) *Human Factors Evaluation of Level 2 and Level 3 Automated Driving Concepts*. *Human Factors in Automated Driving Scenarios: Assessment of Research, Technology, and Concepts*. Washington, DC.

Blom, B. and Morén, S. (2011) 'Analysis of Generative Mechanisms.' *Journal of Critical Realism*, 10(1) pp. 60–79.

Boon, W. P. C. and Bakker, S. (2016) 'Learning to shield – Policy learning in socio-technical transitions.' *Environmental Innovation and Societal Transitions*. Elsevier, 18, March, pp. 181–200.

Van Den Bosch, S. J. M., Brezet, J. C. and Vergragt, P. J. (2005) 'How to kick off system innovation: A Rotterdam case study of the transition to a fuel cell transport system.' *Journal of Cleaner Production*, 13(10–11) pp. 1027–1035.

Brannan, M. J., Fleetwood, S., O'Mahoney, J. and Vincent, S. (2016) 'Critical Essay: Meta-analysis: A critical realist critique and alternative:' *https://doi.org/10.1177/0018726716674063*. SAGE PublicationsSage UK: London, England, 70(1) pp. 11–39.

van Bree, B., Verbong, G. P. J. and Kramer, G. J. (2010) 'A multi-level perspective on the introduction of hydrogen and battery-electric vehicles.' *Technological Forecasting and Social Change*. North-Holland, 77(4) pp. 529–540.

Brown, A., Gonder, J. and Repac, B. (2014) 'An Analysis of Possible Energy Impacts of Automated Vehicles.' *In*. Springer, Cham, pp. 137–153.

Büscher, M., Coulton, P., Efstratiou, C., Gellersen, H., Hemment, D., Mehmood, R. and Sangiorgi, D. (2009) 'Intelligent Mobility Systems:Some Socio-technical Challenges and Opportunities.' Mehmood, R., Cerqueira, E., Piesiewicz, R., and Chlamtac, I. (eds). Berlin, Heidelberg: Springer Berlin Heidelberg (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering), 16 pp. 140–152.

Bygstad, B. and Munkvold, B. E. (2011) ‘In search of mechanisms. Conducting a critical realist data analysis.’ *International Conference on Information Systems 2011, ICIS 2011*, 3 pp. 1978–1992.

Calhoun, C. (1998) ‘Explanation in historical sociology: Narrative, general theory, and historically specific theory.’ *American Journal of Sociology*, 104(3) pp. 846–871.

Canıtez, F. (2021) ‘The Adoption of Autonomous Vehicles: A Socio-Technical Transition Perspective.’ *Alphanumeric Journal*, 9(2) p. 2021.

Cass, N., Shove, E. and Urry, J. (2005) ‘Social exclusion, mobility and access.’ *Sociological Review*, 53(3) pp. 539–555.

CCAV (2018) *UK Connected and autonomous vehicle research and development projects | Enhanced Reader*.

Centre for Connected & Autonomous Vehicles (2017) *Pathway to driverless cars : Consultation on proposals to support Advanced Driver Assistance Systems and Automated Vehicles Government Response*.

Centre for Connected & Autonomous Vehicles (2018) *UK Connected & Autonomous Vehicle Research & Development Projects 2018*.

Chijioke, O. C., Ikechukwu, A. and Aloysius, A. (2020) ‘Understanding theory in social science research: Public administration in perspective:’ *https://doi.org/10.1177/0144739420963153*. SAGE PublicationsSage UK: London, England, 39(2) pp. 156–174.

Church, A., Frost, M. and Sullivan, K. (2000) ‘Transport and social exclusion in London.’ *Transport Policy*, 7(3) pp. 195–205.

Clarke, J. and Butcher, L. (2017) *Briefing Paper: Connected and autonomous road vehicles*. *House of Commons Library*.

Clayton, W., Paddeu, D., Parkhurst, G. and Parkin, J. (2020) ‘Autonomous vehicles: who will use them, and will they share?’ *Transportation Planning and Technology*. Taylor & Francis, 43(4) pp. 343–364.

Cohen, T. and Cavoli, C. (2019) ‘Automated vehicles: exploring possible consequences of government (non)intervention for congestion and accessibility.’ *Transport Reviews*. Taylor & Francis, 39(1) pp. 129–151.

Cohen, T., Stilgoe, J. and Cavoli, C. (2018) ‘Reframing the governance of automotive automation: insights from UK stakeholder workshops.’ *Journal of Responsible*

Innovation. Taylor & Francis, 5(3) pp. 257–279.

Cohen, T., Stilgoe, J., Stares, S., Akyelken, N., Cavoli, C., Day, J., Dickinson, J., Fors, V., Hopkins, D., Lyons, G., Marres, N., Newman, J., Reardon, L., Sipe, N., Tennant, C., Wadud, Z. and Wigley, E. (2020) 'A constructive role for social science in the development of automated vehicles.' *Transportation Research Interdisciplinary Perspectives*. Elsevier, 6, July, p. 100133.

Cookson, G. and Pishue, B. (2018) *INRIX Global Traffic Scorecard*. *INRIX Global Traffic Scorecard*.

Corbin, J. and Strauss, A. (2012) 'Basics of Qualitative Research (3rd ed.): Techniques and Procedures for Developing Grounded Theory.' *Basics of Qualitative Research (3rd ed.): Techniques and Procedures for Developing Grounded Theory*. SAGE Publications, Inc., April.

Cunneen, M., Mullins, M., Murphy, F., Shannon, D., Furxhi, I. and Ryan, C. (2019) 'Autonomous Vehicles and Avoiding the Trolley (Dilemma): Vehicle Perception, Classification, and the Challenges of Framing Decision Ethics.' *https://doi.org/10.1080/01969722.2019.1660541*. Taylor & Francis, 51(1) pp. 59–80.

Danermark, B., Ekström, M. and Karlsson, J. C. (2002) *Explaining society: Critical realism in the social sciences*. *Explaining Society: Critical Realism in the Social Sciences*.

Daramy-Williams, E., Anable, J. and Grant-Muller, S. (2019) 'A systematic review of the evidence on plug-in electric vehicle user experience.' *Transportation Research Part D: Transport and Environment*. Elsevier Ltd, 71, June, pp. 22–36.

Dennis, K. and Urry, J. (2009) *After the Car*.

Department for Business, E. & I. S. (2021) *Final UK greenhouse gas emissions national statistics: 1990 to 2019 - GOV.UK*.

Department for Transport (2015) *The Pathway to Driverless Cars: Summary repot and action plan*.

Department for Transport (2019a) *Future of Mobility: Urban Strategy*.

Department for Transport (2019b) *National Travel Survey: England 2018*.

Department for Transport (2020) *National Travel Attitudes Study : Wave 2*.

Department for Transport (2021) *DecarbonisingTransport: A Better Greener Britain*.

Department of Transport (2015) *The Pathway to Driverless Cars*. *The Pathway to Driverless Cars*.
DfT (2015) *The Pathway to Driverless Cars. Summary report and action plan*.
DfT (2016) *Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow. Summary Report*.
DfT (2021a) *Average number of trips made and distance travelled*. [Online] [Accessed on 17th June 2022] https://www.gov.uk/government/statistical-data-sets/nts01-average-number-of-trips-made-and-distance-travelled.
DfT (2021b) *Science Plan: The vision for science in DfT*.
DfT, CCAV and Maclean, R. (2021) *Government paves the way for self-driving vehicles on UK roads - GOV.UK*. [Online] [Accessed on 23rd June 2022] https://www.gov.uk/government/news/government-paves-the-way-for-self-driving-vehicles-on-uk-roads.
Dijk, M., Orsato, R. J. and Kemp, R. (2013) 'The emergence of an electric mobility trajectory.' *Energy Policy*, 52 pp. 135–145.
Docherty, I., Marsden, G. and Anable, J. (2017) 'The governance of smart mobility.' *Transportation Research Part A: Policy and Practice*, (xxxx) October.
Docherty, I., Marsden, G. and Anable, J. (2018) 'The governance of smart mobility.' *Transportation Research Part A: Policy and Practice*. Elsevier, 115(October 2017) pp. 114–125.
Dogan, E., Chatila, R., Chauvier, S., Evans, K., Hadjixenophontos, P. and Perrin, J. (2016) 'Ethics in the design of automated vehicles: The AVEthics project.' *CEUR Workshop Proceedings*, 1668 pp. 10–13.
Duarte, F. and Ratti, C. (2018) 'The Impact of Autonomous Vehicles on Cities: A Review.' *Journal of Urban Technology*. Taylor & Francis, 0(0) pp. 1–16.
Dudley, G., Banister, D. and Schwanen, T. I. M. (2017) 'The Dynamics of Public Participation in New Technology Transitions : The Case of Dockless Bicycle Hire in Manchester' pp. 93–111.
Earnest, L. (2012) *Stanford Cart*. [Online] [Accessed on 13th June 2022] https://web.stanford.edu/~learnest/sail/oldcart.html.
Easton, G. (2010) 'Critical realism in case study research.' *Industrial Marketing Management*. Elsevier Inc., 39(1) pp. 118–128.

