Motorsport and Autonomous Vehicles:

Examining the EU's regulatory framework for energy-efficient innovation (EEI) in the automotive industry

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Doctor of Philosophy

University of York

Politics

August 2017

Abstract

This thesis examines the regulation of innovation and sociotechnical transitions within the European automotive sector, as they relate to energy-efficient innovations (EEI) in the aftermath of the 2008 global economic crisis. Energy-efficient innovation is a technological solution, which offers a way to decouple mobility from harmful greenhouse gas (GHG) emissions, and has become a key problem-solving framework. These innovations also require stringent regulations and market-based incentives to influence automakers and other production firms to develop cleaner vehicles and technologies. This thesis format is one that incorporates publishable papers, and as such, covers the following four subject areas within the automotive industry:

- The challenges of regulating EU automotive emissions.
- The link between motorsport and 'low-carbon' innovations in passenger cars.
- A theoretical argument for established automakers as 'radical' innovators.
- The early disruptive effects of connected and autonomous vehicles (AVs).

This research seeks to contribute to a deeper understanding of sustainable sociotechnical transitions, through the examination of government interventions via policy instruments, meant to incentivize R&D within private firms, and result society's adoption of new technologies. This thesis also seeks to better explain the dynamics of disruptive innovation, and its impact on society and the economy. Understanding the processes of sociotechnical change at the sectoral level not only enables better policy design and policy outcomes, but also facilitates more accurate assessments when evaluating the implications of future sociotechnical transitions. The findings in this thesis are also timely, as they provide future researchers with additional resources to consider, as the global automotive industry prepares once more to undergo several significant transformations.

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Acknowledgements

I have often likened a PhD to gaining superpowers in critical thinking. If this is in fact the case, then I am indebted to my supervisors - Prof Neil Carter and Dr Samarthia Thankappan - for guiding me along this journey with care and attention, while nurturing my newfound abilities, and bestowing upon me a great sense of responsibility. When I first arrived at the University of York in 2014, I had been accepted to conduct a completely different research project to the one presented in this thesis. However, due to the incredible open-mindedness of my supervisors, when I pitched my brand-new research topic at our very first meeting, they generously obliged. I would like to thank Professor Carter for his tireless, clinical critiques of my work, his incredible generosity in forwarding me any news clippings or articles he thought were relevant, and his kind guidance which allowed me to grow as a 'young' researcher, under his tutelage. I would like to thank Dr Thankappan for encouraging me to pursue a thesis in publishable paper format, which in retrospect was one of the best decisions I could have made. I also thank her for generously providing me with many opportunities to teach and even create content for undergraduate students, which greatly helped my formation as an aspiring academic. I would also like to say a very special thank you to Professor Tony Heron, who was tremendously helpful in his role as my external thesis advisory panel member. I could honestly not have been gifted with better supervisors, and I shall be eternally thankful for their guidance and wisdom.

I would like to thank the many respondents who participated in this research, and who gave so generously of their time and experience during our interviews. Not only did they make this research project possible, but they also indulged some part of my childhood, by allowing me to speak with the designers of some of my favourite cars of all time. I would also like to thank the policymakers who participated in this study for their frankness and insight regarding the future of sustainable mobility. Likewise, I am indebted to the many scholars upon whose shoulders I stand, and who have made it possible for me to submit this contribution to the Academy.

To my esteemed PhD colleagues at the University of York Department of Politics, I thank you for the laughs, the support, the ideas, the camaraderie, and the sense of community over these past three years. I would especially like to thank Pupak Mohebali for her steadfast support as my sister from another mother, John Mellors who befriended me upon arrival, and got me my first job in the Department when I needed the money, Carlos Solar for his friendship and advice on academic publishing and jobhunting, and Jay Coombs, for her encouragement, kind words, wisdom and friendly smile.

Of course, none of this would be possible without the tremendous love and support from all my friends and family around the world. I would especially like to thank my loving parents, Ronald and Evelyne for helping and supporting me along this journey more than I had any right to expect, I love you guys. I would like to thank my loving wife Kerensa, for her unwavering encouragement, as none of this would be possible without her dedication, support, sacrifices, understanding and limitless love. I also thank our beautiful daughter Éva-Lee, for constantly encouraging her 'Papa' to go 'straight to the top'.

I would like to give a special kind of thanks to the dearly departed Jomo Lord for his friendship and instruction, which continues to benefit and motivate me today. I would like to thank Eric Thomas, Kai Greene, the dearly departed Greg Plitt, the dearly departed Albert Johnson, Gary Vaynerchuk, Les Brown, Will Smith, Kyle Defoor, Rev TD Jakes, Inky Johnson, Hip-hop music, and the countless other men and women who have kept me motivated throughout the many twists and turns of this wonderful journey. I would like to end by thanking God Almighty, for bestowing upon me the health and strength to successfully see this project come to fruition.

Author’s Declaration

I certify that this thesis, which I have presented for examination for the PhD degree of the University of York, is my own original work, and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References. The copyright of this thesis rests with the author. Quotation from it is permitted, provided that full acknowledgement is made. This thesis may not be reproduced without my prior written consent. I warrant that this authorisation does not, to the best of my knowledge, infringe upon the rights of any third party.

I declare that my thesis consists of 52,003 words.

Chapter 1

Introduction and Transition Theory Review

1.1. Introduction

This thesis provides a multifaceted examination of present-day energy-efficient innovation (EEI) within the European Union's (EU) automotive industry. The subject of this investigation is the European Union Domestic Market for automobiles (EUDM), with regards to the production and sale of cars (light duty vehicles) for the purposes of personal mobility. The thesis is presented in the format of a 'Ph.D. incorporating publications', which comprises four academic papers in publishable format, with a common theme running throughout. These four 'papers' are preceded by two introductory chapters that establish this project's theoretical foundations and outline the methodological approach used. The conclusion chapter brings the thesis to a close by discussing the common threads throughout the four discreet - yet related - papers, resulting in a coherent metanarrative about sustainable mobility in the EU.

While there are several theoretical approaches to technological transitions (supply-side/technical vs demand-side/behavioural), the key focus of this thesis is the examination of EI within the automotive sector as one of the most significant – perhaps the most significant – determinant in tackling negative externalities related to modern road transport. Throughout the history of civilisation, technology has been crucial to human, social and economic development (McCarthy et al., 1985), and over the years, scholars have explained the systemic nature of innovation and highlighted the importance of social and technical interactions in shaping technological change (IPCC, 2014a). An extensive study on climate mitigation by Schwanen et al. (2011, p. 1002) concluded that 'there is a strong emphasis on mitigation via technology, economic instruments and infrastructure provision, and to a lesser degree on reconfigurations of travellers' psyche through information campaigns.'

This thesis therefore focuses on the ‘technology fix’ perspective, and the argument that EI (and the policies that drive them) are the main elements of present-day mobility transitions (Geels and Kemp, 2012).

Most of society’s productive activities and supporting infrastructures rely nearly exclusively on a non-renewable resource; namely petroleum. Compounding this dilemma is the fact that the rate at which the earth’s fossil fuels are being extracted and consumed is increasing, and this fossil fuel usage is the primary source of Carbon Dioxide (CO_2), which accounts for 65% of total greenhouse gas (GHG) emissions globally. In fact, GHG emissions have risen by 250% between 1970 and 2010 (IPCC, 2014a) and the time left for meaningful human intervention before pollutants cause irreversible damage to the planet’s ecosystem is limited (IPCC, 2014a). However, ‘mitigation via technology’ has long been a pillar strategy in the automotive sector, and is characterised by EEI within the context of this thesis.

This research therefore seeks to explain various processes related EEIs, and aims contribute theoretically by addressing three major gaps in knowledge, which have been identified as significant by the Intergovernmental Panel on Climate Change (IPCC) in its 2014 Fifth Assessment Report (AR5) publication, as follows:

- ‘Limited understanding exists of how and when people will choose to buy and use new types of low-carbon vehicles or mobility services.
- Understanding how low-carbon transport and energy technologies will evolve (via innovation processes) is not well developed.
- Decoupling of transport GHG from economic growth needs further elaboration, especially the policy frameworks that can enable this decoupling to accelerate’(IPCC, 2014a).

The manner in which this thesis will go about addressing these broad gaps in knowledge, is by making focused scholarly contributions in the format of four - distinct yet related - chapters as publishable papers, which are as follows:

<u>Chapter 1:</u> Explaining how the EU emissions legislation framework failed to regulate the regional automotive industry, as uncovered by the recent Volkswagen “dieselgate” scandal.

Chapter 2: Exploring undertheorized linkages that exist between the motorsport industry and low-carbon innovations in passenger vehicles.

Chapter 3: Re-examining the role played by established firms in the innovation process, identifying previously obscured industry actors, and reconceptualising technological discontinuity within the EU automotive industry.

Chapter 4: Assessing the early implications of the sociotechnical transition to driverless vehicles, and the future of sustainable mobility.

1.2. The Challenge of Sustainable Mobility and Energy-Efficient Innovation (EEI)

The widely accepted definition of sustainable mobility is the ability to meet society's mobility needs, without sacrificing the human or ecological values of present or future generations (Black, 1996; Goldman and Gorham, 2006; Nykvist and Whitmarsh, 2008). Given this definition, it is important to acknowledge that within it, exists an inherent tension between sustainability and technological development (Jabareen, 2008). The reality is that increasing car dependency and decentralisation of cities will be difficult processes to reverse in a transport-led future (Banister, 2008). In the case of the UK, between 1976 and 2001, car use increased by 67% (Knowles, 2006), and currently, 83% of the UK's population lives in cities (and rising). Given what we know today about the negative impacts of road transport emissions on urban air quality (Walton et al., 2015), it is evident that the environmental and social consequences of mobility increase with the adoption of mass motorisation (Knowles, 2006; Lyons and Urry, 2005). This phenomenon thus prompts the following questions: How much mobility does society need? How much mobility can the planet sustain (Thomsen et al., 2005)? These questions stem from the recognition that mobility-driven externalities must be restrained in an increasingly mobile society (Graham, 1999), because facilitating higher levels of personal mobility undermines sustainable mobility itself (Hall, 2010).

It is precisely this tension which has led to the primacy of 'low-carbon' or Energy-efficient Innovation (EEI) as the dominant response to sustainable mobility. The area of transport showing the most potential for large reductions in GHG emissions by 2050 is the reduction of energy and fuel carbon intensities of automobiles. It is estimated that by 2030, all modes of road transportation could improve energy efficiency and vehicle performance by 30-50% (IPCC, 2014a). The transition to EEI therefore, as a guiding principle, fundamentally seeks to decouple material resource consumption (fossil fuels) and environmental impacts (climate change) from economic growth. Hence the dematerialisation of the economy is considered crucial to meeting sustainable development goals (IPCC, 2014a), as it gradually detaches sustainability from economic development.

Thus, is thesis frames EEIs as regulatory-driven, technological campaigns, whose purpose is to facilitate society’s transition from one technological regime to another, most often incrementally, but also sometimes radically, in the interest of more sustainable mobility. This thesis however does not go beyond existing literature in trying to prove that EEIs lead to sustainable mobility, but rather, explains the role that regulations play in the successful development and adoption of these technologies in various areas of the EU automotive industry.

1.3. Theoretical underpinnings: A brief review of transition theory on technological change

It has been argued that to stabilise CO_2 levels to the point where human activity no longer degrades the natural environment would require a complete dismantling of existing energy systems and development of new technologies. This kind of technological change is generally characterised by a three-step process where new activities are invented, these inventions are made suitable for adoption (innovation), and finally the diffusion or dissemination of these innovations occur (Sandén and Azar, 2005).

Transitions, however, are not easy as they are influenced by historical trajectories, knowledge embeddedness (Leszczyńska, 2013; Madhavan and Grover, 1998) and tend to be ‘sticky’ or path-dependent, which is characterised by increasing returns to adoption. Simply put, the performance of new technologies are less certain and more expensive than widely used, entrenched technologies (Jaffe, 2002). It is easy to see, therefore, how this path dependency mechanism favours entrenched technologies over newer ones, not because they are necessarily of superior quality, but because there are more widely used (Simmie, 2012).

It is also important to consider the sheer size of incumbent industries. Unruh (2000) calls these, techno-institutional complexes; places where technologies and institutions co-evolve together and penetrate economies at the highest levels. An example would be the techno-institutional complex formed around fossil fuels, which has been accumulating over the past two centuries and has arguably created a carbon lock-in. Historical considerations aside, certain physical properties of fossil fuels such as costs and transportability also contribute to its attractiveness. Finally, the many stakeholders, habits, institutions and technological networks adapted to fossil fuels guarantee and reinforce its continued pervasiveness. This also ensures that any attempt at a significant transition away from this source of energy will be met with a wide spectrum of resistances. In a sense, increasing returns to adoption lead to technological lock-in (Sandén and Azar, 2005). The automotive industry is part of this techno-institutional complex, and as laid out in the introduction above, this research will explore how change occurs in the automotive industry, given these high levels of entrenchment.

Over the past two decades, growing dissatisfaction with ‘old’ neo-classical theories of economic growth have given way to new models of growth and technological change. The theoretical framework for this research finds its roots in such a model; the evolutionary growth model. Evolutionary systems inherently make use of both ‘carrots’ (incentives) and ‘sticks’ (penalties) to motivate firms to develop lower-cost products; or products that consumers are willing to pay a premium for. Early popular evolutionary approaches (Nelson and Winter, 1977) to economic growth and technological change emphasised heterogeneity (technological and behavioural diversity), uncertainty, and path dependency (Mulder et al., 2001). Some dissenting scholars, however, argued that technological development doesn’t quite follow the evolutionary process, and that while biological mutations are random, technological variations are influenced by technological paradigms that guide an organisation’s research behaviour (Dosi, 1982). It could be argued then, that technological development can be seen as a form of self-fulfilling prophecy due to the nature of path dependency (Lente, 1993). Still, others (Faber and Frenken, 2009) maintain that technological development can be considered an evolutionary process because agents can never be truly certain - ex-ante - about the outcome of their research and development (R&D) efforts. This argument, however, does not appear to account for the stringency of regulatory policies whose express purpose is to mitigate, as best as possible, against these kinds of uncertainties (Lee et al., 2010). Technical processes aside, researchers (Faber and Frenken, 2009) continue to stress the overall importance of technological innovation as the key determinant in decreasing society’s industrial impact on the environment.

Traditionally, technological restructuring is said to be radical, based on reconstruction rather than relying on existing practices. It is argued that firms must abstract from their current situations and apply different knowledge bases in the development process in order to achieve sufficient technological transformation (Dolfsma and Leydesdorff, 2009). This thesis argues that not only is technological restructuring in the automotive industry incremental, but that existing knowledge bases and practices enable firms to competently integrate new technologies into their value chains. The following section provides an overview of the work of key theorists, who have heavily influenced technological transition scholarship throughout the years. These contributions have been ordered by theme, and demonstrate not only the evolution of academic thought, but also historically situate these contributions within the overarching theoretical narrative of technological transition scholarship.

1.3.1. Creative Destruction

Joseph Schumpeter famously argued that the capitalist engine is sustained by new consumer goods, methods of production and transportation, markets and forms of industrial organisation. He elaborated that these innovations illustrated the ‘process of industrial mutation that incessantly revolutionises the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of creative destruction is the essential fact about capitalism…’ (Schumpeter, 1942, p. 83). Schumpeter’s concept of ‘creative destruction’ ignited the debate about systematic technological succession, by asking us to consider the evolutionary and reflexive nature of not only the markets, but of the innovation processes that make them possible.

Decades later, researchers (Nelson and Winter, 1977) would aggressively revisit this evolutionary theory of technical change, and refine the definition of innovation as a ‘portmanteau’ that covers a ‘wide range of variegated processes by which man’s technologies evolve over time’ (Nelson and Winter, 1977, p. 37). This new understanding of innovation also insisted that any theory involving innovation must be predictive, and go beyond the particulars of what had already been observed. The rationale was that the usefulness of scholarly knowledge was its contribution to policy design and this approach was described as ‘Schumpeterian’ in its expression of technical change (Ruttan, 1997).