Elzen, B., Geels, F., Hofman, P. and Umist, K. G. (2002) 'Socio-Technical Scenarios as a tool for Transition Policy An example from the traffic and transport domain,' (June) pp. 23–26.
Elzen, B., Geels, F. W. and Green, K. (2004) *System innovation and the transition to sustainability*. *System Innovation and the Transition to Sustainability*. Edward Elgar Publishing.
Emery, F. (2016) 'Characteristics of Socio-Technical Systems.' *The Social Engagement of Social Science, Volume 2*. University of Pennsylvania Press, April.
Emery, F. E. and Marek, J. (1962) 'Some Socio-technical Aspects of Automation.' *Human Relations*, 15(1) pp. 17–25.
Ernst, L., de Graaf-Van Dinther, R. E., Peek, G. J. and Loorbach, D. A. (2016) 'Sustainable urban transformation and sustainability transitions; conceptual framework and case study.' *Journal of Cleaner Production*. Elsevier, 112, January, pp. 2988–2999.
European Environment Agency (EEA) (2015) *SOER 2015—the European environment—state and outlook 2015: a comprehensive assessment ofthe European environment's state, trends and prospects, in a global context.*
Evans, K., de Moura, N., Chauvier, S., Chatila, R. and Dogan, E. (2020) 'Ethical Decision Making in Autonomous Vehicles: The AV Ethics Project.' *Science and Engineering Ethics 2020 26:6*. Springer, 26(6) pp. 3285–3312.
Eyerman, R. and Jamison, A. (1991) *Social movements : a cognitive approach*. Polity Press in association with Basil Blackwell.
Fagnant, D. J. and Kockelman, K. (2015) 'Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations.' *Transportation Research Part A: Policy and Practice*. Elsevier Ltd, 77, July, pp. 167–181.
Fagnant, D. J. and Kockelman, K. M. (2014) 'The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios.' *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, 40 pp. 1–13.
Fidel, R. (1984) 'The case study method: A case study.' *Library and Information Science Research*, 6(3) pp. 273–288.
Fischer-Kowalski, M., Haas, W., Wiedenhofer, D., Weisz, U., Pallua, I., Possanner, N., Behrens, A., Serio, G., Alessi, M. and Weis, E. (2012) *Socio-ecological transitions:*

definition, dynamics and related global scenarios. *State of the art report no. 6/D1.1 and Working paper/D1.2*.

Fischer-kowalski, M. and Rotmans, J. (2009) 'Conceptualizing , Observing , and Influencing Social – Ecological Transitions.' *Ecology and Society*, 14(2) p. 3.

Fischer, L. B. and Newig, J. (2016) 'Importance of actors and agency in sustainability transitions: A systematic exploration of the literature.' *Sustainability (Switzerland)*, 8(5).

Fletcher, A. J. (2017) 'Applying critical realism in qualitative research: methodology meets method.' *International Journal of Social Research Methodology*. Routledge, 20(2) pp. 181–194.

Földes, D. and Csiszár, C. (2018) 'Framework for planning the mobility service based on autonomous vehicles.' *2018 Smart City Symposium Prague (SCSP)*. IEEE pp. 1–6.

Forrester, J. W. (1958) 'Industrial Dynamics.' *Harvard Business Review*, 36(August) pp. 37–66.

Foxon, T. J., Hammond, G. P. and Pearson, P. J. G. (2010) 'Developing transition pathways for a low carbon electricity system in the UK.' *Technological Forecasting and Social Change*. Elsevier Inc., 77(8) pp. 1203–1213.

Fraedrich, E., Beiker, S. and Lenz, B. (2015) 'Transition pathways to fully automated driving and its implications for the sociotechnical system of automobility.' *European Journal of Futures Research*, 3(1).

Fraedrich, E., Heinrichs, D., Bahamonde-birke, F. J. and Cyganski, R. (2018) 'Autonomous driving, the built environment and policy implications.' *Transportation Research Part A*. Elsevier, (xxxx) pp. 0–1.

Freudendal-Pedersen, M., Hartmann-Petersen, K., Kjærulff, A. A. and Nielsen, L. D. (2017) 'Interactive environmental planning: creating utopias and storylines within a mobilities planning project.' *Journal of Environmental Planning and Management*, 60(6) pp. 941–958.

Freund, P. and Martin, G. (1993) *The ecology of the automobile*. Montreal: Black Rose Books.

Furtado, F. (2017) *Shared Mobility Simulations for Helsinki*.

Gandia, R. M., Antonialli, F., Cavazza, B. H., Neto, A. M., Lima, D. A. de, Sugano, J. Y., Nicolai, I. and Zambalde, A. L. (2018) 'Autonomous vehicles: scientometric and bibliometric review*.' *https://doi.org/10.1080/01441647.2018.1518937*. Routledge, 39(1) pp. 9–28.

Geels, F. (2005a) 'Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850-1930) - A case study in multi-level perspective.' *Technology in Society*, 27(3) pp. 363–397.

Geels, F. (2005b) 'Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850–1930)—a case study in multi-level perspective.' *Technology in Society*. Pergamon, 27(3) pp. 363–397.

Geels, F. (2005c) *Technological Transitions and System Innovations*. *Technological Transitions and System Innovations*. Edward Elgar Publishing.

Geels, F. (2005d) 'The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930).' *Technology Analysis & Strategic Management*, 17(4) pp. 445–476.

Geels, F. W. (2002) 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study.' *Research Policy*, 31(8–9) pp. 1257–1274.

Geels, F. W. (2004) 'From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory.' *Research Policy*, 33(6–7) pp. 897–920.

Geels, F. W. (2006) 'The hygienic transition from cesspools to sewer systems (1840–1930): The dynamics of regime transformation.' *Research Policy*. North-Holland, 35(7) pp. 1069–1082.

Geels, F. W. (2007) 'Feelings of discontent and the promise of middle range theory for STS: Examples from technology dynamics.' *Science Technology and Human Values*, 32(6) pp. 627–651.

Geels, F. W. (2010b) 'Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective.' *Research Policy*, 39(4) pp. 495–510.

Geels, F. W. (2010a) 'Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective.' *Research Policy*. Elsevier B.V., 39(4) pp. 495–510.

Geels, F. W. (2011) 'The multi-level perspective on sustainability transitions: Responses to seven criticisms.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 1(1) pp. 24–40.

Geels, F. W. (2012a) ‘A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies.’ *Journal of Transport Geography*. Elsevier Ltd, 24 pp. 471–482.
Geels, F. W. (2012b) ‘A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies.’ *Journal of Transport Geography*, 24, September, pp. 471–482.
Geels, F. W. (2014a) ‘Reconceptualising the co-evolution of firms-in-industries and their environments: Developing an inter-disciplinary Triple Embeddedness Framework.’ *Research Policy*. North-Holland, 43(2) pp. 261–277.
Geels, F. W. (2014b) ‘Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective.’ *Theory, Culture & Society*, 31(5) pp. 21–40.
Geels, F. W. (2018) ‘Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016).’ *Energy Research & Social Science*. Elsevier, 46, December, pp. 86–102.
Geels, F. W. (2019) ‘Socio-technical transitions to sustainability : a review of criticisms and elaborations of the Multi-Level Perspective.’ *Current Opinion in Environmental Sustainability*. Elsevier B.V., 39 pp. 187–201.
Geels, F. W. (2020) ‘Micro-foundations of the multi-level perspective on socio-technical transitions: Developing a multi-dimensional model of agency through crossovers between social constructivism, evolutionary economics and neo-institutional theory.’ *Technological Forecasting and Social Change*. Elsevier, 152(December 2019) p. 119894.
Geels, F. W. and Johnson, V. (2018) ‘Towards a modular and temporal understanding of system diffusion: Adoption models and socio-technical theories applied to Austrian biomass district-heating (1979–2013).’ *Energy Research and Social Science*. Elsevier, 38(November 2017) pp. 138–153.
Geels, F. W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M. and Wassermann, S. (2016) ‘The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014).’ *Research Policy*. Elsevier B.V., 45(4) pp. 896–913.

Geels, F. W., McMeekin, A. and Pfluger, B. (2018) 'Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050).' *Technological Forecasting and Social Change*, (February).

Geels, F. W. and Schot, J. (2007) 'Typology of sociotechnical transition pathways.' *Research Policy*, 36(3) pp. 399–417.

Geels, F. W. and Schot, J. (2017) *The Dynamics of Transitions : A Socio-Technical Perspective Transitions to*.

Geels, F. W., Sovacool, B. K., Schwanen, T. and Sorrell, S. (2017) 'The Socio-Technical Dynamics of Low-Carbon Transitions.' *Joule*. Elsevier Inc., 1(3) pp. 463–479.

Geels, F. W. and Verhees, B. (2011) 'Cultural legitimacy and framing struggles in innovation journeys: A cultural-performative perspective and a case study of Dutch nuclear energy (1945-1986).' *Technological Forecasting and Social Change*. Elsevier Inc., 78(6) pp. 910–930.

Geisslinger, M., Poszler, F., Betz, J., Lütge, C. and Lienkamp, M. (2021) 'Autonomous Driving Ethics: from Trolley Problem to Ethics of Risk.' *Philosophy & Technology 2021*. Springer, April, pp. 1–23.

Genus, A. and Coles, A. M. (2008) 'Rethinking the multi-level perspective of technological transitions.' *Research Policy*, 37(9) pp. 1436–1445.

Giddens, A. (1986) *The constitution of society: Outline of the theory of structuration*. Univ of California Press.

Gilgun, J. (2011) 'Coding in deductive qualitative analysis.' *Current Issues in Qualitative Research: An Occasional Publication for Field Researchers from a Variety of Disciplines*, 2(1) pp. 1–4.

Goertz, G. and Mahoney, J. (2012) 'Concepts and measurement: Ontology and epistemology:' *http://dx.doi.org/10.1177/0539018412437108*. SAGE PublicationsSage UK: London, England, 51(2) pp. 205–216.