1.3.2. Innovation Policy

This new era of scholarship proposed that innovation policy was based on two fundamental principles. The first principle was that advances in technology were a powerful instrument of human progress, and secondly society possessed the knowledge to guide those technologies toward achieving its prioritised objectives. While the first principle was considered to be unquestionable, the latter was described as being somewhat presumptuous, citing that the scholarly community had done little in the way of being able to predict with confidence the effects of significant policy changes (Nelson and Winter, 1977). It was also argued that with regards to technological transitions, the challenge would be to reshape institutions rather than reallocate resources (Nelson and Winter, 1977). Modern-day scholars contend, however, that policies aimed at institutional change are unlikely to forego social change (Sandén and Azar, 2005).

Another key assertion which began to emerge was that effective policies should be designed to target very specific economic sectors and activities. This argument reinforced a new epistemological outlook on theory building, which advocated that general analytic arguments have little 'bite' since they tend to ignore sectoral differences. 'Any useful and coherent theory of innovation must recognise explicitly the factors that differ across industries' (Nelson and Winter, 1977, p. 41). The value of sector-specific studies is their ability to deliver operational insights into the process of change or non-change, and understandings of transitions in general relies critically on the contextual examination of the phenomenon (Wells and Nieuwenhuis, 2012). Over the period of this research, I have become increasingly convinced that sustainable transition scholarship should be conducted at the sectoral level, as it appears to provide the academic investigator with an optimal amount of resolution with which to conduct highly contextual, yet widely relevant inquiries.

The main contribution from this evolving school of thought is that good innovation policies are sector specific and informed by predictive theories of innovation which are based on the concept of evolution. We are also left with a final question: 'to what extent are the directions in which science advances inevitable, and to what extent can these be moulded by conscious policy' (Nelson and Winter, 1977, p. 73)?

1.3.3 Paradigms and Regimes

Early on, the idea of technological regimes was perceived (Nelson and Winter, 1977) as a cognitive concept among engineers that defined what was technologically possible or at least worth attempting, as the boundaries of a regime defined the limits of various design trajectories. To illustrate this, the example of the DC3 aircraft was given, which in the 1930s, embodied the technological regime. During that period, the regime was defined by metal skinned, low winged, piston powered aircrafts, and for more than two decades innovations in aircraft design were incremental (more powerful and efficient engines, larger planes) and occurred within cognitive boundaries (Nelson and Winter, 1977).

Some years later, there were attempts to address the revived debate surrounding the Schumpeterian problematique of the long-standing relationship between technological transitions and economic growth (Dosi, 1982). Scholars defined technology as pieces of knowledge, possessing both ‘practical’ and ‘theoretical’ properties, a combination of know-how, methods, procedures, experiences of success and failure, as well as physical devices and equipment (Dosi, 1982). The definition of technology was also expanded to include perceptions of constrained technological possibilities as well as notions of future developments. The concept of scientific paradigms took shape, and was described very similarly to earlier ideations of technological regimes (Nelson and Winter, 1977). Scientific paradigms are outlooks that define relevant problems, and are models and patterns of inquiry, but these logical paradigms also have a powerful exclusion effect. While they guide the technological efforts of engineers and organisations in focused and precise directions, they also create among these actors a blind spot to other technological possibilities (Dosi, 1982).

The policy related value of this model is being able to explain in general terms the role of continuity versus discontinuity in technological transitions; the ability to differentiate between incremental innovations versus radical innovation, normal technical processes versus emerging technological paradigms. This model also tries to shed some light on the processes that occur during technological transitions, and assumes that the search for new products and processes is never an entirely random process. We are reminded that technological paradigms are constantly drawing the gaze of engineers and scientists in predetermined directions, and are ‘metaphors of interplay between continuity and ruptures in the process of incorporation of knowledge and technology into industrial growth’ (Dosi, 1982, p. 161).

1.3.4. “Selection Environments” as Early Concepts of Technological Change

Another evolution in thought was the notion of selective devices, whichis similar to the earlier concept of ‘selection environment’, and is described as a function of economic forces accompanied by institutional and social factors (Dosi, 1982). Once a path has been selected and begins to gain momentum, it can be defined as the natural trajectory of technological progress, which is the normative problem solving activity determined by a paradigm. The technological trajectory can also be represented as the movement of multidimensional trade-offs between technological and economic variables which the paradigm identifies as relevant. Thus technological progress can be seen as improvements in such trade-offs (Dosi, 1982), and positive or negative correlations can exist among trajectories.

At the final stage of selection, the market operates as a final selective environment. While earlier scholars (Nelson and Winter, 1977) described the final market selection as equivalent to the environmental selection of mutations in keeping with their evolutionary mechanism, this version of final selection is perceived as a two-pronged process (Dosi, 1982). First, the economic and social environment selects the direction of the mutation, and then at a more granular level selects among individual mutations in a more Darwinian manner. In a manner of speaking, not only do selective environments choose specific technologies as winners, but at higher levels of abstraction, they also select technological trajectories to be pursued. It is argued that changing economic conditions affects the selection, development, and ultimately the obsolescence and substitution of technologies (Dosi, 1982).

Throughout the process of selection and emergence of new technologies, three critical institutional factors appear to be of key importance. Firstly, the accumulation of knowledge in both science and its applied form. Secondly the nature of institutional intervention and to what extent they permit firms the freedom to technologically explore and attempt manufacturing. Lastly, the selective and focusing effect induced by various non-economic interests such as the military, regulatory bodies and even wider political metanarratives (Dosi, 1982).

1.3.5. *Technical Limits*

A technological frontier was defined as the highest level attainable on a given technological path. When a trajectory is especially powerful, switching to an alternative one may prove difficult, which hints at the concept of ‘lock-in’. It is improbable to assess a priori, the superiority of one technological path over another, but given some objective criteria and indicators, an ex-post examination could produce a more robust assessment (Dosi, 1982).

This concept of technical limits was eventually expanded upon, and began an in-depth analysis of the interactions between incumbents and newcomer firms in a competitive market. According to Foster (1985), the aim of R&D is to approach both the practical and theoretical limits of a particular technology, but as one approaches the limits of a particular technology, one must expect diminishing returns from further R&D efforts. This is important because as firms approach the technical limits of one technology, they may have failed to investigate other potential avenues for new technologies. In doing so, they also fail to capture and exploit other powerful means of competitive leverage (Foster, 1985).

1.3.6. Newcomers and Incumbents (Established Firms)

In the early stages of transition scholarship, Schumpeter (1942), in his Theory of Economic Development, described a world where entrepreneurs sought out established firms or started new ones to give life to their inventions. Later on however, scholars took issue with how entrepreneurs and established firms were characterised by this school of thought. They argued that this old Schumpeterian distinction was less useful than it used to be, given the current institutional environment where internal R&D produced most of the contemporary innovation (Nelson and Winter, 1977). This point is particularly relevant to this thesis, where the role of established automakers and their contribution to automotive innovation is revaluated. It must be noted, however, that in some instances, innovation retains some of its old Schumpeterian flavour and can be viewed as a two-step process where an innovation produced by one firm is then sold to, and adopted by, another (Nelson and Winter, 1977).

Others characterised established organizations as ‘internally blind’ to technological discontinuities since exploring new technologies is economically counter-productive, while entrepreneurs have nothing to lose (Foster, 1985). In the case where a newcomer enters the industry through a window of opportunity with a new technology, the incumbent’s response is usually to try and extract marginal improvements from the old technology. By defending the old technology, and neglecting to begin development of new ones, the entrenched incumbent only increases his economic disadvantage by allowing the attacker to develop his product or process unchallenged (Foster, 1985). Arguably the most famous real-world example this is the spectacular fall of the Kodak film company. The company's management culture and rigid, bureaucratic structure prevented it from adequately responding to the radical innovation that was digital photography. Despite several changes in leadership, Kodak was simply unable to make the transition to 'thinking digitally', and was forced to retreat from the photography industry it once dominated (Lucas and Goh, 2009).

Having identified that incumbent firms often wait for competitive threats to develop before committing resources to new technological development, scholars recommend they head off technological decay by addressing strategic and cultural issues as soon as they can be identified (Foster, 1985). A company's proximity to its technical limits tends to signal the onset of technological decay, and the reward for anticipating future needs is exceeded only by the cost of ignoring them, hence companies are encouraged to broaden their horizons by pushing hard for the identification of technological alternatives (Foster, 1985).

1.3.7. Disruptive Innovation

'Disruption', or more specifically, the concept of disruptive innovation was developed in management studies in the early to mid-1990s (Christensen and Rosenbloom, 1995). It proposes that it is not the company with the most resources that prevails in the marketplace, but the context in which innovation comes about that determines whether industry-leading incumbents or upstarts win a competitive fight. Newcomers are more likely to supplant entrenched industry leaders in disruptive circumstances, where the challenge is to commercialise a simpler, more convenient and cheaper product to a new audience. Savvy, established companies, who are aware of the circumstances of disruptive innovations, can leverage this understanding to their benefit by capturing disruptive growth rather than falling victim to it (Christensen and Raynor, 2013).

A distinction is also made between sustaining and disruptive innovations. Sustaining innovations usually target high-end consumers by offering them better performance than was previously available. This could either be an incremental improvement or a breakthrough leap in performance. Disruptive innovations, on the other hand, do not target existing markets with better performance; instead they introduce products and services which do not perform as well as existing products, but are simpler, more convenient and less expensive (Christensen and Raynor, 2013). The core hypothesis of disruption is that it often paralyzes industry-leading corporations that specialise in producing sustaining innovations. In simpler terms, while established companies are focused on pushing innovations to meet the needs of their high-end customers, they neglect consumers at the lower end of the spectrum, which leaves the door open for new entrants. Eventually these new entrants make improvements to their products, move upmarket and eventually begin targeting the traditional high-end consumer. Also, disruptions create and exist within value networks, which is the context and medium in which companies respond profitably to the common needs of a class of customer (Christensen and Raynor, 2013).

Originally, this phenomenon was mislabelled as ‘disruptive technologies’; however, it was recognized that it was not the technology that made the incumbent response difficult, but rather that the business models used by newcomers were especially vexing (Christensen, 2006). The term was subsequently changed to ‘disruptive innovation’, and characterised as ‘financially unattractive for the leading incumbents to pursue, relative to its profit model and relative to other investments that are competing for the organization’s resources’ (Christensen, 2006, p. 49). One major critique of Christensen’s work is that disruptive innovations are not measurable, have little predictive value and thus claims that ‘disruptive technologies displace incumbent technologies’ can only be ascertained in hindsight or ex-post (Hardman et al., 2013).

1.3.8. Multi-Level Perspective

Frank Geels’ Multi-Level Perspective (MLP) has become increasingly popular over the years and has gained wide acceptance in the field among transition scholars. The MLP forms the basis for this project’s theoretical framework, and thus is accorded its own section here. The MLP attempts to develop an understanding of systems at the sectoral level as sociotechnical systems. It is comprised of a clustering of elements including technology, science, regulation, user practices, markets, cultural meaning, infrastructure, production and supply networks. The elements of this sociotechnical system are created and maintained by supply-side actors (firms, research institutes, universities, policymakers) and demand-side actors (users, special interest groups, media). These actors do not act autonomously in the traditional sense, but within the context of social structures, regulative, normative and cognitive rules. These rules consist of search heuristics which can include problem agendas, guiding principles, standards, government regulations, corporate identity and consumer ways of life, routines and understandings. Likewise these rules do not exist individually and are linked together as a semi-coherent set, which the MLP defines as a regime (Geels and Kemp, 2007). While others (Nelson and Winter, 1977) have described technological regimes as cognitive routines shared by a community of engineers which guides their R&D

activities, this definition has been expanded to include a sociological category of rules (Rip and Kemp, 1998). The concept of sociotechnical regimes consists of scientists, users, policymakers and societal groups besides engineers and firms. The interaction between these actors results in networks and interdependencies, which coalesce to align their collective activities within the sector. This coordination of entities embodies the concept of the sociotechnical regime (Geels and Kemp, 2007).

The sociotechnical regime occupies the mid-level of the MLP and accounts for the stability of the sociotechnical system itself. While cognitive routines enable engineers and designers to pursue specific developmental directions, it also makes them blind to developments outside of that focus. Geels argues that the dominance of certain technologies is not only due to economics as path dependence literature implies, but is also influenced by the rules of the system. This established system, stabilised by roles, routines, ways of thinking, and ways of doing is also reinforced by legally binding contracts. Systems are similarly stabilised by adaptation of lifestyles, favourable institutional arrangements, formal regulations, and accompanying infrastructures which in turn drives technological momentum. Social relationships, organisational commitments, and vested interests of existing organisations further reinforce these existing systems. Finally, the material component of sociotechnical systems contributes to its stability because of sunk investments and economics of use. As artefacts are put into use and material networks develop, they are not usually abandoned but become a self-reproducing entity, and for this reason, sociotechnical systems are characterised by stability (Geels and Kemp, 2007). Specific to the transport sector, other factors which help stabilise the automotive regime are demand-side societal factors such as cultural preferences for private property as opposed to collective ownership, preferences for speed and time saving, physical landscape: the separation of work, home, and the road network, cultural values of freedom, choice, progress, wealth, status and privacy. Macro-economic growth in developing economies as well as demand for mobility due to globalization play a role in reinforcing the regime (Geels, 2012). Lock-in mechanisms also stabilise the regime at various levels and these include sunk investments (infrastructure and manufacturing), user patterns and lifestyles, consumer preferences of attributes (speed, convenience, cost, etc), cultural values (joy of driving, automotive enthusiast), vested interests (industry, car lobby, etc) and beliefs of established actors (transport planners, policy makers, industry actors) (Geels, 2012).

Given these levels of stability within sociotechnical systems, how then does change occur? Sociology scholars in the fields of technology and evolutionary economics have identified niches as the locus of radical innovation around which new systems may emerge. The general idea is that niches act as incubators for radical novelties, protecting them from mainstream market competition. These technologies require a level of protection as most inventions are usually crude, inefficient, and usually badly adapted to the many uses they will eventually cater to. Niches can either be small market niches where selection conditions are different from those in the mainstream or they may be technological niches where resources are publicly subsidised or are part of a private strategic investment. Niches provide new innovations with a space to learn and improve processes and build up social networks that will support and sustain these innovations throughout their development. Conceptually, niches are lower-level (micro) phenomena within the MLP, and interact with established regimes at the mid-level within the macro landscape. The macro or upper-level is formed by sociotechnical landscapes which are characterised by aspects of the exogenous environment that are usually outside the direct influence of individual actors. The MLP contends that the contents of landscapes are heterogeneous and include forces such as economic growth, broad political coalitions, cultural and normative values, environmental problems and resource scarcity. Landscape is also a useful metaphor used to envision the large-scale material context of society such as the structural and spatial arrangements of cities or the pervasive technologies that affect society as a whole (Geels et al., 2012).

1.3.8.1. MLP: Critiques and debates

According to the MLP, niche groups have been shown to prefer modal shifts and demand management policies as opposed to the technological innovation policies preferred by established firms. Within the MLP, the niche is not simply the categorization of a minority actor in an industry, but encompasses all emerging solutions and is not restricted to the technology fix. In this manner, problems can be reframed, and non-technical concepts such as modes of mobility and behavioural reconfigurations are considered. This can lead to a reconfiguration of regime membership, resources and nodes of power, hence putting the ‘radical’ in ‘radical innovation’. This broad system-wide focus is seen as a distinct advantage of the MLP in tackling the problem of climate change as opposed to the preferred ‘techno-fix’ of regime actors (Whitmarsh, 2012). An example given to demonstrate this is the carbon intensity of electricity used in electric vehicle charging from 'well-to-wheel[1]', rather than solely focusing on zero tailpipe emissions.

An admitted weakness of the MLP, however, is that the landscape or 'macro level' remains somewhat of a black box, where exogenous determinants such as oil prices, climate policies and environmental awareness are assigned to this tier as they do not neatly fit into the lower levels. Global long-term trends and everyday institutional decision-making are linked where causality is bi-directional and thus a better understanding of societal systems is needed. Demand side considerations and the identity of technology consumers and users as voters, activists, friends, parents, employers, employees, community group members as opposed to a static 'public' identity is also problematic (Whitmarsh, 2012). Sociotechnical transitions involve the transition to different, but increased consumption of technical innovations and resources, however, a sustainability transition in the transportation sector is likely to be a transition to less consumption. For this reason, Whitmarsh (2012) questions the usefulness of the MLP, which is based on evolutionary economics and technological innovation studies, in explaining radical and social change. She echoes the concerns of others that 'consumption becomes a substitute for the genuine development of the self' (Hanlon and Carlisle, 2009, p. 28).

The MLP maintains that the core contention in transition studies revolves around (dynamic) stability and (radical) change and how this interaction plays itself across multiple dimensions (Geels, 2012). While this concept provides a useful way to investigate these issues in land transport, its application to low-carbon transitions in the automotive sector is not without its caveats. The empirical application of MLP is an interpretive assessment where breadth and depth must be balanced. While the MLP address various dimensions of transport systems and changes in a broad manner, many real world nuances are backgrounded for the sake of 'the big picture' or larger patterns (Geels, 2012).

Also, relevant to this research, is the MLP's acknowledgement of the effectiveness of EU emissions regulations. Researchers observe that while initial targets could be met with incremental innovations, longer-term targets would in all likelihood require technological innovations such as fuel cells, hybrids and battery electric vehicles (Geels, 2012). It is argued that policymakers

[1] Well-to-wheel (also referred to as cradle-to-grave) analysis in this instance, is the environmental impact assessment of electricity production, for the purposes of EV charging, throughout the entire value chain.

metaphorically govern from within 'the cockpit', pulling levers and toggling switches in order to steer the transport system. This description is justified by pointing out that policymakers are beholden to the electorate and public opinion as well as the automotive industry for jobs, taxes and economic growth. For these reasons, proponents of the MLP classify policy makers as being part of the regime as they are constrained by their dependence on other actors (Geels, 2012). Therefore, understanding the behaviour and interactions between industry, policy makers, consumers and civil society, should lead to a deeper understanding of the cooperation and support needed to initiate meaningful change. The sociotechnical approach and the MLP were designed to examine these multi-actor processes in transitions, and allow transport scholars to analyse the multi-dimensional possibilities, barriers, and drivers involved in low-carbon transitions towards sustainable transport (Geels, 2012). In closing, MLP scholars pose the following: 'are cars and technologies the main elements?... Is consumer behaviour and mobility practices a (political) no-go area, or do these form the crucial dimensions of transport systems (Geels et al., 2012, p. 74)?' These questions are significant because they speak to the fundamental debate between technological vs. social innovations as the most effective approach to meaningful, sustainable change and furthermore, questions the extent of the state's remit to execute such changes.

1.3.8.2. Going beyond the MLP in the automotive industry

While the multi-level perspective has become especially popular (Markard and Truffer, 2008), it has been accused of having a firm intellectual grip on innovation studies. There have been calls for a deviation away from the multi-level model as the only model in town, and for the exploration of other social scientific and systemic theories of change (Shove and Walker, 2007). Recent research is beginning to show that new technological eras are influenced by both old and new fields of technological opportunities (Bergek et al., 2013; Berggren et al., 2014). This would seem to support the burgeoning view that creative incremental accumulation has been occurring in a recent times rather than radical shifts of creative destruction and it also suggests that new paradigms do not destroy old ones, but rather complement and extend them (Andersen, 1998).

Some researchers (Geels and Kemp, 2007) describe the automotive industry as a routinized regime, characterised by conditions of high variability and cumulativeness which allows incumbents to accumulate technological knowledge and innovative advantages over industry newcomers. This results in technological leadership among incumbents which would explain the concentration of innovation and hierarchical stability among them and the low rate of entry typically observed in the automotive industry (Oltra and Saint Jean, 2009). Complex (knowledge) systems regimes like the automotive industry are characterised by medium to high levels of technological opportunity, high entry requirements in knowledge and scale, and a high persistence of innovation (Marsili, 2001). A distinctive feature of this regime is the high level of knowledge diversification that firms possess, particularly in upstream technologies and their access to external sources of knowledge. These firms are 'active in a wide range of technological fields along similar search trajectories' (Oltra and Saint Jean, 2009, p. 569) and possess the ability to exploit opportunities with high degrees of relevance within their network of R&D activities. This variation in knowledge assets is an important feature of the automotive regime and may explain the innovative strategies of automotive firms. Oltra and Saint Jean (2009) argue that the sheer complexity of the knowledge base is the fundamental technological entry barrier. Even suppliers who represent a source of external knowledge cannot capitalise on their innovations as a means of entry into the sector because of the high levels of complexity involved. While there exist obvious technical complexities, there is also a complex web of actors, institutions, users, and competitors which must be taken into consideration. These complex relationships between suppliers and producers are crucial to the analysis of low-carbon innovations within the automotive industry (Oltra and Saint Jean, 2009). Others also argue that if radical low-carbon innovations are required, the high degree of cumulativeness in the automotive industry may block such innovations (Faber and Frenken, 2009).

1.4. Creative Accumulation

The common assumption in industrial innovation and technological development studies is that industry incumbents are burdened with 'core rigidities' of the old technological regime (Leonard-Barton, 1992). Therefore, technological discontinuities may occur when new entrants into the industry enact a modern version of Schumpeter's creative destruction (1942). Much of the work that followed Schumpeter's concept of creative destruction focused on the attacker's advantage over the incumbent, where 'creation' was usually effected by the invader, new firms or entrants to the industry, while the 'destruction' was the fate of incumbent firms (Christensen, 2006; Tushman and Anderson, 1985). The creative destruction hypothesises (and competence-based scholarship) relies on the individual competencies (resources, skills and knowledge) of existing firms for results. Some innovations will refine and improve existing technological competencies whereas, others will destroy them, thus the terms ‘competency enhancing’ and ‘competency destroying’ came to be (Bergek et al., 2013). Competency enhancing discontinuities are simply incremental improvements by virtue of refining and extending established product designs. They are generally introduced by incumbent firms, and tend to reinforce their position within the industry by allowing them to exploit existing competencies and raising the barrier of entry to newcomers (Bergek et al., 2013). Inversely, competence-destroying discontinuities make existing knowledge obsolete by changing the knowledge base and skills required to produce that product. These tend to be introduced by new entrants into the industry and lower the barriers of entry for other newcomers. Competence-destroying innovations tend to favour new entrants at the expense of the incumbents. Industry incumbents are incapacitated by their previous success within the old technological paradigm, and they find it difficult to respond effectively to the new threat (Bergek et al., 2013). I argue however that in the case of the automotive industry, it would be difficult to destroy the competencies of established automakers (OEMs), because they specialise in complex capital goods (automobiles). It is because of the modular nature of the automobile, that automakers have become extremely efficient systems integrators, who frequently add and subtract new and old technologies on a regular basis.

Two recent automotive industry case studies (Bergek et al., 2013; Berggren et al., 2015) demonstrated a need for innovation scholarship to go beyond the attacker’s advantage. Thus Bergek et al. proposed an elaboration on Pavitt’s (1986) creative accumulation as a conceptual understanding of the processes of accumulation and creativity in complex products industries such as the automotive sector (Bergek et al., 2013). While previous literature has presented cumulative innovation as incremental, step-by-step refinements, Bergek et al. develop a notion of creative accumulation stressing the tension between creativity and accumulation. Creativity implies responses ‘outside of the range of existing practice’ (Schumpeter, 1947, p. 150). This is manifested through improvements in cost, performance or quality over previous iterations or the introduction of new performance attributes based on new components, new product architecture or both. Accumulation, on the other hand, implies knowledge creation based on existing practices, rather than making them obsolete. (Bergek et al., 2013). Therefore creative accumulation cannot be described as competence-enhancing since it forces incumbent firms to explore outside their current repository of knowledge based on the search for new competencies (Bergek et al., 2013). Geels refers to this type of innovation as 'competence-expanding' (Geels and Schot, 2007). Firms in complex product industries involved in creative accumulation must find a balance between deep component related knowledge and broad systems related architectural knowledge. This implies the added challenge of balancing and using existing knowledge with new knowledge at both of these levels (Bergek et al., 2013).

To meet the challenge of creative accumulation, firms must continuously fine-tune existing technologies at a rapid pace, acquire and develop new technologies and resources, and integrate these two tasks into superior products and solutions. They must engage in technological searches and experimentation as the basis for accumulating in-house knowledge and absorptive capacities. They must also implement variation in their search process as seen through partnering with new suppliers and specialists, and the development of new integrated technologies (Bergek et al., 2013). The concept of creative accumulation highlights the limits of existing market and competency-based explanations of technological discontinuities in the automotive market. In this industry, technological discontinuities will most likely not lead to creative destruction, or disruptive innovation (Christensen, 2006), or competence-destroying innovation (Tushman and Anderson, 1985). Bergek et al. (2013) have thus developed and extended the concept of creative accumulation by explaining some of the challenges facing new entrants competing in capital intensive and complex products industries. It also examines the challenges threatening incumbents when technological discontinuities correlate with competitive advantages. Creative accumulation highlights the significance of accelerated development of entrenched technologies, while acquiring new technological competencies and integrating them within the existing ones. To develop, explore and integrate new competencies is the order of the day. This perspective potentially explains why competence-destroying or disruptive innovations have thus far failed to supplant industry leaders in the automotive industry and why they have managed to survive and increase their competitive capabilities (Bergek et al., 2013).

Attackers are unable to match incumbents' accumulated knowledge and experience, thus making it very difficult to successfully develop and manufacture a comparative product for the main market. Furthermore, the depth and breadth of incumbents' knowledgebase allows them to effectively develop solutions at a much faster rate than new entrants can improve their technologies. Also, the creative responses between firms within the automotive industry towards each other's products means that new entrants are constantly trying to hit a moving target (Bohnsack et al., 2014). Finally, creative accumulation also conceptualises a different organisational setup than that proposed by attacker's advantage based theories. These theories implore managers facing competence destroying and potentially disruptive innovations to deploy autonomous units in market niches to assess the new technology and pursue it without interference from the firms mainstream operations based on established knowledge and networks (Christensen et al., 2004). This advice is questionable given the way creative accumulation is conceptualised, and thus Bergek et al. (2013) recommend that firms should integrate their efforts rather than establish ambidextrous organisations (Hockerts and Wüstenhagen, 2010) which separate and search for alternative types of innovation independently (Bergek et al., 2013). One contemporary example is the automaker Tesla, who is well known for its premium EVs, that are supported with cutting edge autonomous technology, and a supercharging network, all of which were developed in parallel. The results of this study confirm this by demonstrating how knowledge transfer occurs across an automaker's diversified (yet highly relevant and integrated) network of R&D activities in various technological fields, which in turn promotes the creative accumulation effect.

Therefore, from a transitions theory standpoint, this research uses Geels' (2012) multi-level perspective as the overarching theoretical framework with which to examine the EU automotive sector. However, regarding the process by which technological change occurs at lower levels of abstraction, this thesis will rely on Bergek et al.'s (2013) development of the creative accumulation concept, as it seems to convey the most accurate representation of technological change within the automotive sector. Incidentally, it must be noted that Geels has recently revised (Geels et al., 2016) his original typologies of the four transition pathways (Geels and Schot, 2007). Most significantly, the 'transformation' pathway has been amended to acknowledge the acuity of Bergek et al.'s creative accumulation concept (Bergek et al., 2013; Berggren et al., 2014). This is an important acknowledgement, because the transformation pathway most resembles the creative accumulation concept. This is relevant to this study because it will be argued in the forthcoming chapters that creative accumulation most accurately reflects the sociotechnical changes occurring in the EU automotive sector.

1.5. Thesis format and research objectives

The following chapter (Chapter 2) is a second introductory chapter that reviews the economic and regulatory concepts that underpin the EU's road transport emission policies. The second half of Chapter 2 is dedicated to discussing the research methods used in this project. As described in the introduction above (see section 1.), Chapters 3, 4, 5 and 6 make up the core of this research project's theoretical contributions, and are presented as four – discreet yet related – publishable papers. Chapter 7 brings this thesis to a close by aggregating the four paper chapters into a coherent discussion and conclusion about technological change in the EU automotive sector.

There are three main overarching research questions that drive this thesis, and as stated above, I address all three of these core research questions across four chapters in publishable paper format:

1. How do low-carbon transport technologies evolve via innovation processes? In this thesis, evolution of low-carbon transport technologies via innovation processes is captured by the energy-efficient innovation (EEI) concept, and paper's 1-3 address this question from various perspectives. Paper 1 discusses regulatory stringency and predictability as being facilitators of EEI. Paper 2 explains how EEI can emerge in motorsport and crossover to commercial automotive, and Paper 3 describes the governance framework which allows industry incumbents to dominate EEI research and development throughout the EU automotive value chain.
2. How do policy frameworks accelerate the decoupling of transport GHGs from economic growth? Paper 1 describes the process by which stringent and predictable regulations reduce the negative externalities (toxic and carbon emissions) caused by road transport in the EU. Paper 2 argues that regulations and EEI developed in a related but separate (motorsport) industry, can successfully crossover, via tacit knowledge, and result in lower-emissions private vehicles.
3. How and when people will choose to buy and use new types of low-carbon vehicles or mobility services? Paper 2 proposes that motorsport's integration of EEI on the racetrack is changing the public's perception about electric vehicles (EVs). Paper 4 argues that the significance of autonomous vehicles (AVs) goes beyond radical technological innovation. AVs also changes the systems of use (modality) of personal mobility, and consequently

challenges the hegemony of the private ownership business model by proposing one of shared autonomy.

The overarching aim of this thesis is to conduct a multi-faceted exploration of CAC regulations, and their effectiveness in 'forcing' innovation within the automotive industry. This broad exploration is subdivided into four discreet, yet related case studies and presented in publishable paper format in chapters 3-6. These chapters shall be referred to as papers 1-4 respectively, given this thesis' particular format. Paper 1 examines how stringent EU regulations failed to prevent nitrogen oxides and carbon dioxide emissions gaps between reported testing results and real-world driving. This paper seeks to advance the understanding of regulatory frameworks aimed at reducing emissions, as well as the unexpected consequences of 'policy mixing'. Paper 2 explores the obscure relationship between motorsport engineering and low-carbon innovation in the automotive sector, which addresses the question of how low-carbon technologies evolve via innovation processes. Paper 3 is a theoretical re-examination of the role of incumbent firms in the innovation process, based on empirical evidence from the post-2008 automotive industry. This also examines the evolution of EEI, but from the perspective of the firms driving these innovations. Paper 4 is a study of the early disruptive implications of autonomous and connected vehicles, and the various challenges that policymakers will face with the rapid adoption of this technology. This final paper also explores how society could adopt new modes of mobility.

The common thread throughout these papers is government intervention in the form of strict command-and-control (CAC) regulations, which are "technology-forcing", and their influence on EEIs. Paper 1 focuses on the role of regulatory stringency and predictability in curbing emissions, and Paper 2 explains how and why commercial regulatory pressure influences 'relevant regulations' within motorsport. Paper 3 argues that command-and-control regulations reinforces the established automotive regime, while Paper 4 offers a preview of the regulatory hurdles that will have to be negotiated with the introduction of autonomous vehicles (AVs) on public roads. Each paper examines a different aspect of CAC regulations, and how they affect various facets of automotive innovation. Together, these four case studies contribute to a deeper understanding of how CAC regulations facilitate the deployment of EEIs, and their pivotal role in effecting sociotechnical transitions.