Golbabaei, F., Yigitcanlar, T., Paz, A. and Bunker, J. (2020) 'Individual Predictors of Autonomous Vehicle Public Acceptance and Intention to Use: A Systematic Review of the Literature.' *Journal of Open Innovation: Technology, Market, and Complexity*,

6(4) p. 106.
Goldstone, J. A. (1998) ‘Initial conditions, general laws, path dependence, and explanation in historical sociology.’ *American Journal of Sociology*, 104(3) pp. 829–845.
Gorski, P. S. (2013) ‘“What is Critical Realism? And Why Should You Care?”’ *Contemporary Sociology: A Journal of Reviews*, 42(5) pp. 658–670.
Gössling, S. (2020) ‘Integrating e-scooters in urban transportation: Problems, policies, and the prospect of system change.’ *Transportation Research Part D: Transport and Environment*. Pergamon, 79, February, p. 102230.
Gould, E. (2017) *The transition to electric vehicle fleets : an e-mobility services approach.* University of Surrey.
Great Britain Ministry of Transport and Buchanan, C. (1964) *Traffic in Towns*. Harmondsworth, England: Penguin Books.
Greenblatt, J. B. and Shaheen, S. (2015) ‘Automated Vehicles, On-Demand Mobility, and Environmental Impacts.’ *Current Sustainable/Renewable Energy Reports*, 2(3) pp. 74–81.
GRIFFIN, L. J. (1992) ‘Temporality, Events, and Explanation in Historical Sociology.’ *Sociological Methods & Research*, 20(4) pp. 403–427.
Gross, N., Joas, H., Kilpinen, E., Lamont, M., Martin, L., Sampson, R., Stevens, M., Tarrow, S., Turner, S., Whitford, J., Winship, C., Wray, M. and Vaisey, S. (2009) ‘Social Mechanisms,’ 74(2000) pp. 358–379.
Grubler, A. (2012) ‘Energy transitions research: Insights and cautionary tales.’ *Energy Policy*. Elsevier, 50, November, pp. 8–16.
Gruel, W. and Stanford, J. M. (2016) ‘Assessing the Long-term Effects of Autonomous Vehicles: A Speculative Approach.’ *Transportation Research Procedia*. Elsevier B.V., 13 pp. 18–29.
Gunn, P. S. (2018) ‘The history of transport systems in the UK Future of Mobility : Evidence Review.’ *Future of Mobility: Evidence Review* p. 36.
Haboucha, C. J., Ishaq, R. and Shiftan, Y. (2017) ‘User preferences regarding autonomous vehicles.’ *Transportation Research Part C: Emerging Technologies*, 78 pp. 37–49.
Hall, P. A. (1993) ‘Policy Paradigms, Social Learning, and the State: The Case of

Economic Policymaking in Britain.’ *Comparative Politics*. JSTOR, 25(3) p. 275.
Hansen, P., Liu, X. and Morrison, G. M. (2019) ‘Agent-based modelling and socio-technical energy transitions: A systematic literature review.’ *Energy Research and Social Science*. Elsevier, 49(June 2018) pp. 41–52.
Harris, M. (2014) *How Google’s Autonomous Car Passed the First U.S. State Self-Driving Test - IEEE Spectrum*. [Online] [Accessed on 13th June 2022] https://spectrum.ieee.org/how-googles-autonomous-car-passed-the-first-us-state-selfdriving-test.
Haxeltine, A., Whitmarsh, L., Bergman, N., Rotmans, J., Schilperoord, M. and Kohler, J. (2008) ‘A Conceptual Framework for transition modelling.’ *International Journal of Innovation and Sustainable Development*, 3(1/2) p. 93.
Heaphy, E. (2020) *UK car sales hit six-year low amid Brexit and diesel slump*. [Online] [Accessed on 16th June 2022] https://uk.finance.yahoo.com/news/uk-car-sales-hit-six-year-low-thanks-to-brexit-and-diesel-slump-vehicle-emissions-091026331.html?guccounter=1.
Heath, J. (2020) ‘Methodological Individualism.’ *In* Zalta, E. N. (ed.) *The {Stanford} Encyclopedia of Philosophy*. {S}ummer 2, Metaphysics Research Lab, Stanford University.
Hedström, P. and Bearman, P. (2009) *The Oxford Handbook of Analytical Sociology*. Bearman, P. and Hedström, P. (eds) *The Oxford Handbook of Analytical Sociology*. Oxford University Press.
Hedström, P. and Swedberg, R. (1996) ‘Social Mechanisms.’ *Acta Sociologica*, 39(3) pp. 281–308.
Heineke, K., Möller, T., Padhi, A. and Tschiesner, A. (2017) ‘THE AUTOMOTIVE REVOLUTION IS SPEEDING UP: A perspective on the emerging personal-mobility landscape,’ September.
Hickman, R., Hall, P. and Banister, D. (2013) ‘Planning more for sustainable mobility.’ *Journal of Transport Geography*. Elsevier Ltd, 33, December, pp. 210–219.
Hilgarter, K. and Granig, P. (2020) ‘Public perception of autonomous vehicles: A qualitative study based on interviews after riding an autonomous shuttle.’ *Transportation Research Part F: Traffic Psychology and Behaviour*, 72, July, pp. 226–243.

HM Government (2017) *Industrial Strategy*.

HM Government (2020) *The Ten Point Plan for a Green Industrial Revolution*.

HM Government (2021) *Industrial Decarbonisation Strategy*. *HM Government*.

HM Treasury (2013) *National Infrastructure Plan 2013*.

HM Treasury (2015) *Fixing the foundations*.

HM Treasury and BEIS (2011) *The Plan for Growth*.

Hohenberger, C., Spörrle, M. and Welpe, I. M. (2017) 'Not fearless, but self-enhanced: The effects of anxiety on the willingness to use autonomous cars depend on individual levels of self-enhancement.' *Technological Forecasting and Social Change*. Elsevier Inc., 116, March, pp. 40–52.

Holland-Letz, D., Kloss, B., Kässer, M. and Müller, T. (2019) *Start me up : Where mobility investments are going*.

Holland, J. H. (John H. (1998) 'Emergence : from chaos to order.' Addison-Wesley p. 258.

Holling, C. S. (1973) 'Resilience and Stability of Ecological Systems.' *Annual Review of Ecology and Systematics*. Annual Reviews 4139 El Camino Way, P.O. Box 10139, Palo Alto, CA 94303-0139, USA , 4(1) pp. 1–23.

Holstein, T., Dodig-Crnkovic, G. and Pelliccione, P. (2018) 'Ethical and Social Aspects of Self-Driving Cars.'

Holtz, G. (2011) 'Modelling transitions: An appraisal of experiences and suggestions for research.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 1(2) pp. 167–186.

Holtz, G., Alkemade, F., De Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J. and Ruutu, S. (2015) 'Prospects of modelling societal transitions: Position paper of an emerging community.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 17 pp. 41–58.

House of Commons Transport Committee (2019) 'Active travel: increasing levels of walking and cycling in England,' (July).

Hsieh, H. F. and Shannon, S. E. (2005) 'Three approaches to qualitative content analysis.' *Qualitative Health Research*, 15(9) pp. 1277–1288.

Hughes, T. P. (1987) 'The evolution of large technological systems.' *In* Wiebe E. Bijker; Thomas Parke Hughes; Trevor Pinch (ed.) *The social construction of* *technological systems. New directions in the sociology and history of technology*. Cambridge, MA: MIT Press, pp. 51–82.

Imai, K., Keele, L., Tingley, D. and Yamamoto, T. (2011) ‘Unpacking the Black Box of Causality: Learning about Causal Mechanisms from Experimental and Observational Studies.’ *American Political Science Review*. Cambridge University Press, 105(4) pp. 765–789.

Innovate UK and UK Research and Innovation (2020) *Innovate UK funded projects since 2004*. [Online] [Accessed on 28th February 2020] https://www.gov.uk/government/publications/innovate-uk-funded-projects.

Jänicke, M. (2000) *Ecological modernization: innovation and diffusion of policy and technology*. Berlin.

Jänicke, M. and Jacob, K. (2004) ‘Lead Markets for Environmental Innovations: A New Role for the Nation State.’ *Global Environmental Politics*. MIT Press, 4(1) pp. 29–46.

Jing, P., Xu, G., Chen, Y., Shi, Y. and Zhan, F. (2020) ‘The Determinants behind the Acceptance of Autonomous Vehicles: A Systematic Review.’ *Sustainability*, 12(5) p. 1719.

Jittrapirom, P., Caiati, V., Feneri, A.-M., Ebrahimigharehbaghi, S., González, M. J. A. and Narayan, J. (2017) ‘D4 Mobility as a Service: A Critical Review of Definitions, Assessments of Schemes, and Key Challenges.’ *Urban Planning*, 2(2) pp. 13–25.

Johnson, C. (2017) *Readiness of the road network for connected and autonomous vehicles*.

Johnstone, P. and Newell, P. (2018) ‘Sustainability transitions and the state.’ *Environmental Innovation and Societal Transitions*. Elsevier, 27(February) pp. 72–82.

Jolly, J. (2020) *Car industry lobbied UK government to delay ban on petrol and diesel cars*. [Online] [Accessed on 16th June 2022] https://www.theguardian.com/business/2021/mar/15/car-industry-lobbied-uk-government-delay-ban-petrol-diesel-cars.

Kaidesoja, T. (2013) ‘Overcoming the Biases of Microfoundationalism: Social Mechanisms and Collective Agents.’ *Philosophy of the Social Sciences*, 43(3) pp. 301–322.