This thesis focuses on regulatory intervention at the industrial level, and the main contribution for the most part is the application of accepted theoretical principles, which have been established in the existing literature, to the contemporary empirical case of the post-2008 EU automotive industry. Thus, emerges new theoretical insights, into how regulatory mechanisms fail, the relevance of motorsport to EEI, a revised understanding of established firms as multi-level innovators, and the intersectionality of AVs as a packaged technical and non-technical solution. The four papers in this thesis consistently rely on the same theoretical assumptions and methods outlined in Chapters 1 and 2, and converge into a cohesive theoretical conclusion in Chapter 7.

Chapter 2

Innovation Policy review and Methods

Following on from Chapter 1, this chapter begins with a review of the essential academic literature needed to understand the basic economic and regulatory concepts that underpin the EU's automotive emissions control regime. This section also briefly acknowledges relevant basic concepts of human behaviour as it relates to preferences and sustainability, and the rationale for its exclusion from this study. The second half of this chapter is dedicated to discussing the qualitative methods of data collection and analysis used in developing the findings of this thesis.

2.1. Emission control legislation

Governance is defined as the interaction and decision-making among actors involved in a common dilemma (Hufty, 2011) and in this case, that dilemma is climate change. The concept of governance goes beyond political authorities and includes other stakeholders, networks, informal institutions, and incentive structures that operate at various levels of society (Stoker and Chhotray, 2009). This section is primarily concerned with reviewing literature relevant to the governance of low-carbon innovation within the EU automotive industry. As mentioned in Chapter 1 (see section 2.), the area of transport showing the most potential for large reductions in GHG emissions is the reduction of energy and fuel carbon intensities of automobiles (IPCC, 2014b). One of the most significant determinants for the dramatic improvements in vehicle efficiency has been the adoption of aggressive policies, targets and standards (Mock et al., 2012). The following section is not a comprehensive discussion on environmental legislation, as that would go beyond the scope of this research project. Rather, the emphasis will be on 'emission control legislation' which explains the innovation dimension of environmental legislation (Lee et al., 2010). The overall goal here is to guide the reader to a holistic understanding of emission control legislation within the European Union Domestic Market (EUDM), while highlighting its major theoretical underpinnings.

Understanding how legislation in the European automotive industry works is key to understanding the present-day governance of road transportation, and the tools available to policymakers to effect more sustainable mobility. In this research project the key focus is on the regulatory design of EU command-and-control (CAC) policies deployed in the EU automotive sector, classified as general regulatory instruments. For the purposes of this study, these instruments are specifically the performance standard regulation (Bergek and Berggren, 2014) of Nitrogen Oxides (NO_x) and Carbon Dioxide (CO_2) tailpipe emissions. NO_x in the EU has been regulated as a toxic emission under the Euro 1–6 legal frameworks, first introduced in 1993, and CO_2 is regulated under EU regulation (EC) No 443/2009, which was phased in between 2012 – 2015. These regulations set by the EU mandate that each automaker meets a certain level of emissions based on a fleet average.

2.2. The economics of technological innovation and the environment

The relevance of economics to the environment is based on the idea that economic activity has potentially harmful impacts on the environment, and these negative impacts are known as 'externalities'; a concept developed by Arthur Pigou (Santos et al., 2010). Externalities are positive or negative consequences which are borne by members of society, other than those controlling the externality-producing activity (Jaffe et al., 2005). For example, road transport externalities include accidents, road damage, noise pollution, environmental damage (NO_x, CO, SO_2, PM, DMP), congestion and oil dependency (Greene, 1998; Santos et al., 2010). It must be noted that Diesel Particulate Matter (DPM) is a combination of solids and liquids, and is generally divided into three basic fractions: Solids (soot), Soluble Organic Fraction (SOF), and hydrated sulfuric acid or Sulphate Fraction (SO4) (NETT, 2017).

The presence of toxic emissions (negative externalities) prompts governments to act and correct these 'market failures'[2] (Santos et al., 2010). Thus, environmental policies are deployed as interventions, which attempt to equalize imbalances by incentivizing firms to reduce the externalities they produce. Pollutants that are very harmful are restricted, as they incur high social costs, however, pollutants that are very costly to eliminate enjoy some level of tolerance because

[2] Left to its own devices, the market 'fails' to take into account a consequence of economic activity, in this case environmental externalities. Government intervention is now justified.

the cost of reducing them is high (Jaffe et al., 2005). Environmental policies have two main objectives. First and foremost; to get companies to adopt cleaner technologies which they previously ignored due to cheaper, but higher-polluting alternatives. Secondly, to encourage firms to invest in research and development (R&D) that leads to innovations in cleaner technologies (Carraro and Siniscaico, 1994).

In a simple scenario where a polluting firm invests in technological innovation (pollution control equipment, cleaner production methods, or new substitutes), those innovations ideally result in greater overall benefits to society (Jaffe et al., 2005). As the firm invests in new technologies, the cost of reducing pollution (abatement costs) decreases, while environmental health is improved. At this basic level, technological innovation is good for the environment and good for the firm that must abide by environmental regulations (Santos et al., 2010). What the simple scenario fails to consider, however, is that investing in new technologies isn't free. Thus, when firms are incentivised to reduce pollution, this also simultaneously creates an incentive to find the cheapest way to reduce that pollution. This investment of a firm's resources is comprised of two main components; innovation and adoption, both of which are required to reduce pollution (Schumpeter, 1942). Innovation involves scientific R&D, and adoption is the process by which a new product or process gradually replaces older technology. These processes are costly, because firms must learn about new technologies, purchase new equipment, and adapt them to their particular circumstances (Jaffe et al., 2005). Objectively speaking, firms tend to incur substantial expenses when integrating new technologies for the purposes of reducing pollution.

The scenario above becomes more complex, because independent of the externalities associated with pollution, innovation and adoption also produce externalities of their own:

- Knowledge externalities: A firm that invests in or implements new technology typically creates benefits for others while incurring all the costs. Just as pollution creates a negative externality, innovation creates positive externalities. This positive externality comes from the public good nature of new knowledge. Innovating firms find it difficult to keep other firms from also benefiting from their new knowledge (Griliches, 1992). Patents and other methods which protect intellectual property do so imperfectly, meaning that a successful innovator only captures a fraction of the overall benefits of the innovation. Innovation thus creates positive externalities in the form of 'knowledge spillover' for other firms, and 'spillover' benefits to society[3].

- Adoption externalities: For several reasons, the cost of a new technology for one user may depend on how many other users have adopted that same technology. In general, users will be better off (get cheaper prices) the more people use the same technology. This benefit is also referred to as 'dynamic increasing returns' (Jaffe, 2002).
- Network externalities: These exist if a product becomes technologically more valuable to an individual user as other users adopt a compatible product (like a telephone or computer network) (Jaffe et al., 2005).

Ironically, innovation and adoption appear to set technological development on a path dependant course because of the additional positive externalities they produce (Krysiak, 2011). Simply put, the more a new technology is adopted by society, these positive externalities act as multipliers, further guaranteeing use of the technology over a period of time, like a technological self-fulfilling prophesy (Sandén and Azar, 2005). The concept of path dependency or 'lock-in' has already been discussed in Chapter 1 (see section 1.3.).

Finally, apart from the externalities described above, innovation and adoption of new technologies also creates additional market failures related to 'incomplete information' (Faber and Frenken, 2009). Incomplete information refers to large uncertainties associated with investment in new innovations. In the context of climate change, these are significant uncertainties surrounding its future impacts, the magnitude of policy response, and thus the likely returns on R&D investments (Lee et al., 2010, 2011). Imperfect information, or uncertainty, can slow the diffusion and adoption of new technologies if firms lack the confidence to innovate (Gerard and Lave, 2005). Given the above, it is reasonable to argue that technological change, relative to the environment, occurs at the intersection of two distinct and important market failures: pollution - which represents a negative externality, and new innovations - which generate positive externalities. The indication, that the risk of society becoming technologically path dependant as discussed in Chapter 1 (see section 1.3.), is in fact a double-edged sword. If government encourages the diffusion of a technology, it is possible that it becomes so entrenched in the marketplace (or 'locked-in'), that it stifles the development of other superior technologies. To avoid this, policies should be

[3] The public-good nature of a cleaner environment.

'technology neutral', and encourage all attempts at achieving regulatory targets without favouring one particular technological approach (Jaffe et al., 2005). In their controversial paper, Porter and Linde (1995) proposed that properly designed environmental standards could trigger innovations that promote both environmental health and industrial competitiveness. Since then, there has been a lively debate as to whether environmental regulations serve as a constraint or stimulus to technological innovation (Oltra and Saint Jean, 2009). The fact remains that most firms underinvest in new technologies (Oltra and Saint Jean, 2009), and for this reason, environmental policies should be designed to foster, rather than inhibit innovation, as the beneficial environmental impacts of these specific technologies are always socially desirable. These basic economic principles are key to understanding the evolution of the technologies discussed in this research, and the potential effects of related policy interventions (Jaffe et al., 2005).

2.3. Types of emission control policies

Thus far, it has been established that economic development leads to overproduction of pollutants if left unchecked, and that pollution is regarded as a public good with negative externalities. Since the 1960s, OECD countries and emerging economies have sought ways to encourage the development of technologies to reduce pollution (Oltra and Saint Jean, 2009). The two most widely used policy instruments to achieve these ends are strict command-and-control (CAC) environmental regulations and market-based instruments (MBI) (Bergek and Berggren, 2012). CAC policies are regulations that force consumers and producers to change their behaviour, while MBIs provide financial incentives to stakeholders in exchange for shifts in their behaviour. MBIs can be further categorized into price controls and quantity control (e.g. carbon taxes and tradable permits respectively) (Santos et al., 2010).

While CAC regulations reduce pollution immediately, they may retard economic growth due to higher production costs. Porter and Linde (1995), however, argue the opposite. The so-called 'Porter hypothesis' proposes that stringent environmental regulations can achieve a win-win situation for the economy and the environment. This adds value to the argument that technological change is one of the predominant factors for solving long term environmental problems (IPCC, 2014b; Yang et al., 2012).

Of equal importance is the crucial role of public policy in creating a demand for technologies which serve the public good (IPCC, 2014b). Economists argue that MBIs outperform CAC measures and similarly, that general measures are more efficient than technology-specific ones such as subsidies or targeted technologies. It must be acknowledged that there are dangers regarding the targeted support of specific technologies, in that it can lead to inefficient resource allocation. The risk is that as support for a promising technology grows, it creates a ‘blind spot’ to better technologies not yet fully developed at the time. As stated in Chapter 1 (see section 1.3.), an industry then risks becoming ‘locked-in’ to that particular, less effective technology (Bergek and Berggren, 2012). While MBIs are a powerful tool and have been shown to influence more sustainable consumption, studies credit CAC regulations for encouraging more innovation from producers (Creutzig et al., 2011; Dahl, 1995; Greene, 1998; Van Dender, 2009).

2.3.1. Focusing on CAC regulations: A Rationale

Command-and-Control regulation as defined by one early policy scholar:

> ‘Commands are enforced through orders, injunctions, civil penalties, and criminal fines. Regulated firms generally are not permitted to deviate from specified conduct by paying fees proportionate to the degree of noncompliance (Stewart, 1981).'

Several historical reasons have been given for governments’ reliance on command-and-control rather that market-based incentives. Of these, the most important are: CAC regulations appeal to policymakers because they appear to offer a precise, predictable and effective means of government intervention in the marketplace. In the case of the automotive industry, the application of uniform performance standards means that all firms are treated equally, and the agreed upon regulations are generally perceived as equitable. Uniform performance standards in the automotive industry also have the added advantage of high levels or compliance, meaning that in general, there is rarely a need for investigations on an individual basis. Finally, the judicial and administrative backing of the European Union makes European domestic market (EUDM) emissions regulations immune (in theory) to manipulation, bestowing upon it public legitimacy. These are some of the major reasons why regulation is the most widely used instrument in environmental policy (Carter, 2007).

However, several economic studies characterise CAC regulations as ‘bad’ policy making, describing them as rigid, and less flexible than MBIs (Ambec et al., 2013; Ashford, 2002; Palmer et al., 1995). Some energy-efficient analyses also claim that MBIs are more efficient than CAC regulations at encouraging cost-effective adoption of environmentally friendly technologies. (Cleff and Rennings, 1999; Demirel and Kesidou, 2011; Jaffe et al., 2002; Johnstone, 2007; Kemp and Pontoglio, 2011). Older studies have even compared CACs to ‘Soviet-style’ regulations and ‘socialist central planning’, describing this type of governance as both ‘endemically inefficient and democratically illegitimate’ (Ackerman and Stewart, 1985). At the opposite end of the debate, studies have shown that CACs are at least as efficient as economic instruments, and in some cases they can be more efficient (Cole and Grossman, 1999). It has also been argued that CAC regulations are more effective in stimulating end-of-pipe solutions, despite being less effective at incentivising precautionary clean technologies (Ashford, 2002; Demirel and Kesidou, 2011; Hamamoto, 2006; Weidner, 1995).

Outside of this heated debate about the effectiveness CAC regulations, there have been some especially compelling, and prophetic, theoretical arguments for CAC regulations. Ashford’s critique (2002) of neoliberal ecological modernization, which views CAC regulations as inflexible, expensive, and short-sighted, is one such instance. The antiregulatory climate in the United States during the 1980s, and lax EU regulations implemented with industry consensus up until the early 2000s encouraged some scholars (Kemp, 1995) to put their faith in evolutionary, stepwise change within technological regimes. Ashford (2002) argues, however, that this school of thought’s weakest formulation, is the proposition that ‘problem industries’ can transform into ‘green or sustainable’ ones through incremental institutional learning, life-cycle analysis, dialogue with actors, and the implementation of ‘environmental management systems’.

Ashford (2002) concedes that while inviting industries to solve externalities in a more enlightened manner can complement conventional environmental governance, counting on industrial regimes to endogenously transform, ignores increasing evidence of their inability to change. Historically, dominant design technologies rarely, if ever, displace themselves (Christensen, 2002; Schumpeter, 1942), and exceptions to this rule are exactly that. Ashford argues that ‘markets are inherently unable to internalize (unpriced) social costs without intervention’ (2002, p. 4), and that while bureaucracies are imperfect, they are not fundamentally flawed. In fact, Ashford asserts that incumbent firms are unlikely to create new markets for innovations, and predicted that regulations may be necessary to create these niche spaces (2002). Given the nature of the post-2008 UK automotive industry and its highly regulated, public-private innovation framework, it is reasonable to conclude that in hindsight, Ashford was correct.

It has been said that 'the choice of regulatory regime depends on the goals and concerns of policymakers' (Cole and Grossman, 1999). Hence, in a society that looks to innovation as a primary means of GHG mitigation, it is not surprising that technology-forcing policies are relied upon to drive these emission reducing technologies (Lee et al., 2010; Oltra and Saint Jean, 2009), and the development of cleaner automobiles (Schot et al., 1994). Effective CAC regulations are theoretically relevant therefore, because they explain the innovative dimension of environmental legislation (Lee et al., 2010). Given that the EU's innovation framework for the automotive industry is primarily based on stringent performance standards, I determined that a focused examination of these regulations was the most appropriate approach to this multi-faceted study of automotive innovation.