Kanger, L., Geels, F. W., Sovacool, B. and Schot, J. (2019) ‘Technological diffusion as a process of societal embedding: Lessons from historical automobile transitions for future electric mobility.’ *Transportation Research Part D: Transport and Environment*. Elsevier, 71(December 2018) pp. 47–66.
Kantar (2020) *Transport and Technology: Public Attitudes Tracker - Wave 5 summary report*.
Kantar Public (2018) *Department for Transport Future Roads : Public Dialogue Final report*.
Kantar Public (2019) *Transport and technology: public attitudes tracker wave 3 summary report*.
Kennedy, B. L. and Thornberg, R. (2018) ‘Deduction, Induction, and Abduction.’ *The SAGE Handbook of Qualitative Data Collection*. SAGE Publications Ltd, January, pp. 49–64.
Kern, F. (2012) ‘Using the multi-level perspective on socio-technical transitions to assess innovation policy.’ *Technological Forecasting and Social Change*. Elsevier Inc., 79(2) pp. 298–310.
Kern, F. and Markard, J. (2016) ‘Analysing Energy Transitions: Combining Insights from Transition Studies and International Political Economy.’ *The Palgrave Handbook of the International Political Economy of Energy*. Palgrave Macmillan, London pp. 291–318.
Kern, F. and Smith, A. (2008) ‘Restructuring energy systems for sustainability? Energy transition policy in the Netherlands.’ *Energy Policy*, 36(11) pp. 4093–4103.
Kincaid, H. (ed.) (2012) *The Oxford handbook of philosophy of social science*. Oxford University Press.
Kiser, E. and Hechter, M. (2015) ‘The Role of General Theory in Comparative-Historical Sociology.’ *https://doi.org/10.1086/229738*. University of Chicago Press , 97(1) pp. 1–30.
Klein, H. K. and Kleinman, D. L. (2002) ‘The social construction of technology: Structural considerations.’ *Science Technology and Human Values*, 27(1) pp. 28–52.
Klein, L. (2014) ‘What do we actually mean by “sociotechnical”? On values, boundaries and the problems of language.’ *Applied Ergonomics*. Elsevier, 45(2 Part A) pp. 137–142.

Klitkou, A., Bolwig, S., Hansen, T. and Wessberg, N. (2015) 'The role of lock-in mechanisms in transition processes: The case of energy for road transport.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 16, September, pp. 22–37.

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D. and Wells, P. (2019) 'An agenda for sustainability transitions research: State of the art and future directions.' *Environmental Innovation and Societal Transitions*. Elsevier, 31(January) pp. 1–32.

Köhler, J., Turnheim, B. and Hodson, M. (2018) 'Low carbon transitions pathways in mobility: Applying the MLP in a combined case study and simulation bridging analysis of passenger transport in the Netherlands.'

Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N. and Haxeltine, A. (2009) 'A transitions model for sustainable mobility.' *Ecological Economics*. Elsevier B.V., 68(12) pp. 2985–2995.

KPMG (2015) *Connected and Autonomous Vehicles – The UK Economic Opportunity. KPMG International*.

Kuzemko, C., Lockwood, M., Mitchell, C. and Hoggett, R. (2016) 'Governing for sustainable energy system change: Politics, contexts and contingency.' *Energy Research and Social Science*. Elsevier Ltd, 12 pp. 96–105.

Lachmann, R. (2013) *What is Historical Sociology?* Wiley (What is Sociology?).

Laszlo, A. and Krippner, S. (n.d.) 'Systems Theories: Their Origins, Foundations, and Development ~~~~~~.'

Law Commission (2020) *Automated Vehicles*. [Online] [Accessed on 28th February 2020] https://www.lawcom.gov.uk/project/automated-vehicles/.

Law Commission (2022) *Automated Vehicles*. [Online] [Accessed on 15th June 2022] https://www.lawcom.gov.uk/project/automated-vehicles/.

Lawson, G. (2006) 'The promise of historical sociology in international relations.' *International Studies Review*, 8(3) pp. 397–423.

Legacy, C., Ashmore, D., Scheurer, J., Stone, J. and Curtis, C. (2018) 'Planning the

driverless city.’ *Transport Reviews*. Taylor & Francis, 0(0) pp. 1–19.
Lewis-Beck, M., Bryman, A. and Futing Liao, T. (2012) ‘The SAGE Encyclopedia of Social Science Research Methods.’ *The SAGE Encyclopedia of Social Science Research Methods* pp. 187–189.
Lim, H. S. M. and Taeihagh, A. (2018) ‘Autonomous vehicles for smart and sustainable cities: An in-depth exploration of privacy and cybersecurity implications.’ *Energies*, 11(5).
Lindgren, T., Pink, S. and Fors, V. (2021) ‘Fore-sighting autonomous driving - An Ethnographic approach.’ *Technological Forecasting and Social Change*. Elsevier Inc., 173, December.
Litman, T. (2014) ‘Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.’ *Transportation Research Board Annual Meeting*, (2014) pp. 36–42.
Little, D. (2012) ‘Analytical Sociology and the Rest of Sociology.’ *Revue européenne des sciences sociales*, (50–2) pp. 7–34.
Lloyd, C. (1991) ‘The Methodologies of Social History: A Critical Survey and Defense of Structurism.’ *History and Theory*, 30(2) p. 180.
Loorbach, D., Avelino, F., Haxeltine, A., Wittmayer, J. M., O’Riordan, T., Weaver, P. and Kemp, R. (2015) ‘The economic crisis as a game changer? Exploring the role of social construction in sustainability transitions.’ *Ecology and Society*, 21(4).
Loorbach, D., Frantzeskaki, N. and Avelino, F. (2017) ‘Sustainability Transitions Research: Transforming Science and Practice for Societal Change.’ *Annual Review of Environment and Resources*, 42(1) pp. 599–626.
Lyons, G. (2016) ‘Getting smart about urban mobility – Aligning the paradigms of smart and sustainable.’ *Transportation Research Part A: Policy and Practice*. Elsevier Ltd, December, pp. 1–11.
Lyons, G. (2022) ‘The Driverless Cars Emulsion: Using participatory foresight and constructive conflict to address transport’s wicked problems.’ *Futures*. Pergamon, 136, February, p. 102889.
Lyons, G. and Davidson, C. (2016) ‘Guidance for transport planning and policymaking in the face of an uncertain future.’ *Transportation Research Part A: Policy and Practice*. Pergamon, 88, June, pp. 104–116.

Lyons, G., Jain, J., Mitchell, V. and May, A. (2012) ‘The emergent role of user innovation in reshaping traveler information services.’ *In* Geels, F., Kemp, R., Dudley, G. and Lyons, G. (ed.) *Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport*, pp. 268–285.
Lyons, G. and Urry, J. (2005) ‘Travel time use in the information age.’ *Transportation Research Part A: Policy and Practice*, 39(2–3) pp. 257–276.
Machamer, P., Darden, L. and Craver, C. F. (2000) ‘Thinking about mechanisms.’ *Philosophy of Science*, 67(1) pp. 1–25.
Mahoney, J. (2000) ‘ath Dependence in Historical Sociology.’ *Theory and Society*, 29(4) pp. 507–548.
Mahoney, J. (2004) ‘Revisiting general theory in historical sociology.’ *Social Forces*, 83(2) pp. 459–489.
Mahoney, J. (2015) ‘Process Tracing and Historical Explanation.’ *Security Studies*, 24(2) pp. 200–218.
Markard, J. (2018) ‘The next phase of the energy transition and its implications for research and policy.’ *Nature Energy*. Springer US, 3(8) pp. 628–633.
Markard, J., Raven, R. and Truffer, B. (2012) ‘Sustainability transitions: An emerging field of research and its prospects.’ *Research Policy*, 41(6) pp. 955–967.
Markard, J. and Truffer, B. (2008) ‘Technological innovation systems and the multi-level perspective: Towards an integrated framework.’ *Research Policy*, 37(4) pp. 596–615.
Marsden, G. and Lyons, G. (2019) ‘Opening out and closing down: the treatment of uncertainty in transport planning’s forecasting paradigm.’ *Transportation*. Springer US, (0123456789).
Marsden, G. and Rye, T. (2010) ‘The governance of transport and climate change.’ *Journal of Transport Geography*. Elsevier Ltd, 18(6) pp. 669–678.
Martin, R. (2021) ‘AV futures or futures with AVs? Bridging sociotechnical imaginaries and a multi-level perspective of autonomous vehicle visualisations in praxis.’ *Humanities and Social Sciences Communications*. Springer US, 8(1) pp. 1–15.
Martinez, O. P. L. and Furtado, F. (2017) *Shared Mobility Simulations for Auckland*. *OECD Case-Specific Policy Analysis*.
Maxwell, J. (2011) ‘What Is Realism, and Why Should Qualitative Researchers Care?’