2.3.2. Command-and-control regulations

CAC regulation is a technology-forcing strategy where the regulator sets an objective for the future that cannot be met by employing existing technologies (Nentjes et al., 2007; Tarui and Polasky, 2005). A command-and-control policy is essentially a regulation or 'command' which needs to be 'controlled' or enforced. When there is an externality, the regulator (or government agency) either imposes an upper limit on the activity causing it, restricts the behaviour of economic agents, or restricts certain characteristics of the product. While there is some debate about how easy it is to implement CAC policies, they are usually well understood and enforceable. The predictability of their outcomes is also a source of debate. One cited flaw of CAC policies is that they are static, in the sense that they do not provide incentives to go beyond what is initially mandated. This means these policies must be constantly revised over time, and can suffer setbacks due to bureaucratic 'red tape' (Santos et al., 2010). Thus, it is argued that regulatory standards require strong market instruments to align market signals with regulations as they become more stringent over time (IPCC, 2014b). The annual UK vehicle tax based on carbon emissions is a prime example of a market instrument that has been deployed by a national government to induce the adoption of lower CO_2 emitting vehicles. However, in Chapter 3 of this thesis, the discussion will focus on how this alignment has had the unintended effect of locking-in the UK market to diesel vehicles, which has created additional negative externalities in the form of significant health risks due to poor air quality caused by high NOx emissions (BBC, 2017a, 2017b).

The basic premise of technology-forcing is based on interactions between industry and regulators; more specifically how regulators can influence firms to invest in R&D. It has been found that firms are more likely to invest in R&D when (1) regulators are committed to enforcing the regulations and (2) when there is competitive pressure to develop new technologies (Gerard and Lave, 2005). The discussions below will include these factors and other determinants known to influence the interaction between regulators and firms.

2.3.2.1. Regulator legitimacy

When regulators set a standard, firms may argue that they are too stringent or unfeasible. If the regulators have no basis to refute these claims, then firms are unlikely to engage in any kind of serious R&D effort. Firms may sometimes actually lobby regulators to delay or rescind a standard because typically firms possess more 'information' about their own technological capabilities than regulators. Firms can then exploit this information asymmetry by hiding their true innovative capabilities, underinvest in R&D and then claim the regulatory targets cannot be met (Kleit, 1992). To be fair, collusion among firms is not always the case, because if firms genuinely believe that no other firm can technically meet the regulation, they tend to autonomously scale down their R&D efforts (Gerard and Lave, 2005), and the belief becomes self-fulfilling. Regulators must therefore establish legitimacy by having a good technical understanding of the industry, a good regulatory programme, and political support behind them (Gerard and Lave, 2007).

2.3.2.2. Competitive pressures

Competitive pressures go hand in hand with regulations as an incentive for firms to invest in R&D. If the average firm believes a regulation will be implemented, it will invest in R&D to reduce its compliance costs. More aggressive firms will lobby regulators to implement new regulations based on innovations the firm has already developed, thus putting them ahead of their competitors (Puller, 2006). Domestic firms may also believe that while regulators may not shut them down, they may ban imports from foreign firms, and thus domestic firms will delay their compliance. On the other hand, if foreign firms come into compliance first, it then gives regulators empirical support for penalizing domestic firms. Component suppliers, in their eagerness to expand market share, may run R&D programmes of their own to show regulators that more stringent regulatory targets can be met (Gerard and Lave, 2005). These are some of the competitive pressures that can influence firm behaviour in relation to regulations.

2.3.2.3. Stringency

While the literature suggests that regulations are a driver for realizing environmental innovation (Gerard and Lave, 2005; Yang et al., 2012), regulatory design, and in particular regulatory stringency, has been empirically linked to motivating firms to innovate. Stringency in this context specifically has two prerequisites (1) absolute reduction of harm to the environment (e.g. volume of pollutants generated) and (2) compliance with existing technologies is either impossible or too costly (Oltra and Saint Jean, 2009). This correlation between regulatory stringency and technological innovation lends empirical support for a 'narrow' reading of the Porter hypothesis. A word of caution, however; overly stringent CAC policies run the risk of being unattainable, as there is no way of knowing beforehand how much innovation a policy can legitimately 'force' (Lee et al., 2010).

2.3.2.4. Uncertainty / Predictability

Another important determinant in the regulator-firm equation is levels of uncertainty. Lee et al (2010) argue that some level of uncertainty in anticipation of regulation may actually drive innovation, while Porter and Linde (1995, p. 110) insist that 'the regulatory process should leave as little room as possible for uncertainty at every stage'. Uncertainty among stakeholders is wide and varied. Regulators are responsible for encouraging firms to conduct R&D, they evaluate their progress, assess the costs and benefits of compliance and make decisions regarding the enforcement, relaxation or rescinding of regulations. Should firms fail to meet these standards; regulatory responses range from issuing fines to shutting down entire industries. Legislators must decide whether to abide by regulators decisions, or step in and amend them. Firms, who must allocate their capital resources must decide whether to petition, delay or sue the regulatory agency. Technology-forcing policies therefore create an environment of uncertainty regarding possibilities of a breakthrough, costs of R&D, and the overall reliability and effectiveness of any new technologies generated (Lee et al., 2010). Hasty adoption of an unproven technology may lead to reliability issues or even 'lock-in' to an inferior short-term fix over a superior, sustainable alternative. Regulations can also cause unintended knock-on effects in related industries (Gerard and Lave, 2005). The time horizon for regulation compliance is another indicator of predictability. If it is set aggressively short, firms tend to favour ‘end-of-pipe’ solutions rather than meaningful technological transitions. If the time horizon is overly generous, however, then information gaps between regulators and firms grow, and the compliance deadline runs the risk of being indefinitely extended (Kemp, 1995).

2.3.3. Types of Command-and-Control regulations

CAC policies generally regulate in two different kinds of ways: performance-based regulations (performance standards) and technology-based regulations (technology standards). Technology standards can be more problematic than performance standards when seeking to induce technological innovation. One major reason is that technology standards become obsolete upon achieving their objective, because when firms adopt the prescribed technology, there is no incentive to invest in more efficient technologies that could do the job better and at lower costs. The alternative regulatory approach – performance standards – is the preferred approach when the goal is to induce technological innovation, because the only requirements are target performance outputs and how they are achieved is up to the individual firm. This style of policy gives firms the latitude to innovate without running the risk of locking themselves into a costly inferior technology (Jaffe et al., 2005; Lee et al., 2011). This regulatory approach also has the added benefit of limiting a government’s ability to ‘pick winners’ in the marketplace (Van Bree et al., 2010), which is usually the case when technology-based regulations are deployed. Picking winners refers to any intervention by governments to promote the growth of a specific technology based on its national importance. Even when governments signal their enthusiasm for a new technology, such as autonomous vehicles, they try to avoid specifics, and leave early legislation as broad as possible.

2.3.4. Command-and-Control Criticisms within the automotive industry

The main arguments against environmental CAC policies within that automotive industry, is that they are costlier to implement compared to MBIs, and that they promote increased travel (by reducing the cost of driving due to fuel-efficient vehicles travelling further per tank of fuel). This increased travel is known as the ‘rebound effect’, and CAC critics claim it causes additional externalities such as increased air pollution, congestion, traffic injuries and road fatalities. I argue however, that research has shown that as income grows, the rebound effect decreases because more affluent drivers tend to ignore fuel prices, and thus their driving habits and less likely to be influenced by price fluctuations (Hymel et al., 2010). Plotkin (2009) further contends that the 'rebound' effect is a fuel price issue which should be corrected via fuel pricing; not by attempting to dismantle policies whose primary functions are to decrease harmful emissions. Another criticism of CAC policies is that while they target new vehicles, they largely ignore their after-sale performance (Plotkin, 2009). This is a minor point, as after-sale fuel efficiency can be captured by other regulatory measures such as the Ministry of Transport (MOT) tests in the UK. Gerard and Lave (2005) contend that the opportunity costs of pursuing CAC policies are unacceptably high, and speculate that technologies may have similarly evolved in the absence of regulations. This assertion can be refuted on the grounds that the economic literature has already established that, generally, firms will not innovate if it is cheaper to do nothing, even if there are better technologies or methods of production available (Carraro and Siniscaico, 1994). Others have also argued that CAC policies do nothing to reduce fuel consumption across all uses, including older vehicles and non-vehicular consumption (Crandall, 1992). However, fuel efficiency regulations were never meant to be a comprehensive 'one-stop-shop' for emission reductions; their purpose is to induce emission reductions across new car fleets sold by automakers.

Oltra and Saint Jean, (2009) argue that environmental policies rarely induce radical innovation, but rather support incremental innovation of existing technologies. I propose that technological innovation has in fact significantly affected the relationship between road travel and the environmental degradation it causes. In Europe, improved automotive fuel efficiency has reduced CO_2 emissions by 22g/km between 1998 and 2007 (Fontaras and Samaras, 2010). In the U.S. it is estimated that CAFE[4] will reduce annual oil consumption by 20-40 billion gallons, and GHG emissions by 60-130 billion tons by 2020 (Bezdek and Wendling, 2005). Had there been no reduction in emissions since 1970, highway vehicles would have produced 4.5 times more hydrocarbons, 3.2 times more carbon monoxide and double the nitrogen oxides in under 20 years. It is difficult to imagine how these reductions could have been achieved without the aid of performance-based regulations (Greene, 1998). Standards also have proven effective in inducing technological innovations responsible for lowering tailpipe emissions (Greene, 1998; Santos et al., 2010) by introducing emission control systems like the catalytic converter, and advancing their

[4] The Corporate Average Fuel Economy (CAFE) standards are regulations enacted to improve the average fuel economy of cars and light trucks produced for sale in the United States.

development (Lee et al., 2010). Thus, within the automotive industry, CAC regulations have proven to be effective by demonstrating that low-emission technologies can be driven by technology-forcing policies.

2.4. Emission control legislation in the European Domestic Market (EUDM)

Regulations in different countries vary in design and stringency. For example, regulations in Europe and the US differ in how strongly they incentivise reductions in vehicle size vs. reductions in vehicle weight (CCC, 2011). The following discussion, however, is centred on the EUDM policy framework as it is the focus of this research.

Initially, the European Commission's (EC) efforts to reduce CO_2 emissions was based on a 1998 voluntary agreement of 140gCO_2/km between European, Japanese and Korean car manufacturer associations (Creutzig et al., 2011; EUR-Lex, 2009). However, while there was some decrease in emissions, especially in France by 2006; average global emissions had risen by 20% between 1990 and 2006. At this point the Commission decided that binding regulations would be necessary to correct these levels of negative environmental impacts (Oltra and Saint Jean, 2009). In 2007, the EC issued a proposal to replace the voluntary scheme with a mandatory standard of 130g CO_2/km. The auto industry collectively argued that the regulatory targets were not feasible, and after some negotiations, the EC agreed to stagger the emissions mandates, where 65% of an automaker's fleet would have to reach the target by 2012, 75% by 2013, 85% by 2014 and 100% by 2015. The Commission also set a new target of 95g/km by 2021[5] (Plotkin, 2009; Shiau et al., 2009). When these EU regulations were eventually introduced, they were less stringent than those in the U.S. and Japan, especially regarding the rules governing particle matter and nitrogen (NO_x) emissions. These more relaxed aspects of the regulation explain why Europe is the lead market for diesel vehicles and diesel technology development.(Oltra and Saint Jean, 2009). Very recently, however, diesel has come under political fire with French Prime Minister Manuel Valls declaring in a speech: 'In France, we have long favoured the diesel engine. This was a mistake, and we will progressively undo that, intelligently and pragmatically (Bruce, 2014)'. Shortly after that, Shadow Environment Minister Barry Gardiner of the UK's Labour Party told to the press that 'his

[5] Original citation is 2020, however the revised legislation has been amended to 2021

government's decision to base the country's car taxes on CO2 output was "the wrong decision," because it had the unintended effect of pushing consumers into diesels (Turkus, 2015)’. Lord Drayson, former Labour Science Minister in the Brown government from 2008-10 admitted: ‘We did get it wrong. We now have a much better understanding than we did just a few years ago of what are the health effects of the products of diesel cars and they are literally killing people so it’s clear that in retrospect that was the wrong policy’ (Kollewe, 2015). The recently retired (2012-2016) conservative Secretary of Transport, Patrick McLoughlin, is also on record as saying that former Labour Chancellor, Gordon Brown, made a mistake when he reduced taxes on low-sulphur diesel in 2001 as an incentive for motorists to switch from petrol cars (Asthana, 2016). In fact, in July of 2017, the UK joined France in proposing a ban on the sale of new diesel and petrol vehicles by 2040 (Ryan and Shankleman, 2017), while allowing the continuing sale of hybrids.

EU regulations are also quite flexible on how a firm complies (known as flexibilities), and the time horizons for compliance to be met. This style of governance has less of a technology-forcing effect, and is credited for still encouraging continuous innovation and reducing levels of pollution without evoking the issue of ‘dominant design’ (Oltra and Saint Jean, 2009). One of the major contributions of this thesis, however, explained in detail in Chapter 3, is that flexibilities in regulations present a significant source of vulnerability, which in turn invites exploitation by automakers (Skeete, 2017).

One criticism of EU policy concerns Regulation EC 443/2009, which regulates Carbon Dioxide (CO_2) emissions in new cars. This regulation is based on the average emissions of sales of each automaker, and critics point out that automakers could sell a combination of very high and very low emitting vehicles and still comply by not exceeding the average target of 130g CO_2/km (Bampatsou and Zervas, 2011). Another criticism of EU regulations is that in recent times, automakers have been allowed to make pooling arrangements between themselves to comply with total emissions targets. This means that ‘exotic’ sport car manufacturers can pool with other automakers without having to significantly decrease their emissions (e.g. Ferrari of the Fiat group or Lamborghini of the Volkswagen group). This raises the issue of equity (again), and begs the question: are the top earners in society being allowed to ‘pay to pollute’ (Wells et al., 2010)? Thirdly, critics of EU regulations cite the penalty of €95 per exceeding gram of CO_2/km as problematic. The rationale is that this extra cost will be built into the vehicle’s price, thus making it more expensive than lower emitting vehicles, which should prompt consumers to buy the latter. However, using the same example of exotic sports cars, price is not the first argument for their sale, and we potentially see another case of 'polluter pays' among the most affluent in society (Sullivan et al., 2004), which raises legitimate social/climate justice concerns. A final criticism of EU regulation concerns the upper limit of 95g/km of CO_2. The argument is that this blanket regulation does not consider the economic asymmetries between member states within the European Union. Hence due to their varying capacities, all members cannot comprehensively comply with the mandate (Bampatsou and Zervas, 2011).

The Post-2008 EU & UK consolidated approach to Research and Development in the EUDM's Automotive Sector

Post-2008, the EU automotive industry faced several crises, the first of which was the 'hollowing out' of the UK automotive supply chain, which had started in the 1970s. Hollowing out refers to a gradual reduction in the locally sourced content for vehicles built in the UK, involving the flight or dissolution of many automotive supply chain companies, or their rationalisation within bigger groups. OEMs were partly complicit by encouraging supply chain companies to achieve low-cost sourcing in overseas territories. This loss of productive capacity reduced the local content in UK-built vehicles to approximately 35% in 2008, compared to Italy, Germany and Spain who typically achieve local sourcing content of approximately 60% (Automotive Council, 2014). A second, more immediate, crisis was that several OEMs were in danger of bankruptcy as a result of the global financial crisis (Muller, 2016). The final major problem for the industry was that OEMs were also in the midst of readjusting their corporate strategies to meet CO_2 emissions targets that had just been re-negotiated with the European Commission that same year. The first target to be met was a fleet average of 130g CO_2/km by 2015 (European Commission, 2016), which was considered a relatively short time in the automotive industry.

Consequently, the UK transitioned to a completely different business model for the island's automotive industry. One of the major outcomes of these crises was the establishment of the Catapult network, which has been described as the UK's equivalent of the German Fraunhofer Society. After the Second World War, Germany established a nationwide network of technology innovation centres, part-funded by the federal government, and part-funded by local state funding and regional banks. Their mission was to help small and medium-sized businesses develop their products, processes and commercialisation capabilities in the marketplace. That network, built upon relationships between academia, industry and government, became known as the German Fraunhofer Society.