In A Realist Approach for Qualitative Research. SAGE Publications, Inc.
Maxwell, J. A. (2012) *A Realist Approach for Qualitative Research*. SAGE Publications.
May, A. D. (2015) 'Encouraging good practice in the development of Sustainable Urban Mobility Plans.' *Case Studies on Transport Policy*. World Conference on Transport Research Society, 3(1) pp. 3–11.
Mayntz, R. (2004) 'Mechanisms in the analysis of social macro-phenomena.' *Philosophy of the Social Sciences*, 34(2) pp. 237–259.
Mazur, C., Contestabile, M., Offer, G. J. and Brandon, N. P. (2015) 'Assessing and comparing German and UK transition policies for electric mobility.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 14 pp. 84–100.
McDowall, W. (2014) 'Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling.' *Futures*. Elsevier Ltd, 63 pp. 1–14.
McDowall, W. and Geels, F. W. (2017) 'Ten challenges for computer models in transitions research: Commentary on Holtz et al.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 22 pp. 41–49.
McKinsey&Company (2019) *Race 2050 – a vision for the european automotive industry*.
Meadowcroft, J. (2009) 'What about the politics? Sustainable development, transition management, and long term energy transitions.' *Policy Sciences 2009 42:4*. Springer, 42(4) pp. 323–340.
Meelen, T., Frenken, K. and Hobrink, S. (2019) 'Weak spots for car-sharing in The Netherlands? The geography of socio-technical regimes and the adoption of niche innovations.' *Energy Research and Social Science*. Elsevier, 52(January) pp. 132–143.
Melia, S. and Melia, S. (2020) 'Learning critical realist research by example : political decision-making in transport making in transport.' *Journal of Critical Realism*. Taylor & Francis, 0(0) pp. 1–19.
Merton, R. K. (1948) 'The Self-Fulfilling Prophecy.' *The Antioch Review*, 8(2) p. 193.
Merton, R. K. (1968) *Social theory and social structure*. Simon and Schuster.
Merton, R. K. (2007) 'On Sociological Theories of the Middle Range [1949].' *Classical Sociological Theory* pp. 448–459.

Meyer, J. W. and Rowan, B. (1977) 'Institutionalized Organizations: Formal Structure as Myth and Ceremony.' *American Journal of Sociology*. University of Chicago Press, 83(2) pp. 340–363.

Milakis, D. (2018) 'Long-term implications of automated vehicles: an introduction.' *https://doi.org/10.1080/01441647.2019.1545286*. Routledge, 39(1) pp. 1–8.

Milakis, D., Van Arem, B. and Van Wee, B. (2017) 'Policy and society related implications of automated driving: A review of literature and directions for future research.' *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, 21(4) pp. 324–348.

Milakis, D., Snelder, M., Van Arem, B., Van Wee, B. and De Almeida Correia, G. H. (2017) 'Development and transport implications of automated vehicles in the Netherlands: Scenarios for 2030 and 2050.' *European Journal of Transport and Infrastructure Research*, 17(1) pp. 63–85.

Mingers, J. and Standing, C. (2017) 'Why things happen – Developing the critical realist view of causal mechanisms.' *Information and Organization*. Elsevier, 27(3) pp. 171–189.

Moallemi, E. A. and Köhler, J. (2019) 'Coping with uncertainties of sustainability transitions using exploratory modelling: The case of the MATISSE model and the UK's mobility sector.' *Environmental Innovation and Societal Transitions*. Elsevier, 33(March) pp. 61–83.

Moradi, A. and Vagnoni, E. (2018) 'A multi-level perspective analysis of urban mobility system dynamics: What are the future transition pathways?' *Technological Forecasting and Social Change*. Elsevier, 126(December 2016) pp. 231–243.

Myers, M. D. (2019) *Qualitative Research in Business and Management*. SAGE Publications.

Næss, P. and Strand, A. (2012) 'What Kinds of Traffic Forecasts are Possible?' *Journal of Critical Realism*, 11(3) pp. 277–295.

Nelson, R. R. and Winter, S. G. (1982) *An evolutionary theory of economic change*. Belknap Press of Harvard University Press.

Nijramp, P. (1994) 'Roads Toward Environmentally Sustainable Transport.' *Pergamon Transpn. Res.-A*, 28(4) pp. 261–271.

Noel, L., Sovacool, B. K., Kester, J. and Zarazua de Rubens, G. (2019) 'Conspicuous diffusion: Theorizing how status drives innovation in electric mobility.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 31, June, pp. 154–169.

Nott, G. (2021) *Wilko invests in autonomous delivery vehicle company StreetDrone*. [Online] [Accessed on 20th June 2022] https://www.thegrocer.co.uk/technology-and-supply-chain/wilko-invests-in-autonomous-delivery-vehicle-company-streetdrone/659805.article.

Nunen, J. Van, Huijbregts, P. and Rietveld, P. (2011) *Transitions Towards Sustainable Mobility*. van Nunen, J. A. E. E., Huijbregts, P., and Rietveld, P. (eds). Berlin, Heidelberg: Springer Berlin Heidelberg.

Nykvist, B. and Nilsson, M. (2015) 'The EV paradox - A multilevel study of why Stockholm is not a leader in electric vehicles.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 14 pp. 26–44.

Nykvist, B. and Whitmarsh, L. (2008) 'A multi-level analysis of sustainable mobility transitions: Niche development in the UK and Sweden.' *Technological Forecasting and Social Change*. North-Holland, 75(9) pp. 1373–1387.

OECD (2015) *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*. *Corporate Partnership Board Report*.

ONS (2021) *Three-quarters of adults in Great Britain worry about climate change*. [Online] [Accessed on 25th June 2022] https://www.ons.gov.uk/peoplepopulationandcommunity/wellbeing/articles/threequartersofadultsingreatbritainworryaboutclimatechange/2021-11-05.

Orsato, R. J., Dijk, M., Kemp, R. and Yarime, M. (2012) 'The electrification of automobility: The bumpy Ride of electric vehicles towards regime transition.' *In* Geels, F and Kemp, R and Dudley, G and Lyons, G. (ed.) *Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport*. Routledge, pp. 205–228.

Owens, J. (2011) *An Introduction to Critical Realism as a Meta-Theoretical Research Perspective*. Centre for Public Policy Research, King's College London (Centre for Public Policy Research Working Paper Series).

Papachristos, G. (2018) 'A mechanism based transition research methodology: Bridging analytical approaches.' *Futures*. Elsevier Ltd, 98(February) pp. 57–71.

Papachristos, G. and Adamides, E. (2016) 'A retroductive systems-based

methodology for socio-technical transitions research.’ *Technological Forecasting and Social Change*. North-Holland, 108, July, pp. 1–14.
Papachristos, G., Sofianos, A. and Adamides, E. (2013) ‘System interactions in socio-technical transitions: Extending the multi-level perspective.’ *Environmental Innovation and Societal Transitions*. Elsevier B.V., 7, June, pp. 53–69.
parliament.uk (2020) *House of Commons - Register Of All-Party Parliamentary Groups as at 20 May 2020: Motor*. [Online] [Accessed on 16th June 2022] https://publications.parliament.uk/pa/cm/cmallparty/200520/motor.htm.
PEDERSEN, J. S. and DOBBIN, F. (1997) ‘The Social Invention of Collective Actors.’ *American Behavioral Scientist*, 40(4) pp. 431–443.
Pel, B. and Boons, F. A. (2010) ‘Transition through subsystem innovation? The case of traffic management.’ *Technological Forecasting and Social Change*. Elsevier Inc., 77(8) pp. 1249–1259.
Penmetsa, P., Adanu, E. K., Wood, D., Wang, T. and Jones, S. L. (2019) ‘Perceptions and expectations of autonomous vehicles – A snapshot of vulnerable road user opinion.’ *Technological Forecasting and Social Change*. North-Holland, 143, June, pp. 9–13.
Penna, C. C. R. and Geels, F. W. (2012) ‘Multi-dimensional struggles in the greening of industry: A dialectic issue lifecycle model and case study.’ *Technological Forecasting and Social Change*. Elsevier Inc., 79(6) pp. 999–1020.
Pinch, T. J. and Bijker, W. E. (1984) ‘The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other.’ *Social Studies of Science*, 14(3) pp. 399–441.
Pooley, C., Turnbull, J. and Adams, M. (2006) ‘The Impact of New Transport Technologies on Intraurban Mobility: A View from the Past.’ *Environment and Planning A*, 38(2) pp. 253–267.
Porter, L. (2018) ‘The autonomous vehicle revolution: Implications for planning.’ *Planning Theory and Practice*. Routledge, 19(5) pp. 753–778.
Porter, L., Stone, J., Legacy, C., Curtis, C., Harris, J., Fishman, E., Kent, J., Marsden, G., Reardon, L. and Stilgoe, J. (2018) ‘The Autonomous Vehicle Revolution: Implications for Planning/The Driverless City?/Autonomous Vehicles – A Planner’s Response/Autonomous Vehicles: Opportunities, Challenges and the Need for

Government Action/Three Signs Autonomous Vehicles Will Not Lead to.' *Planning Theory & Practice*. Routledge, 19(5) pp. 753–778.

Powell, R. (1991) 'Absolute and Relative Gains in International Relations Theory.' *American Political Science Review*. Cambridge University Press, 85(4) pp. 1303–1320.

RAC (2020) *Dependency on the car is increasing*. [Online] [Accessed on 24th June 2022] https://www.rac.co.uk/drive/features/rising-car-dependency-2019/.

Raphael, S. and Rice, L. (2002) 'Car ownership, employment, and earnings.' *Journal of Urban Economics*, 52(1) pp. 109–130.

Raven, R., Van Den Bosch, S. and Weterings, R. (2010) 'Transitions and strategic niche management: Towards a competence kit for practitioners.' *International Journal of Technology Management*, 51(1) pp. 57–74.

Reed, T. (2019) *Global traffic scorecard*.

Richardson, B. C. (2005) 'Sustainable transport: Analysis frameworks.' *Journal of Transport Geography*, 13(1 SPEC. ISS.) pp. 29–39.

Rip, A. and Kemp, R. (1998) 'Technological change.' *Human Choice and Climate Change*, 2(Vol. 2: Resources and Technology) pp. 327–399.

Rittel, H. W. J. and Webber, M. M. (1973) 'Dilemmas in a general theory of planning.' *Policy Sciences 1973 4:2*. Springer, 4(2) pp. 155–169.

Roberts, C. and Geels, F. W. (2018) 'Conditions for politically accelerated transitions: Historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture.' *Technological Forecasting and Social Change*. Elsevier, 140(0) pp. 221–240.

Roberts, J. C. D. (2015) *The evolution of discursive story-lines during socio-technical transitions : an analytical model applied to British and American road and rail transport during the twentieth century*. University of Manchester.

Rotmans, J., Kemp, R. and van Asselt, M. (2001) 'More evolution than revolution: transition management in public policy.' Kleinaltenkamp, M. (ed.) *Foresight*, 3(1) pp. 15–31.

Ruef, A. and Markard, J. (2010) 'What happens after a hype? How changing expectations affected innovation activities in the case of stationary fuel cells.' *http://dx.doi.org/10.1080/09537321003647354*. Routledge , 22(3) pp. 317–338.

Saldaña, J. (2014) 'Coding and Analysis Strategies.' *The Oxford Handbook of Qualitative Research*. Oxford University Press, July, pp. 580–598.

Sartori, G. (1970) 'Concept Misformation in Comparative Politics.' *American Political Science Review*, 64(4) pp. 1033–1053.

Sayer, A. (1992) *Method in Social Science*. london: Routledge.

Schmitt, J. (2020) 'The Causal Mechanism Claim in Evaluation: Does the Prophecy Fulfill?' *New Directions for Evaluation*, 2020(167) pp. 11–26.

Schot, J., Hoogma, R. and Elzen, B. (1994) 'Strategies for shifting technological systems. The case of the automobile system.' *Futures*, 26(10) pp. 1060–1076.

Schrag, Z. M. (2000) '"The Bus is Young and Honest". Transportation Politics Technical Choice and the Motorization of Manhattan Surface Transit, 1919-1936.' *Technology and Culture*, 41(1) pp. 51–79.

Schumpeter, J. A. (1934) *The theory of economic development; an inquiry into profits, capital, credit, interest, and the business cycle*. Harvard University Press.

Sengupta, U., Doll, C. N. H., Gasparatos, A., Iossifova, D., Angeloudis, P., Baptista, M. da S., Cheng, S., Graham, D., Hyde, R., Kraenkel, R., Luo, J. and Oren, N. (2017) 'Sustainable Smart Cities: Applying Complexity Science to Achieve Urban Sustainability,' (12).

Sengupta, U., Rauws, W. S. and de Roo, G. (2016) 'Planning and complexity: Engaging with temporal dynamics, uncertainty and complex adaptive systems:' *https://doi.org/10.1177/0265813516675872*. SAGE PublicationsSage UK: London, England, 43(6) pp. 970–974.

Shackley, S. and Green, K. (2007) 'A conceptual framework for exploring transitions to decarbonised energy systems in the United Kingdom.' *Energy*, 32(3) pp. 221–236.

Shaw, J. and Docherty, I. (2014) 'The transport debate.' *The Transport Debate*. Policy Press, January, pp. 1–236.

Sheller, M. and Urry, J. (2000) 'The city and the car.' *International Journal of Urban and Regional Research*, 24(4) pp. 737–757.

Sheller, M. and Urry, J. (2006) 'The New Mobilities Paradigm.' *Environment and Planning A*, 38(2) pp. 207–226.

Sheller, M. and Urry, J. (2016) 'Mobilizing the new mobilities paradigm.' *Applied Mobilities*. Routledge, 1(1) pp. 10–25.

Shove, E., Pantzar, M. and Watson, M. (2012) *The dynamics of social practice: Everyday life and how it changes*. Sage.

Shove, E. and Walker, G. (2010) 'Governing transitions in the sustainability of everyday life.' *Research Policy*. Elsevier B.V., 39(4) pp. 471–476.

Smith, A. and Anderson, M. (2017) 'Automation in everyday life.' *Pew Research Center*.

Smith, A. and Raven, R. (2012) 'What is protective space? Reconsidering niches in transitions to sustainability.' *Research Policy*, 41(6) pp. 1025–1036.

Smith, A., Stirling, A. and Berkhout, F. (2005) 'The governance of sustainable socio-technical transitions.' *Research Policy*, 34(10) pp. 1491–1510.

Smith, A., Voß, J. P. and Grin, J. (2010) 'Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges.' *Research Policy*, 39(4) pp. 435–448.

SMMT (2015) *Connected and Autonomous Vehicles: Revolutionising Mobility in Society*.

SMMT (2017) *Connected and Autonomous Vehicles: Position Paper*.

SMMT (2019a) *Average Vehicle Age*. [Online] [Accessed on 28th February 2020] https://www.smmt.co.uk/industry-topics/sustainability/average-vehicle-age/.

SMMT (2019b) *Connected and Autonomous Vehicles: Winning the global race to market*.

SMMT (2019c) *SMMT Motor Industry Facts 2019*.

SMMT (n.d.) *About SMMT*. [Online] [Accessed on 16th June 2022a] https://www.smmt.co.uk/about/.

SMMT (n.d.) *SMMT History*. [Online] [Accessed on 16th June 2022b] https://www.smmt.co.uk/about/history/.

Sorrell, S. (2018) 'Explaining sociotechnical transitions: A critical realist perspective.' *Research Policy*. Elsevier, 47(7) pp. 1267–1282.

Sousa, M. L. and Marques, R. (2013) 'Political Transitions, Value Change and Motorisation in 1970s Portugal.' *The Journal of Transport History*, 34(1) pp. 1–21.

Sovacool, B. K. and Axsen, J. (2018) 'Functional, symbolic and societal frames for automobility: Implications for sustainability transitions.' *Transportation Research Part A: Policy and Practice*. Elsevier Ltd, 118, December, pp. 730–746.

Sparrow, R. and Howard, M. (2017) ‘When human beings are like drunk robots: Driverless vehicles, ethics, and the future of transport.’ *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, 80 pp. 206–215.

Sprei, F. (2018) ‘Disrupting mobility.’ *Energy Research and Social Science*. Elsevier, 37(October 2017) pp. 238–242.

Squazzoni, F. (2008) ‘A (computational) social science perspective on societal transitions.’ *Computational and Mathematical Organization Theory 2008 14:4*. Springer, 14(4) pp. 266–282.

Steinmetz, G. (2004) ‘Odious comparisons: Incommensurability, the case study, and “small N’s” in sociology.’ *Sociological Theory*, 22(3) pp. 371–400.

Stilgoe, J. (2018) ‘Machine learning, social learning and the governance of self-driving cars.’ *Social Studies of Science*, 48(1) pp. 25–56.

Stilgoe, J. (2019) ‘Self-driving cars will take a while to get right.’ *Nature Machine Intelligence*. Springer US, 1(5) pp. 202–203.

Stinchcombe, A. L. (1998) ‘Monopolistic competition as a mechanism: Corporations, universities, and nation-states in competitive fields.’ *In* Hedström, P. and Swedberg, R. (eds) *Social Mechanisms: An Analytical Approach to Social Theory*. Cambridge University Press (Studies in Rationality and Social Change), pp. 267–305.

Stolz, J. (2016) ‘Opening the black box. How the study of social mechanisms can benefit from the use of explanatory mixed methods*.’ *Analyse und Kritik*. Lucius und Lucius Verlagsgesellschaft mbH, 38(1) pp. 257–285.

Stone, J. (2022) *Government says it could use Brexit ‘freedom’ to ditch new EU car safety regulations*. [Online] [Accessed on 24th June 2022] https://www.newsbreak.com/news/2508033720058/government-says-it-could-use-brexit-freedom-to-ditch-new-eu-car-safety-regulations.

Svensson, O. and Nikoleris, A. (2018) ‘Structure reconsidered: Towards new foundations of explanatory transitions theory.’ *Research Policy*. Elsevier, 47(2) pp. 462–473.

Taeihagh, A. and Lim, H. S. M. (2018) ‘Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks.’ *Transport Reviews*. Taylor & Francis, 0(0) pp. 1–26.

Tennant, C., Howard, S., Franks, B. and Bauer, M. W. (2016) *Autonomous Vehicles -*

Negotiating a Place on the Road A study on how drivers feel about Interacting with Autonomous Vehicles on the road.

THE 17 GOALS | Sustainable Development (n.d.). [Online] [Accessed on 2nd October 2021] https://sdgs.un.org/goals.

The House of Lords Science and Technology Committee (2017) *Connected and Autonomous Vehicles: The future? - Science and Technology Committee*. *2nd Report of Session 2016–17*.

The World Population Prospects: 2015 Revision (2015). New York, NY.

Tilly, C. (2003) 'Mechanisms in Political Processes.' *https://doi.org/10.1146/annurev.polisci.4.1.21*. Annual Reviews 4139 El Camino Way, P.O. Box 10139, Palo Alto, CA 94303-0139, USA , 4, November, pp. 21–41.

Tilly, C. (2006) 'Historical Analysis of Political Processes.' *Handbook of Sociological Theory* pp. 567–588.

Transport Systems Catapult (2018) *Autonomous Vehicles : What can Social Science offer ?*

TRICS (2021) *GUIDANCE NOTE ON THE PRACTICAL IMPLEMENTATION OF THE DECIDE & PROVIDE APPROACH*.

Turienzo, J., Cabanelas, P. and Lampón, J. F. (2022) 'The Mobility Industry Trends Through the Lens of the Social Analysis: A Multi-Level Perspective Approach.' *SAGE Open*. SAGE Publications Inc., 12(1).