What stands out about the UK's new industrial strategy is the highly integrated approach that is now prevalent throughout its automotive industry. Take for example the UK Office for Low Emission Vehicles (OLEV), which is made up of representatives and ministers from the Department of Transport (DfT), the Department of Business, Innovation & Skills (BIS) and the Department of Energy & Climate Change (DECC). OLEV's day-to-day operations are overseen by ministers within those three departments in a collaborative mission to reach 'zero emissions' in the UK. Within the UK automotive industry, the current funding for propulsion technology over the next 10 years is set at £1 billion, which is split 50-50 between government and industry, each contributing £500 million with a total budget of £100 million a year for 10 years (Foy, 2013). This funding is not for production costs; it is strictly allocated to the development of future powertrain concepts.

The UK's Advanced Propulsion Centre (APC) most aptly embodies the theme of collaborative effort within the context of low-emissions innovation. The APC was formed in 2013 as a government-industry collaboration orchestrated by the Automotive Council in an effort to position the UK as a global leader in low-emissions powertrain development and production. The APC hosts biannual competitions where entrants compete by submitting low-emissions technology project proposals. These competitions are completely technology agnostic, meaning that any type of propulsion system (electric, diesel, etc.) is considered as long as its CO_2 emissions are in line with EU regulations. Very importantly, entrants must be part of a collaboration between a SME - generally a university and/or a supply chain company – and an OEM or Tier 1 supplier, because the point of the competition is to advance those types of projects through the 'valley of death'.

The valley of death is an industry term that indicates a specific point in an innovation's lifecycle that is underpinned by an empirical industry measurement: the Technology Readiness Level (TRL). TRL is a method by which the technological maturity of a particular innovation can be estimated on a scale from 1 to 10, and was originally developed by the National Aeronautics and Space Administration (NASA) in the US (NASA, 2015). In the UK automotive industry, the valley of death refers specifically to TRL 4-6, which is perceived as the most perilous phase of any technology's development. A project that is TRL 1 or 2, usually seeks out organizations like the Engineering and Physical Sciences Research Council (EPSRC), which mainly funds university projects that are just starting off. Once an innovation reaches TRL 5, then project leaders may approach an organisation like the APC, where they come with a pre-arranged partnership or the APC can help them find one. At this stage, the project has a working prototype but the innovators don't know how to commercialize it. This is where the APC is able to assist the project in finding solutions, build collaborations and help the project enter the APC competition (APC, 2014). A related concept of equal importance in assessing an innovation is the Manufacturing Readiness Level (MRL). MRL measures the maturity of the manufacturing supply chain, which is highly relevant to the automotive industry in assessing factors like the capabilities of suppliers, quality assurance and the production costs of an innovation that is being considered for mainstream deployment. While newcomers may come forward with innovative technological proposals, TRL and the MRL are very good tests for an innovation's chances of achieving production. Therefore, a newcomer (small innovator / SME) to the automotive industry may have a working prototype, but lack the required funds, effort and know-how to get that innovation through to the open market. Industry respondents refer to that phase as the 'valley of death', the place where many new and innovative ideas perish.

2.5. Behavioural change

Despite being primarily focused on low-carbon innovations and the technology-forcing policies that drive them, it is important that this research briefly acknowledge the scholarship surrounding human behaviour as it relates to choices of modes of transportation. This section also serves to explain why behavioural change and modal choice were excluded from this study.

Effecting behavioural change in society is an important but challenging mitigation strategy, and the possible outcomes (modal shifts) are hard to quantify (IPCC, 2014b; Oskamp and Schultz, 2006). Compounding this challenge is the fact that consumer preferences, depending on the type of technology, can change with market conditions, and evolve as new technologies gain market share (Mau et al., 2008). Researchers agree, however, that financial considerations seem to play a central role in the decision-making process for many new vehicle buyers, especially in the case of low-emission vehicles (Eppstein et al., 2011; Ozaki and Sevastyanova, 2011). Having said that, researchers freely admit that they don't quite understand; or find it difficult to disaggregate data regarding consumers' acceptance of novel vehicle technologies (Axsen et al., 2009; Greene et al., 2013). A critical issue lies in how consumers evaluate the environmental characteristics of products, which strongly determines their adoption and diffusion. In general, consumers are unwilling to trade-off performance attributes of conventional vehicles such as range, acceleration and refuelling time for the sake of being environmentally friendly (Carley et al., 2013; Dagsvik et al., 2002; Ewing and Sarigöllü, 2000; Hidrue et al., 2011; Oltra and Saint Jean, 2009). This has been the key finding among researchers in the field; that consumers' intended actions are disconnected from what they actually do, and this concept is known as the 'value-action gap' (Lane and Potter, 2007; Whitmarsh et al., 2011). It is argued that while some consumers may intend to purchase low-emission vehicles; they end up ultimately being unwilling to make the many compromises involved. Another barrier to entry for electric vehicles is that they are more expensive, costing 30%-80% more than a conventional car (Frenken et al., 2004; Karplus et al., 2010). Studies have suggested therefore, that individuals are unwilling to make these sacrifices to their living standards if they do not perceive that the task of tackling climate change is being shared by others (Whitmarsh, 2009). Thus, I argue as others have (Beirão and Sarsfield Cabral, 2007), that public outreach and change in personal values is unlikely to put humanity on a pathway to sustainable mobility.

2.6. A final word about regulations in the automotive sector

With regards to CAC regulations, it can be argued that with sufficient stringency, regulations can cause technological discontinuities by exerting substantial pressure on OEMs, forcing them to diversify and make R&D investments in alternative forms of propulsion. It has also been found that the relaxation of regulations positively correlates to firms relaxing their own innovative efforts (Skeete, 2017), and can also cause them to extend their R&D across longer timeframes (Dijk and Yarime, 2010). Fuel economy and GHG emissions standards have proven to be some of the most effective tools in reducing oil demand and GHG emissions around the world (Atabani et al., 2011). The many dire predictions preceding the implementation of fuel economy regulations either never manifested themselves or were relatively minor compared to the overall benefits delivered

(Greene, 1998). Europe and Japan have been leading the charge in fuel efficiency among their automobile fleets, with the US trailing behind. The US, however, is making quick progress thanks to California's federal regulations, which has achieved the greatest absolute reduction in emissions of all fuel efficiency regulation regimes (Creutzig et al., 2011). Regulating the transport sector is still a young discipline, but policies must continue to evolve, by committing to abatement and encouraging R&D to ensure emissions reduction through technological innovation (Creutzig et al., 2011; Van Dender, 2009).

At its core, regulation frameworks exist to ensure the transition to a market which includes discontinuous (low-carbon) technologies (Brown et al., 2010). CAC regulations have been responsible for reducing the sulphur content in petrol and more importantly phasing out leaded petrol in many countries, Europe included (Santos et al., 2010). In fact, if European fuel efficiency regulations were to be abandoned, a 50% increase in fuel taxes would be necessary to induce similar fuel savings (Clerides and Zachariadis, 2008). To a large extent technology-forcing regulations in Europe have succeeded, and patenting activity shows that innovation among automakers rose significantly between the 1970s and 1990s (Lee et al., 2011). One very important fact uncovered by Lee et al (2010) is that automakers are the lead innovators in emission control technologies. This further suggests that technological innovation and the ability to respond to regulations depends significantly on the competence of the automotive firm (Lee et al., 2010).

What has been observed several times over the course of this review is that specific conditions must be present for technology-forcing regulations to bear fruit. Regulatory agencies must possess the requisite technical knowledge, in sufficient depth, in order to establish appropriate levels of stringency (Lee et al., 2011). The levels of stringency will very often dictate how firms will respond to regulations, and the levels of success that a given fuel efficiency regulation will achieve (Shiau and Michalek, 2007). The credibility and political competence of regulatory agencies is also a key factor in influencing the outcome of an intervention, as regulators must be able to correctly assess the levels of uncertainty involved in implementing technology-forcing policies (Gerard and Lave, 2005; Tarui and Polasky, 2005).

'Standards or taxes' has been a topic of debate among academics, and cannot be answered definitively across all sectors and regions. What can be said, however, is that in Europe, regulations seem to work better for the simple reason that fuel taxes in European countries are already high.

This reinforces the importance of properly conceived policy instruments which preserve the welfare of producers and consumers alike (Clerides and Zachariadis, 2008). It can also be objectively argued that CAC fuel efficiency standards complement MBIs, which by themselves cannot fully address dynamic market failures (Creutzig et al., 2011; Van Dender, 2009). A simple example of this would be the fact that the effectiveness of catalytic converters depends on the availability of unleaded fuel, however, neither an emission tax or unleaded fuel would, by themselves have forced the innovation of the catalytic converter (Gerard and Lave, 2005). An equally important conclusion that can be drawn is that MBIs (e.g. carbon taxes) fill a policy gap despite being prone to market failures (Flachsland et al., 2011). It can be conceded that while standards are likely to induce significant technological innovation, they are by themselves unlikely to cause a comprehensive migration away from the internal combustion engine (IPCC, 2014b).

2.7. Methods

It is important that I preface this methods section by explaining that the main body of this thesis is comprised of four chapters in the format of publishable papers. This section therefore is a detailed and extended account of the general qualitative methods applied throughout those four 'papers' and the entirety of this thesis. In Paper 1 (Chapter 3), the methods section appears as it does in its published format (Skeete, 2017), with details unique to that paper chapter. Similarly, in the three remaining paper chapters (Chapters 4, 5 and 6), the methods sections include details specific to those paper chapters (such as lists of interviewees), but refer back to this section when describing the general qualitative methods used.

Research in the transport sector frequently makes use of qualitative methods for inductive purposes, as it permits the identification of concepts and interpretations from the respondent's perspective (Dijk et al., 2016; Gardner and Abraham, 2007; Skeete, 2017; Steinhilber et al., 2013). Transport studies often follow the epistemological trend of using quantitative methods with a positivist world view (Curl and Davison, 2014; Vowles, 2006), which at times, has been critiqued as being archaic (Goetz et al., 2009; Hall, 2004). On the other hand, it has been argued that qualitative approaches have been steadily contributing to fuller understandings of transport practices and policies (Aldred and Jungnickel, 2014; Clayton and Musselwhite, 2013; Hall, 2010; Preston and O'Connor, 2008). Hence, there has been an appeal for more critical (qualitative) analysis in transport studies, to compliment the already well-established technical (quantitative) scholarship (Pangbourne and Alvanides, 2014). While comparing the merits of qualitative versus quantitative approaches is a false dichotomy, there have been calls for the application of more varied methodologies and holistic approaches, that offer more robust theoretical underpinnings from a wider range of disciplines (Curl and Davison, 2014). One such example is the multi-level perspective (MLP) used in this paper, which seeks to explain sociotechnical transitions as a systemic theory of change (Geels, 2012). Thus, this paper makes appropriate use of interpretative analysis, which combines theoretical sensitivity with empirical expert assessments, often seen in MLP case studies of the automotive industry (Bergek et al., 2013; Berggren et al., 2015; Geels et al., 2012).

This thesis is a bounded exploration of the European Union Domestic Market for automobiles from 2008 to 2017, comprised of in-depth data collection from multiple sources. The focus of this investigation was to develop an in-depth understanding (description and analysis) of low-carbon innovation within the automotive industry. The background of this exploration was interdisciplinary in nature and drew upon scholarship from political science, business, sustainability, behavioural and innovation studies. The unit of analysis was the EU automotive industry, and for the purposes of this study only two principal groups of actors were considered – regulators/legislators and private firms - with the third major group – consumers – excluded from this study. Data was collected by conducting elite interviews and analysed using thematic analysis, to capture relevant themes from the perspectives of automakers, regulators and other industry stakeholders based on their experiences (Creswell, 2012). The identification of themes thus made it possible to establish linkages between collections of different sets of knowledge within the automotive industry. Thus, the overarching rationale for employing qualitative methods in this study was to achieve a textured understanding of processes within the automotive industry. Qualitative analysis of deep and rich interview data is therefore most appropriate for discerning meaning at the industry specific mid-level, versus quantitative analysis of far removed datasets that discerns behaviour in controlled or artificial settings at the macro-level (Bryman, 2015).

2.7.1. Primary data and data collection

The primary sources of data for this project were collected through recordings of semi-structured elite interviews with key industry decision-makers within the automotive sector. These respondents were based in the UK, US, Germany and Belgium, and were selectively targeted for their opinions about specific areas of the automotive industry. The rationale for elite interviews is that they corroborate what has been established by other sources, they establish what a specific category of actors thinks, and they can be useful in reconstructing events, identifying causal mechanisms, and making inferences about a larger population’s characteristics.

Interviewees were specifically selected (non-probability sampling), and in this case, a combination of purposive and chain-referral sampling, which allowed for the inclusion of key institutional actors in the data gathering process (Tansey, 2007). While these methods of sampling run the risk of suffering from selection bias and limited potential to generalize about the wider population; many of the respondents in this study were from competing multinational firms (automakers and suppliers), and thus their international portfolios often qualified them to give opinions that extended beyond national borders. Respondents also often had competing interests (policy and commercial), and this corroboration of evidence from multiple sources made possible the triangulation of information, which lends validity to these findings (Creswell, 2012). For these reasons, I am confident that the number and variation of actors sampled removed most of the above concerns. Other advantages of non-probability sampling is more direct control over the selection process, and the inclusion of key institutional actors in the data gathering process (Tansey, 2007). Additional primary data was collected from audio recordings of presentations and Q&A panel discussions at select industry conventions in 2015. The data used in this study was also supported with documents published by the automotive sector, official European Commission and UK government documents, and news articles in the press. While reports in the press are not widely used for academic support, this secondary source of data was invaluable in tracking the daily shifting landscape of events within the automotive industry, as well as providing context to what respondents were saying. These secondary sources of data represent the sociotechnical Landscape within the MLP framework, which is characterised by aspects of the exogenous environment that are outside the direct influence of individual actors. In this instance, the Landscape is a useful metaphor used to envision the large-scale material context of how AV technology is being embedded into society (Geels et al., 2012). The use of secondary data also contributes to the triangulation of information effect.

The interviews themselves were loosely structured, while being guided by broad research questions meant to address the gaps in knowledge identified in the four paper topics which make up this thesis. Respondents were allowed to expand their thoughts in certain areas, which allowed me to reflexively pursue interesting threads of dialogue that arose. Interviews were guided in the following manner:

- Before beginning of each interview, respondents were reminded that the interview would be conducted in accordance with the ethics approval guidelines of the University of York. Respondents then gave their verbal (and written) consent to record the interview, they were assured that their identity would be anonymized, and that all recorded data would be destroyed in accordance with the UK’s Data Protection Act 1998 at the end of the research project (PhD).

- Interviewees were first asked to briefly provide an overview of their role within their organization, or asked for an elaboration if their role was already known, but required further clarification or additional details.
- The semi-structured interview then began in a manner which depended on who the interviewee was, the scope of their knowledge or at what stage of the field study the interview was conducted. To clarify, if the interview was conducted early into the field study, initial questions tended to be more basic and broad, as familiarity with the specifics of the industry needed to be established. The latter interviews however, began with a much more advanced dialogue, as my understanding of the industry had matured, and the more basic details had been confirmed multiple times in previous interviews.

During the interviews, as different subject areas emerged, I would prompt respondents to expand on those areas if they had not already done so in the unstructured parts of the interview. These prompts served to fill in any developing clusters of data concerning specific issues, as well as verified or dismissed the presence of phenomena that emerged in previous interviews. Questions were asked in broad, non-directed terms such as, 'Could you please describe what that process is like?' All interviews were recorded with the interviewees' consent, and usually lasted between 30 minutes to an hour. While the subjects being discussed were not sensitive in the traditional sense, there were still some sensitive topics, which is understandable, since most interviewees were highly placed executives in private firms throughout the automotive value chain, who often competed with one another.