Turnheim, B. and Geels, F. W. (2019) 'Incumbent actors, guided search paths, and landmark projects in infra-system transitions: Re-thinking Strategic Niche Management with a case study of French tramway diffusion (1971–2016).' *Research Policy*. Elsevier, 48(6) pp. 1412–1428.

ukri.org (n.d.) *Industrial Strategy Challenge Fund – UKRI*. [Online] [Accessed on 15th June 2022] https://www.ukri.org/what-we-offer/our-main-funds/industrial-strategy-challenge-fund/.

UKRI (2021) *Uk Transport Vision 2050: investing in the future of mobility*.

UKRI (2022) *Innovate UK funded projects since 2004*.

UN (n.d.) *World Urbanization Prospects - Population Division - United Nations*. [Online] [Accessed on 24th June 2022] https://population.un.org/wup/.

Urry, J. (2004a) 'The "System" of Automobility.' *Theory, Culture & Society*, 21(4–5)

pp. 25–39.
Urry, J. (2004b) ‘The “System” of Automobility.’ *Theory, Culture & Society*, 21(5) pp. 25–39.
Urry, J. (2005) ‘The Complexity Turn.’ *Theory, Culture & Society*, 22(5) pp. 1–14.
Urry, J. (2008) ‘Governance, flows, and the end of the car system?’ *Global Environmental Change*, 18(3) pp. 343–349.
Vasileiadou, E. and Safarzyńska, K. (2010) ‘Transitions: Taking complexity seriously.’ *Futures*, 42(10) pp. 1176–1186.
Verbong, G. and Geels, F. (2007a) ‘The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004).’ *Energy Policy*, 35(2) pp. 1025–1037.
Verbong, G. and Geels, F. (2007b) ‘The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004).’ *Energy Policy*. Elsevier, 35(2) pp. 1025–1037.
Verbong, G. P. J. and Geels, F. W. (2010) ‘Exploring sustainability transitions in the electricity sector with socio-technical pathways.’ *Technological Forecasting and Social Change*. Elsevier Inc., 77(8) pp. 1214–1221.
Vincent, S. and O’Mahoney, J. (2018) ‘Critical Realism and Qualitative Research: An Introductory Overview.’ *In* Cassell, C., Cunliffe, A., and Grady, G. (eds) *The SAGE Handbook of Qualitative Business and Management Research Methods*. London: SAGE, pp. 201–216.
Voß, J. P., Smith, A. and Grin, J. (2009) ‘Designing long-term policy: Rethinking transition management.’ *Policy Sciences*. Springer, 42(4) pp. 275–302.
Wadud, Z., MacKenzie, D. and Leiby, P. (2016) ‘Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles.’ *Transportation Research Part A: Policy and Practice*. Elsevier Ltd, 86 pp. 1–18.
Wallerstein, I. (1996) *Open the Social Sciences: Report of the Gulbenkian Commission on the Restructuring of the Social Sciences*. *Mestizo spaces = Espaces métisses*. Stanford University Press (Mestizo Spaces/Espaces Metisses Series).
Walrave, B. and Raven, R. (2016) ‘Modelling the dynamics of technological innovation systems.’ *Research Policy*. Elsevier B.V., 45(9) pp. 1833–1844.
Waugh, R. (2013) *How the first ‘driverless car’ was invented in Britain in 1960*.

[Online] [Accessed on 13th June 2022] https://uk.news.yahoo.com/how-the-first--driverless-car--was-invented-in-britain-in-1960-093127757.html?guccounter=1.
Weber, M., Roth, G. and Wittich, C. (1978) *Economy and Society*. University of California Press (Economy and Society: An Outline of Interpretive Sociology).
Whitmarsh, L. (2012) 'How useful is the Multi-Level Perspective for transport and sustainability research?' *Journal of Transport Geography*. Elsevier Ltd, 24 pp. 483–487.
Wittmayer, J. M., Avelino, F., van Steenbergen, F. and Loorbach, D. (2017) 'Actor roles in transition: Insights from sociological perspectives.' *Environmental Innovation and Societal Transitions*. Elsevier B.V., 24 pp. 45–56.
Wynn and Williams (2012) 'Principles for Conducting Critical Realist Case Study Research in Information Systems.' *MIS Quarterly*, 36(3) p. 787.
Yin, R. (2009) *Case study research: Design and methods*.
Zachariadis, M., Scott, S. and Barrett, M. (2013) 'Methodological Implications of Critical Realism for Mixed-Methods Research Quarterly Methodological Implications of Critical Realism for Mixed-Methods Research1.' *Source: MIS Quarterly*, 37(3) pp. 855–879.
Zenzic (2019) *UK Connected and Automated Mobility Roadmap to 2030*.

Appendix A

List of 61 identified publications with 49 publications used for data analysis highlighted in yellow.

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Connected and autonomous road vehicles	2017	june		House of Commons Library (James Clarke Louise Butcher)	House of Commons Library	briefing paper	yes
The Pathway to Driverless Cars Summary report and action plan	2015	february		DfT	DfT	government report	yes
Future of Mobility: Urban Strategy Moving Britain Ahead	2019	march		DfT + Industrial Strategy	DfT	gov str	no
Industrial Strategy Building a Britain fit for the future	2017	november		HM Government	HM Government	white paper	no
UK Connected & Autonomous Vehicle Research & Development Projects 2018	2018	september		CCAV	CCAV	government report	yes
The Key Principles of Cyber Security for	2017	august		DfT, CCAV, Centre for the Protection of National Infrastructure	HM Government	government report	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Connected and Automated Vehicles							
Summary of Responses to Call for Evidence Future of Mobility Moving Britain Ahead	2019	january		DfT + Industrial Strategy	DfT	government report	no
Social and behavioural questions associated with automated vehicles Scoping study by UCL Transport Institute Final report	2017	january	DfT	UCL Transport Institute	DfT	report(com by gov)	yes
Social and behavioural questions associated with Automated Vehicles A Literature Review	2017	january	DfT	UCL Transport Institute	DfT	report(com by gov)	yes
UK Testing Ecosystem for Connected and Autonomous Vehicles Government response to the call for evidence	2017	march		CCAV	CCAV	government report	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
CAPTURING VALUE IN THE AUTONOMOUS AND CONNECTED VEHICLES INDUSTRY: AN AMBITIOUS PLAN FOR THE UK	2015	july		Council for Science and Technology		other/unsure	yes
Connected and Autonomous Vehicles: The future?	2017	march			Published by the Authority of the House of Lords	government report	yes
PM response to G-19	2015	august		the Prime Minister		other/unsure	yes
Pathway to driverless cars: Consultation on proposals to support Advanced Driver Assistance Systems and Automated Vehicles Government Response	2017	january		CCAV	CCAV	government report	yes
Pathway to Driverless Cars: Insurance for Automated Vehicles - Impact Assessment	2016	october		CCAV	CCAV	other/unsure	yes
Invitation to Comment: Code of	2019	february		CCAV	CCAV	other/unsure	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Practice: Automated vehicle trialling							
GAD Comment: Self-Driving Cars	2017	september		Government Actuary's Department	Government Actuary's Department	other/unsure	yes
Vehicle Technology and Aviation Bill	2017	february		House of Commons	House of Commons	legal doc	yes
Automated and Electric Vehicles Act 2018	2018	july				legal doc	
Code of Practice: Automated vehicle trialling	2019	february		CCAV	CCAV (DfT)	government report	yes
Transport and Technology: Public Attitudes Tracker Waves 1 and 2 summary report	2018	october		Kantar Public	DfT	report(com by gov)	no
Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow Stage 1: Evidence Review	2016	march	DfT	ATKINS	DfT	report(com by gov)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow Stage 2: Traffic Modelling and Analysis Technical Report	2016	may	DfT	ATKINS	DfT	report(com by gov)	yes
Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow	2016	may	DfT	ATKINS	DfT	report(com by gov)	yes
Department for Transport Future Roads: Public Dialogue Exploring the public's reactions to future road technologies Final report	2018	may	DfT	Kantar Public	DfT	report(com by gov)	yes
Mayor's Transport Strategy	2018	march		Greater London Authority	Greater london Authority	local strategy	no
Future transport How is London responding to	2018	february		London Assembly Transport Commision	London Assembly Transport Commision	local strategy	no

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
technological innovation?							
London Infrastructure Plan 2050: Transport Supporting Paper	2014			Mayor of London	Mayor of London	other/unsure	no
A 2050 VISION FOR LONDON: WHAT ARE THE IMPLICATIONS OF DRIVERLESS TRANSPORT	2014		Clear Channel	Professor David Begg	??	other/unsure	yes
UK Connected and Automated Mobility Roadmap to 2030	2019	september		Zenzec	Zenzec	report (other)	yes
Connected and Autonomous Vehicles: Revolutionising Mobility in Society	2017			Society of Motor Manufacturers and Traders (SMMT) (in association with strategy&and pwc)	SMMT	report (other)	yes
Connected and Autonomous Vehicles - The UK Economic Opportunity	2015	march		KPMG; SMMT	KPMG	report (other)	yes
Social and behavioural questions associated with	2017	january	DfT	UCL Transport Institutr	UCL Transport Institutr	report(com by gov)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
automated vehicles							
Governance of UK Transport Infrastructures	2019	january	Government Office for Science	Professor Greg Marsden, Institute for Transport Studies, University of Leeds Professor Iain Docherty, Adam Smith Business School, University of Glasgow	Foresight, Government Office for Science	report(com by gov)	no
MARKET FORECAST FOR CONNECTED AND AUTONOMOUS VEHICLES	2017	july		Transport Systems Catapult	Transport Systems Catapult	report (other)	yes
Connected and autonomous vehicles A UK standards strategy Summary report	2017	march	DfT??	BSI and the Transport Systems Catapult	BSI and the Transport Systems Catapult	report(com by gov)	yes
THE FUTURE OF AUTONOMOUS VEHICLES An Interim Report based on Multiple Expert Discussions THE EMERGING LANDSCAPE	2019			Future Agenda	Future Agenda	report (other)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
An Initial Perspective							
CONNECTED AND AUTONOMOUS VEHICLES 2019 REPORT / WINNING THE GLOBAL RACE TO MARKET	2019		SMMT	Frost&Sullivan (for SMMT)	SMMT	report (other)	yes
Future Proofing Infrastructure for Connected and Automated Vehicles Technical Report	2017	february	DfT	Transport Systems Catapult	Transport Systems Catapult	report(com by gov)	yes
Taxonomy of Scenarios for Automated Driving Technical Report	2017	april	DfT	Transport Systems Catapult	Transport Systems Catapult	report(com by gov)	yes
Station Innovation 2 Work Package 7: Connected and Automated Vehicle (CAV) Impact	2017	march	DfT	Transport Systems Catapult	Transport Systems Catapult	report(com by gov)	yes
Autonomous Vehicles: What can Social	2018	july		Transport Systems Catapult (in	Transport Systems Catapult	report (other)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Science offer?				partnership with UCL)			
REGULATING AND ACCELERATING DEVELOPMENT OF HIGHLY AUTOMATED AND AUTONOMOUS VEHICLES THROUGH SIMULATION AND MODELLING TECHNICAL REPORT	2018	march	DfT	Transport Systems Catapult	Transport Systems Catapult	report(com by gov)	yes
Specification Information to Inform Approvals for Advanced Vehicle Trials FINAL REPORT	2018	february	DfT	Transport Systems Catapult	Transport Systems Catapult	report(com by gov)	yes
Development of self-driving vehicles in the United Kingdom Where science fiction meets science fact	2017			Deloitte	Deloitte University Press	report (other)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Self-driving cars A case study in making new markets	2012	december		Big Innovation Centre Luis Araujo, Katy Mason and Martin Spring Lancaster University	Big Innovation Centre	report (other)	yes
Autonomous Vehicles - Negotiating a Place on the Road A study on how drivers feel about Interacting with Autonomous Vehicles on the road EXECUTIVE SUMMARY	2016			London School of Economics and Political Science Department of Psychological and Behavioural Science	LSE + Goodyear	report (other)	yes
Whitepaper: Autonomous vehicles – will they be safer and where does this leave the “driver”?	2019	january		drivetech	drivetech	report (other)	yes
Readiness of the road network for connected and autonomous vehicles	2017	april		Dr Charles Johnston CAS, RAC Foundation	RAC Foundation	report (other)	yes
Connected and Autonomous Vehicles: Introducing the Future of Mobility	2016			atkins	atkins	report (other)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Connected Roads, Vehicles and People A Key National Opportunity POSITION STATEMENT	2018	july		Transport Technology Forum	Transport Technology Forum	report (other)	yes
National Infrastructure Assessment	2018	july		National Infrastructure Commission	National Infrastructure Commission	report (other)	no
The Second National Infrastructure Assessment: Baseline Report	2021	November		National Infrastructure Commission	National Infrastructure Commission	report (other)	no
ANEX F: TRANSPORT The Second National Infrastructure Assessment: Baseline Report	2021	november		National Infrastructure Commission	National Infrastructure Commission	report (other)	no
Market Forecast For Connected and Autonomous Vehicles	2020	April	CCAV	Element Energy, Cambridge Econometrics, Connected Places Catapult	Connected Places Catapult	report (other)	yes
UK Connected and Automated Mobility Roadmap to 2030: CAM	2020	october		Zenzic	Zencic	report (other)	yes

title	year	month	commissioned by	done by	published by	CATEGORY	AV specific
Creators Update							
Geodata report - analysis and recommendations for self-driving vehicle testing Zenzic consultation findings	2020	june	Zenzic	Ordnance Survey	Zenzic	report (other)	yes
SMMT Motor Industry Facts 2020	2020	june		SMMT	SMMT	report (other)	no
Proposals to support advanced driver assistance systems and automated vehicle technologies	2016	July		CCAV	CCAV	report (other)	yes
The Pathway to Driverless Cars: A detailed review of regulations for automated vehicle technologies	2015	Ffebruary		DfT	DfT	government report	yes
Governance of UK Transport Infrastructures: Technical Annex							

Appendix B

List of all large-scale companies that have participated in funded CAV projects in the UK with industry/sector identified and number of projects. Automotive companies highlighted in green. Data source: UKRI (2022)

Participant	Industry/sector	Number of projects
HORIBA MIRA LIMITED	manufacturer of precision instruments for measurement and analysis	12
JAGUAR LAND ROVER LIMITED	Vehicle manufacturer	10
AVL POWERTRAIN UK LIMITED	Engineering consultancy (development, testing simulation in the automotive sector)	4
CISCO INTERNATIONAL LIMITED	IT, networking, cybersecurity	3
THALES UK LIMITED	Electrical systems; defence	3
IDIADA AUTOMOTIVE TECHNOLOGY UK LTD.	Design, engineering, testing and homologation services for the automotive industry	3
ARRIVAL LIMITED	Electric vehicle manufacturer	3
TRL LIMITED	Transport research and consultancy	3
Amey OW Limited	Engineering consultancy	3
HEATHROW ENTERPRISES LIMITED	Holding company - airports	3
MILLBROOK PROVING GROUND LIMITED	Vehicle testing centre	2
Telefónica UK Limited	Telecommunications services provider (O2)	2
BRITISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY	Telecommunications services provider	2
ORDNANCE SURVEY LTD	National mapping agency (UK)	2
Oxfordshire County Council	Local authority	2
XPI SIMULATION LIMITED	Engineering consultancy (simulations)	2
ESP Systex Holdings Ltd	Public transport services (call centre, smart cards)	2
ADDISON LEE LIMITED	Private hire and courier company	2
NISSAN MOTOR MANUFACTURING (UK) LIMITED	Vehicle manufacturer	2
HITACHI EUROPE LIMITED	Multinational conglomerate	2
Costain Ltd	Construction and engineering firm	2

DL Insurance Services Ltd	Insurance company	2
AXA INSURANCE UK PLC	Insurance company	2
ROBERT BOSCH LIMITED	Engineering and technology company	2
ATKINS LIMITED	Engineering, design, planning, consultancy	2
ROKE MANOR RESEARCH LIMITED	Engineering research and consultancy	2
DYNNIQ UK LTD	Mobility/traffic research, development, and products	2
SIEMENS PUBLIC LIMITED COMPANY	Multinational conglomerate	2
SPIRENT COMMUNICATIONS PLC	Telecommunications testing	1
IBM LIMITED	Technology company (IT)	1
TOSHIBA EUROPE LIMITED	Multinational conglomerate	1
F-Secure Consulting	Cyber-security consultancy	1
SAIC MOTOR UK TECHNICAL CENTRE LIMITED	Chinese vehicle manufacturer, including EVs	1
TRANSPORT FOR LONDON FINANCE LIMITED	Local government transport body	1
ARCADIS CONSULTING (UK) LIMITED	Design, engineering consultancy	1
EUI LIMITED	Insurance company	1
ALEXANDER DENNIS LIMITED	Bus manufacturer	1
STAGECOACH GROUP PLC	Bus operator	1
Transport for West Midlands	Local government transport body	1
McLaren Applied Technologies Ltd	Automotive technology company	1
XL CATLIN SERVICES SE	Insurance company	1
UPS LIMITED	Global logistics company	1
CUBIC TRANSPORTATION SYSTEMS LIMITED	Mobility/traffic research, development, and products	1
OPEN NETWORK SYSTEMS LIMITED	IT networking and infrastructure services	1
VODAFONE LIMITED	Telecommunications company	1
Transport for London	Local government transport body	1
SIEMENS MOBILITY LIMITED	Mobility (rail, traffic management) company	1
CATERPILLAR (U.K.) LIMITED	Heavy machinery manufacturer	1
FIRSTGROUP HOLDINGS LIMITED	Transport group (Rail, Bus)	1
MEPC MILTON GP LIMITED	Property company	1

Cambridgeshire County Council	Local authority	1
United Kingdom Atomic Energy Authority (UKAEA)	Government research organisation - Nuclear	1
Birmingham City Council	Local Authority	1
Ove Arup & Partners Limited	Design, engineering, architecture, planning consultancy	1
RICARDO UK LIMITED	Engineering consultancy	1
COSWORTH ELECTRONICS LIMITED	Engineering consultancy	1
AECOM LIMITED	Design, engineering, architecture, consultancy	1
Dynniq UK Limited	Mobility/traffic research, development, and products	1
FORD MOTOR COMPANY LIMITED	Vehicle manufacturer	1
E-Car Club Limited	Low-emission car hire company	1
AMEY GROUP INFORMATION SERVICES LIMITED	Transport consultancy	1
Cubic Transportation Systems Ltd	Mobility/traffic research, development, and products	1
HALCROW GROUP LIMITED	Engineering consultancy	1
VISTEON ENGINEERING SERVICES LIMITED	Vehicle electronics design, engineering, and manufacture	1
HUAWEI TECHNOLOGIES (UK) CO., LTD.	Telecommunications equipment provider	1
VODAFONE GROUP SERVICES LIMITED	Telecommunications provider	1
AIRBUS GROUP LIMITED	Aerospace company	1
AIRBUS OPERATIONS LIMITED	Aerospace company	1
Robert Bosch Limited	Engineering and technology company	1
Connect Plus Services	M25 operation and maintenance consortium	1