Overall 48 interviews were conducted, where just over half of those were by telephone, with the rest being face-to-face. While some prior research (Aquilino, 1991; Jordan et al., 1980) suggests that interview modes may yield varying results, more recent comparisons of interview transcripts revealed no significant differences in the quality of telephone interview responses when compared to interviews conducted in person (Colombotos, 1969; Sturges and Hanrahan, 2004). Furthermore, the quality of data pertaining to knowledge items (Rogers, 1976), where research interests are more narrowly focused, is also comparable to that of data collected in person. Researchers argue that when the respondents own and use telephones for both brief instrumental and extended expressive phone conversations, to a large extent, the technology is 'transparent' (Sturges and Hanrahan, 2004). There are of course, instances when telephone interviews are not ideal, such as when dealing with complex subjects over extended conversations (Colombotos, 1969), or when research requires face-to-face contact or immersion into the respondent's world (ethnography) (Sturges and Hanrahan, 2004).

Telephone interviews can be justified on both practical grounds - economy, time savings, and flexible scheduling - and on methodological grounds - comparability of data with in-person interviews (Colombotos, 1969). This was especially evident when gaining access to, and interviewing elite and ultra-elite respondents (Stephens, 2007). Therefore, the use of telephone interviews was both a productive and valid research option in the collection of qualitative data. Any other concerns do not sufficiently override the economic and logistic advantages of telephone interviewing (Rohde et al., 1997) as an efficient fieldwork resource (Fenig et al., 1993).

2.7.2. Data analysis

The first step of the data analysis phase was to 'clean' any 'raw' data in order to make it useable. As the data was collected, raw interview recordings were processed, meaning that they were transcribed from audio into text format. The second step of data analysis concerns the actual method of analysis used to generate findings from the data. At this stage, transcribed interviews (or other primary data) were thematically coded using the Template Analysis method, which gives an account structured around central themes that have emerged, and draws on examples from interview transcripts as required (King, 1998). The coding structure was developed from a combination of a priori interests and initial engagements with the data, also referred to as the 'codebook' approach (Crabtree and Miller, 1992). This study took a 'subtle realist' approach (Hammersley, 2013) to the Template Analysis method which recognises that researchers are inevitably influenced by their inability to divorce themselves from their positions in the social world. However, this approach also maintains that researchers can know phenomena that are independent of themselves though research. This 'mid-level' approach makes it possible to claim that a representation emerging from research is valid, while recognizing that other perspectives on that phenomenon are possible as well (Brooks et al., 2015). Direct quotes from the stakeholders have been included in the results sections as evidence of sound analysis conducted by the author. It should be noted that data from several respondents were used as empirical evidence for more than one paper, and the reason for this is that these respondents, given their senior positions, were able to give their expert assessment on more than one area of the EU automotive industry. Thus, their in-depth knowledge contributed to the analysis of various themes, that were spread across various papers. The conclusions of this study are meant to provide a robust overview of various phenomena within the EU automotive industry, highlighted by this study's participants, along with appropriate theoretical conclusions by the author.

2.7.3. Ex-post reflections on the methods used in this research project

The first easily identifiable challenge in collecting and analysing data throughout this research project was the technical difficulty of simultaneously collecting data for four distinct yet related research questions. The reason this was challenging was because during interviews, I always had to keep in mind which interviewee could speak to which research question (or paper theme). For example, some interviewees, by the nature of their work in their organisation, could address all four paper themes within the thesis, while others were only qualified to speak about one paper theme. This not only required me to have a crystal-clear idea of what may paper themes were at all times, but also demanded a more meticulous preparation of interview questions beforehand given the time constraints and the breadth of topics I wished to cover. This also logically required me to anticipate what each respondent was, and was not qualified to speak about. In this context, I would define the term 'qualified' as possessing enough objective experience with the subject matter to give an informed perspective, versus a surface level opinion on a topic with which the respondent may be familiar with, but has no real experience.

In general, I had few problems gaining access to high-level respondents. Obviously, some were more difficult to contact than others, and required some creativity which included spamming multiple email addresses, and even attending industry conventions where I could engage several desirable interviewees at the same location.

During the data analysis phase, I would say that I was always mindful of the 'directionality of analysis'. By directionality of analysis, I mean the balance of deductive versus inductive reasoning, and adopting a mid-level perspective where I entered the field study with a priori assumptions about the automotive industry, but was willing to modify that knowledge based on interactions with the primary data.

Nearing the end of this research project, I also had some trepidation about 'ending the study'. What compounded this was the very nature of the automotive industry, which is an ongoing treadmill of events that is covered by the media on a daily basis. Thus, it became somewhat difficult to identify a discrete endpoint where it felt appropriate to terminate the study, given the fact that events would continue to unfold with consequences that could not be captured by this study. Some examples of these events were the ongoing Volkswagen emissions scandal, and the effects that Brexit will have on the UK automotive industry.

Lastly, I would say that after having conducted semi-structured elite interviews, I would like to attempt to move beyond this method of primary data collection in my future research projects. There is some exciting new work being done using ‘big data’ (qualitative data from social media and other digital platforms) which I think can greatly advance the science of qualitative analysis (thematic analysis in particular), which seems to trail behind quantitative analysis in its sophistication and development over the years.

Chapter 3

Paper Title: Examining the role of policy design and policy interaction in EU automotive emissions performance gaps

Accepted and published manuscript in *Energy Policy* 104 (2017) 373–381

Abstract

In the wake of the 2015 'Dieselgate' scandal, the US and European governments publicly confronted automakers about their behaviour, which raised concerns about the integrity of the current emissions legislation regimes. In this article, I argue that 'flexibilities' within the EU's emissions legislative framework afforded automakers the opportunity to legally sidestep strict performance standards laid out in the law and resulted in a significant performance gap in real world driving emissions. This article provides a timely examination of EU emission legislation policy design and policy interaction within the European Union with the aim of explaining why the EU policy framework failed to regulate the regional automotive industry. Current research is mostly concerned with the typology and effectiveness of individual environmental policy instruments, be it regulatory or economic incentives, that aim to influence industry behaviour. This article approaches the current EU policy regime in a more holistic manner and focuses on the exploitation of weaknesses in the regulatory framework by private firms, which has received little academic attention in the innovation and transition literature. A major contribution of this article therefore is a body of primary qualitative interview data from industry elites concerning relevant emissions policies.

3.1. Introduction

European real-world automotive emissions have been fiercely, yet quietly, debated within the EU over the past decade (Oltra and Saint Jean, 2009), but gained international attention in 2015 when the United States' Environmental Protection Agency (EPA) alleged that the world's largest automaker, Volkswagen (VW), had equipped diesel passenger cars with software that circumvented the EPA's emissions testing standards for nitrogen oxides. According to the EPA, this software is classified as a 'defeat device' in the Clean Air Act, and VW 'failed its obligation to comply with the law that protects clean air for all Americans' (US EPA, 2015a; Volkswagen AG, 2015). The EPA would expand its investigation to include VW's subsidiary companies Porsche and Audi (US EPA, 2015b). In a chain reaction of events across the EU, top VW executives resigned, the company was stripped of prestigious industry awards, official inquiries were initiated, lawsuits were filed, recalls were made and the sale of VW diesel cars was banned in Switzerland and elsewhere. The 'Dieselgate' scandal itself is not the focus of this article, but merely an extreme example of similar practices found in the EU, where automakers chose to exploit EU emissions regulations. In this article I argue that as these exploits became 'best practice' among automakers, the EU's ability to enforce automobile emissions regulations began to fail, and this was further compounded by the unintended consequences of economic incentives within EU member states.

Despite the backlash against diesel, it is important to recall that this technology is part of a normative policy agenda, which focuses on reducing CO_2 as a means of moving society closer to the 'sustainable mobility'. Sustainable mobility is broadly defined as the ability to meet society's mobility and transport needs, without sacrificing the essential human or ecological values of present or future generations (Black, 1996; Goldman and Gorham, 2006; Nykvist and Whitmarsh, 2008). As it stands, the transport sector (road, aviation, waterborne and rail) produces approximately 25% of total global energy-related CO_2 emissions, and road transport accounts for 72.06% of those emissions (IPCC, 2014b). Fortunately, the continuing trend in decreasing roadside emissions appears to be sustained, and is being driven primarily by technological innovation (Fontaras and Dilara, 2012; Jaffe et al., 2005). Furthermore, the IPCC (2014b, p. 58) Fifth Assessment Report (AR5) found that the area of transport showing the greatest potential to meet 2050 greenhouse gas (GHG) emissions targets is the reduction of fuel carbon intensities in passenger cars and commercial vans. Given that diesel engines emit 15% less CO_2 than their petrol counterparts, it is understandable why diesel technology was deployed as an interim solution to lower road transport CO_2 emissions.

The article examines why EU regulations failed to enforce strict compliance by automakers, which resulted in millions of vehicles being unable to achieve their stated fuel efficiency figures in the real world. To explain this causal chain of events, I assess the significance of two policy variables and their role in the European Union's failure to implement real world automotive emissions targets:

(1) EU Regulatory Design of command-and control (CAC) policies deployed in the EU automotive sector, classified as general regulatory instruments; specifically the performance standard regulation (Bergek and Berggren, 2014) of Nitrogen Oxides (NO_x) and Carbon Dioxide (CO_2) tailpipe emissions. NO_x in the EU is regulated as a toxic emission under the Euro 1–6 legal frameworks, first introduced in 1993, and CO_2 is regulated under EU regulation (EC) No 443/2009, which was phased in between 2012 – 2015. These EU regulations mandate that automakers meet a certain level of emissions based on a fleet average, yet numerous industry reports (ICCT, 2015; Transport & Environment, 2015a) have revealed that there is a significant gap between emissions reported by automakers and actual real-world performance figures. This article therefore examines the policy mechanisms that were established to prevent such occurrences.

(2) Policy Interaction between EU CAC policies and EU member state market based instruments (MBIs), incentivising low-carbon emissions and diesel in particular. Policy interaction is significant because policies are often crafted in isolation, and as will be shown, there are sometimes unintended consequences when multiple policies take effect on a market.

Section 2 provides a brief overview of CAC regulation and policy interaction research in academic literature, specifically technology-forcing literature, as new innovation is the primary desired outcome of CAC policy interventions. I argue that while the technology-forcing nature of environmental CACs has been extensively covered in previous research, the exploitation of poorly designed regulations has received little academic attention in environmental policy, innovation and transition literature. Section 3 provides some background industry context to important events leading up to 'dieselgate' and Section 4 lays out the methods used in this article. Section 5 presents the main findings and Section 6 discusses the central problematique which is: How were automakers able to skirt the EU's strict performance standards for reducing emissions in road cars? Section 7 brings the discussion to a close by arguing that stringent EU environmental regulations, if poorly designed, will be exploited by industry stakeholders, and in this case, the consequences of poor design were compounded by economic policies implemented at the member state level.

3.2. Theoretical underpinnings

Since the 1960s, OECD countries and emerging economies have sought ways to encourage the development of technologies to reduce pollution (Bergek and Berggren, 2012). The two most widely used policy instruments are strict CAC environmental regulations and MBIs (ibid). CAC policies are regulations that force producers to change their behaviour, while MBIs provide financial incentives to private firms and consumers in exchange for shifts in their behaviour (Santos et al., 2010), for example tax reductions, exemptions and bonus payments. Informal regulation such as independent fuel economy tests carried out by car magazines also adds to the complex policy environment.

3.2.1. Command-and-control regulations

CAC regulations are a technology-forcing strategy where the regulator sets an objective for the future that cannot be met by employing existing technologies (Nentjes et al., 2007; Tarui and Polasky, 2005). CAC policies generally regulate in two different ways: performance-based regulations (performance standards) and technology-based regulations (technology standards). A performance standard is the preferred approach when the goal is to induce technological innovation, because the only requirements are target performance outputs and how they are achieved is up to the individual firm (Jaffe et al., 2005; Lee et al., 2011). For this reason, Van Bree et al (2010) argue that this style of regulation has the added benefit of limiting a government's ability to 'pick winners' in the marketplace, which is what generally happens when technology-based regulations are deployed. Picking winners is any industrial intervention by governments to promote the growth of particular technology based on an innovation strategy for sectors of national importance. In this case, an emission standard for the automotive industry based on CO_2 emissions is technologically 'agnostic', because in theory, petrol, diesel, electric and hybrid propulsion technologies all have an equal opportunity to meet the specified target. The reality however, is that EU regulations for toxic emissions are relatively laxer than those for CO_2 and hence diesel engines have an easier time hitting emissions targets than their petrol counterparts. For the practical reason that the EU does not use technology-based policies to regulate road transport emissions, they were not considered in this article.

3.2.2. Policy Design

The literature indicates that the impacts on innovation of individual policy instruments are more influenced by their inherent design features, than by the particular instrument type deployed (Bergek and Berggren, 2014; Kemp and Pontoglio, 2011). This article examines regulatory stringency and predictability as key environmental policy design features and assesses their influence on the EU's ability to effectively implement emission control legislation. While regulator legitimacy is also a crucial factor in the implementation process of technology-forcing strategies (Kemp, 1995; Kleit, 1992; Rogge et al., 2011), the focus here is solely on endogenous aspects of regulatory design in the form of stringency and predictability as determinants in influencing industrial activity and policy outcomes. If regulator legitimacy had been considered, these findings and recommendations would have been much more context-specific and less widely applicable.

3.2.2.1. Predictability

Despite a government's best intentions, technology-forcing regulations by their very nature create uncertainties about the likelihood of technological breakthroughs, the various costs involved and ultimately, the effectiveness of a new technology (Leone, 1999). Uncertainties include reliability, unanticipated environmental impacts and the possibility of being locked-in to an inferior technology. There are also opportunity costs associated with forcing firms to invest in R&D via regulatory compliance, as this may crowd out other promising technologies (Gerard and Lave, 2005). Thus, predictability accounts for the degree of certainty associated with a policy instrument in present and future scenarios, and is especially relevant for capital intensive sectors (Rogge et al., 2011) like the automotive industry. This article focuses on the time horizon for regulation compliance as the key factor of predictability (Kleit, 1992). Research shows that if compliance dates are set aggressively short, firms tend to favour 'end-of-pipe' solutions rather than meaningful technological transitions. If time horizons are overly generous (open ended with no set re-evaluation date), then information gaps between regulators and firms grow, and the compliance deadline runs the risk of being indefinitely extended (Kemp, 1995). Firms have been known to lobby regulators in order to delay or rescind a standard because firms typically possess more 'information' about their own technological capabilities than regulators. Firms can then exploit this information asymmetry by hiding their true innovative capabilities, underinvest in R&D and claim that regulatory targets cannot be met (Kleit, 1992).

3.2.2.2. Stringency

Regulations are a driver for realizing technological innovation (Gerard and Lave, 2005; Yang et al., 2012) and regulatory design, in particular regulation stringency, has been empirically linked to motivating firms to innovate. This article focuses on stringency as the other key policy design element. Stringency specifically has two prerequisites, (1) absolute reduction of harm to the environment and (2) compliance using existing technologies is impossible or too costly (Oltra and Saint Jean, 2009). Caution must be exercised, however, as overly stringent CAC policies run the risk of being unattainable, as it is difficult to know beforehand how much innovation a policy can ‘force’ (Lee et al., 2010).

‘Technology-forcing’ is complex as it involves interactions between firms and governments; specifically how regulators influence firms to invest in R&D. Firms are more likely to invest in R&D when regulators are committed to enforcing the regulations (Nelson and Winter, 1977; Nentjes et al., 2007). Ideally, governments are encouraged to adopt fail-soft strategies, where if firms in good faith fail to meet the standards set, they are not punished for non-compliance. While technology-forcing can lead to innovation, outright hostility between industry and government must be avoided (Schot et al., 1994; Vogel, 2003). Relaxing stringency CAC regulations can result in firms relaxing their own innovative efforts and causes them to extend their R&D over a longer timeframe (Dijk and Yarime, 2010).

3.2.3. Policy Interaction

While many studies examine policy instruments in isolation, others suggest that policy instruments are most effective when embedded in an appropriate policy portfolio comprising both economic and regulatory instruments (Bergek and Berggren, 2014). A variety of instruments, regulations, taxes and subsidies; deployed in a credible and consistent manner, are especially effective in encouraging firms to develop technologies that reduce CO_2 emissions (Veugelers, 2012). A contemporary example would be Holweg’s (2014) examination of the UK Automotive Council’s more holistic, government-industry strategy for innovation by way of R&D support, technological roadmaps, nonfinancial incentives and precompetitive strengthening of industry. However, a common complaint about the coordinated use of various policy instruments, or 'policy mixes', is that the actual process of integrating and synergising policies is given little attention (Foxon and Pearson, 2008). Interactions between policies are either 'black boxed' or relegated to exercises in design 'by way of better coordination'. Policy studies could remedy this by highlighting trade-offs and tensions within policy mixes and openly debate the contending issues (Flanagan et al., 2011). Consequently, this article highlights these trade-offs by examining the interactions between EU emissions legislation and relevant EU member-state economic policies.

3.2.4. Command-and-Control policies in the EU automotive industry

In the automotive industry, research shows that emission technologies are driven by technology-forcing policies. These regulations not only forced the introduction of emission control systems[6], but also advanced their development (Lee et al., 2010). Research (Oltra and Saint Jean, 2009) also suggests that the absence of regulation (or presence of lax regulations) hampers innovation substantially. Thus the technology-forcing approach appears to successfully stimulate the development of cleaner automobiles (Schot et al., 1994).

Initially in 1995, the European Commission's (EC) proposal to reduce CO_2 emissions was based on a set of voluntary commitments from automakers (Creutzig et al., 2011). However, while there was some decrease in emissions, especially in France, average global emissions rose by 20% between 1990 and 2006. At this point the EC decided that binding regulations were necessary to correct these levels of negative environmental impacts (Oltra and Saint Jean, 2009). In 2007 the EC issued a proposal to replace the voluntary scheme with a mandatory standard of 130g CO_2/km. The auto industry collectively argued that the regulatory targets were not feasible, and after some negotiations, all parties agreed to stagger the emissions mandates as follows: 65% of an automaker's fleet would have to reach the target by 2012, 75% by 2013, 85% by 2014 and 100% by 2015. The Commission also set a new target of 95g/km by 2021 (Plotkin, 2009; Shiau et al., 2009). These EU regulations are less stringent than those in the U.S. and Japan in restricting particle matter and NO_x emissions and is the primary reason why Europe has become the lead market for diesel vehicles and diesel technology development (Oltra and Saint Jean, 2009). The EU regulations are also more flexible regarding the means by which a firm complies and the time

[6] The Catalytic Converter is one popular example.

horizons for compliance to be met. While EU emissions regulations may have a reduced technology-forcing effect, they still encourage continuous innovation and reduce levels of pollution without invoking a ‘dominant design’ (Oltra and Saint Jean, 2009).

Fuel economy and GHG performance standards have proven to be some of the most effective tools in reducing oil demand and GHG emissions globally (Atabani et al., 2011). At their core, environmental regulation frameworks exist to ensure the transition to a market which includes discontinuous (low-emission) technologies (Brown et al., 2010). CAC regulation has been responsible for reducing the sulphur content in petrol and more importantly, the phasing out of leaded petrol in many countries, Europe included (Santos et al., 2010). In fact, if European fuel efficiency regulations were abandoned, it is estimated that a 50% increase in fuel taxes would be necessary to induce similar fuel savings (Clerides and Zachariadis, 2008). Therefore, given the importance of policy design, predictability, stringency and interaction, these four indicators will be used to structure the analysis of the results in Section 5.

3.3. Background: EU preferential treatment of diesel and the real-world emissions gap

Before the events of 2015, there was already an atmosphere of contention between governments and the automotive industry across Western Europe as politicians, institutions and other stakeholders became more vocal about diesel engine technology and the compromises being made to air quality in the name of lower CO_2 emissions. In late 2014, diesel came under fire from French Prime Minister Manuel Valls when he conceded in a speech that France had long favoured the diesel engine and while that was a mistake, he was committed to systematically dismantling those preferences (Bruce, 2014). This was significant given the fact that the French government owns approximately 20 percent of the French carmaker, Renault (Renault Press, 2015). In early 2015, Shadow Environment Minister Barry Gardiner of the UK's Labour Party echoed those sentiments when admitting that the previous Labour government's decision to base the country's car taxes on CO_2 output was misguided because it had the unintended effect of skewing the market in the favour of diesel cars (Turkus, 2015).

In 2001, Gordon Brown, then UK chancellor, introduced a tax incentive for diesel cars based on their lower CO_2 emissions. It is important to note however, that diesels emit four times more NO_x

and 22 times more particulate soot than petrol cars. According to a study by the Greater London Authority and Transport of London, diesel exhaust is a major contributor to the dangerous levels of air pollution in London that prematurely kills approximately 9,500 people each year (Walton et al., 2015). The London Assembly also estimates that diesel vehicles account for 40% of the capital's air pollution (BBC, 2015). MP Gardiner has subsequently gone on record to state: 'Hands up, I can say there's absolutely no question that the decision we took was the wrong decision, but at that time we didn't have the evidence that subsequently we did have and we had cleaner diesel engines, which we thought meant that any potential problem was a lower grade problem than the problem we were trying to solve of CO_2.' He also claimed that the incentives given for diesel represented the 'right move away from those vehicles who were pushing out CO_2 emissions,' but conceded that: 'Certainly the impact of that decision has been a massive problem for public health in this country' (Owen and Merrill, 2015). Throughout London, progressive local councils, including Camden, Kensington and Chelsea were already placing additional annual charges on older diesel vehicles of up to £18.

In 2015, the UK auto industry conveyed its disappointment at the 'blanket' crackdown on diesel cars, with many in the industry describing it as the 'demonization' of diesels. CEO of the Society of Motor Manufacturers and Traders (SMMT) Mike Hawes defended diesels by saying: 'Blanket polices which fail to distinguish between modern clean [diesel] vehicles and decades-old technologies are not the solution.' He also added: 'The decision to impose new financial penalties on diesel owners who bought their cars in good faith is unreasonable and demonstrates a concerning lack of understanding about the huge technological advances that are already making diesel vehicles cleaner' (Owen and Merrill, 2015). Retroactive anti-diesel legislation is a legitimate concern for used car buyers given that used cars in the UK accounted for 51% of all sales in 2014 (Forbes, 2016), and increased by another 8% in 2015 (BBC, 2016).

Up until this point, the debate over diesel in the EU was mainly between automakers and lawmakers, but in early 2015, Transport and Environment, a sustainable transport NGO, released a series of scathing reports on the European auto industry. These reports (along with data from the International Council on Clean Transportation) exposed the widening gap in the claimed CO_2 and NO_x emissions and addressed the newly proposed World-Harmonized Light-duty Vehicle Test Procedure (WLTP) and Real Driving Emission (RDE) testing procedures to rectify these problems.

They revealed that the gap between test results and real-world performance in CO_2 emissions grew from 8% in 2001 to 40% in 2014 and was projected to grow to 50% by 2020 if left unchecked (Transport & Environment, 2015a). Moreover, the average diesel engine released NO_x emissions 7 times over the regulatory limit (Transport & Environment, 2015b). It should be noted too that independent publications and car magazines have consistently flagged discrepancies in advertised fuel economy estimates by automakers (Consumer Reports, 2013).

After ‘Dieselgate’ exploded that same year, the French government began discussions about reducing or even outright eliminating diesel subsidies which make it nearly U.S. 90 cents per gallon cheaper than gasoline. The French Environment Minister Segolene Royal is quoted as saying ‘It’s obvious today that there’s an inconsistency between the advantages given to diesel and its drawbacks in terms of pollution.’ The strategy being discussed would raise taxes on diesel while lowering taxes on gasoline ‘to neutralise the difference’. The under-taxation of diesel has helped it become one of the dominant technologies in Western Europe. One can imagine the impact that such a reversal in policy would have and according to the CCFA, the French automaker association, nearly 68% of all cars on French roads are diesels (Rosemain, 2015).

In the UK, Lord Drayson, former Labour science minister in the Brown government from 2008-10 admitted: ‘We did get it wrong. We now have a much better understanding than we did just a few years ago of what are the health effects of the products of diesel cars and they are literally killing people so it’s clear that in retrospect that was the wrong policy’ (Kollewe, 2015). Overall, this change in attitude among European policy makers is problematic for the EU’s largest automakers which include two French state-backed companies and the German ‘big three’ (BMW, Daimler AG (Mercedes) and Volkswagen). According to an industry report, the ‘diesel mix’ – diesel vehicles as a proportion of total sales in Europe – in several EU states ranges between 70%-80% among these automakers, rising to 90% for Volvo (Sharman, 2015).

3.4. Methods

Research in the transport sector frequently makes use of qualitative methods for inductive purposes, as it permits the identification of concepts and interpretations from the respondent’s perspective (Gardner and Abraham, 2007; Steinhilber et al., 2013). This article applies qualitative methods with the intent to capture relevant themes from the perspectives of automakers, regulators and other industry stakeholders based on their experiences. It then becomes possible to establish linkages between collections of different sets of knowledge within the automotive industry.

The primary sources of data for this article were collected through recordings of semi-structured elite interviews with key industry decision-makers within the automotive sector. These respondents were based in the UK, US, Germany and Belgium, and were selectively targeted for their opinions on how the automotive industry has responded to current EU emissions legislation and the persistent real-world performance gap in emissions. **Table 1.** lists the elite respondents interviewed during this study.

Interviewees were specifically selected (non-probability sampling), and in this case, a combination of purposive and chain-referral sampling which allowed for the inclusion of key institutional actors in the data gathering process (Tansey, 2007). In accordance with the ethics approval guidelines of this study, express permission was granted before the recording of each interview, participants were guaranteed anonymity and were assured that recorded data would be destroyed in accordance with the UK's Data Protection Act 1998.

Recorded interviews were transcribed and thematically coded using the Template Analysis method, which gives an account structured around central themes that have emerged, and draws on examples from interview transcripts as required (King, 1998). The conclusions of this article are meant to provide a robust overview of problem areas within the EU's current regulatory framework, highlighted by this study's participants, along with possible avenues of redress.

Table 1.

List of interviewees

Institution / Organization	**Title / Department**
Advanced Propulsion Centre (APC)	Senior Executive, Business Development
Advanced Propulsion Centre (APC)	Executive, Marketing and Events
Qualcomm	Senior Executive, Business Development
Ford Motor Company UK	Former Chairman
Ford Motor Company	Senior Executive, Global Vehicle Evaluation &Verification
Office for Low Emission Vehicles (OLEV)	Senior Executive, Regulation, R&D and Procurement
Office for Low Emission Vehicles (OLEV)	Senior Management
Major Tier 1 Supplier	Chief Engineer
European Commission	Policy Officer, DG Climate Action
European Commission	Unit Senior, DG Climate Action
Society of Motor Manufacturers and Traders (SMMT)	Senior Executive
BMW	Senior Executive, Government Affairs
BMW	Senior Executive, Government Affairs
Jaguar Land Rover	Senior Executive, Research and Technology
Motorsport Industry Association (MIA)	Senior Executive

3.5. Results

This study took place between 2014 and 2016 in the midst of the ongoing VW diesel scandal. Interviews were conducted with senior members of the European automotive industry, the UK Government and the EC. The relevant issues they raised are discussed below.

3.5.1. Policy Design - Predictability

At the broader level, the EU regulatory framework provides a measure of certainty and stability for the region's member states, as evidenced by the direct application of EU emission performance standards to the UK domestic market. Also, the EU model of performance standards is mirrored in UK Government-Industry collaborations like the Advanced Propulsion Centre (APC), where national innovation competitions focus on 'technology agnostic' low-carbon innovations that meet future EU emissions targets (APC, 2016). Caution should be observed, however, when considering UK Government-Industry collaborations. Many automakers operating in the UK are part of larger multinational groups, and these organizations have demonstrated their willingness to leave the UK and seek lower costs in overseas territories.

Timescales attached to emission regulations were used as a measure of certainty for the industry and a clear indication of the direction the industry is expected to move. Targets are set out to 2050 with a final expectation of 80%-95% reduction in the EU's road transport emissions. This timescale is incremental, with the next CO_2 performance target set for 2021 at 95 grams of CO_2 per kilometre (European Union, 2014), so there is no ambiguity about what is expected from automakers and when it is expected. The eventual phase out of government incentives for electric vehicles in the UK (GOV.UK, 2017) and Norway (Lambert, 2016) is another example of how automakers are being encouraged to continue the development of affordable, low-carbon vehicles in a time-sensitive manner.

Incremental timescales set by EU regulators appear to encourage incremental rather than radical innovation. This incremental approach affords automakers additional certainty as they progress towards the emissions targets that have been set. According to one EU regulator:

> I think it's more likely that manufacturers will innovate incrementally rather than radically for a number of reasons. It's much easier for manufacturers to adapt their manufacturing processes in an incremental manner than in a radical manner. Evolution is what you see

> throughout the industry in the past, it's much less risky for them. If you imagine putting a battery electric vehicle on the market, you have no idea how many people are going to buy it. You can make some predictions, you can carry out lots of market research, but at the end of the day, you don't know what will happen. And we've seen this from lots of OEMs (Original Equipment Manufacturers or Automakers) they have very different perspectives on how this market will develop, and frankly they will tell us that none of them really know.

While radical innovation has always received a normative primacy in socio-technical transition scholarship (Geels, 2012; Hoogma et al., 2004; Kemp and Pontoglio, 2011), I argue that incremental innovation offers regulators the crucial opportunity for policy learning (Flanagan et al., 2011), also referred to by EU regulators as 'learning by doing'. Policy learning affords regulators the opportunity to redress unforeseen outcomes and reduce the chances of the sector becoming locked-in to a suboptimal technology. An example of this is the EC's multiple research probes into the current performance gap problem in an effort to prevent the issue from plaguing the new WLTP test procedures. These independent studies increase the Commission's knowledge and the likelihood of crafting more effective policies in the future.

Despite the reality of long development cycles and extended platform lifetimes, OEMs appear to still be mindful of regulatory time horizons, which in this context are synonymous with emissions target figures of '95 grams of carbon by 2021'. These are the current 'magic numbers' within the European automotive industry, as illustrated by a top tier executive within BMW's leadership, defending diesel on the basis of achieving time-sensitive emissions targets:

> First of all, diesel technology has, and will continue to, improve. It will also in the future have a considerable edge in terms of efficiency and CO_2 emissions over gasoline engines. So can we afford not to use diesel to the highest degree as an option for CO_2 reduction? If we are talking about targets like 95g by 2020, I think we can't.

3.5.2. Policy Design - Stringency

Stringency has always been cited as crucial to the technology-forcing nature of CAC regulation (Lee et al., 2010; Oltra and Saint Jean, 2009), and currently, manufacturers are obliged to attain a fleet average of 120g CO_2 / Km regardless of what kind or combination of technologies is used to achieve it. According to one EU regulator:

> I think the regulations force manufacturers to deploy CO_2 reducing technology in the widest sense of what technology is, because of course vehicle light-weighting is also a CO_2 reducing approach. So while it forces the deployment of CO_2 reducing technologies, it doesn't oblige or force any particular technology.

EU regulations are also perceived as significantly stringent by the European automotive industry as a senior executive of a major UK automotive trade association explains:

> If you look at the regulations around CO_2, if you don't hit your CO_2 targets, as a manufacturer, the fines are absolutely punitive, so it's just not an option not to hit them, because its hugely expensive.

Currently the EU fine (Excess Emissions Premium) for each car registered is €5, €15, and €25 for the first, second and third g/km of exceedance respectively and €95 for each subsequent g/km. From 2019, however, the fine will be €95 from the first gram of exceedance onwards (European Commission, 2016).

Stakeholders vary on exactly how stringent these regulations should be, given their individual interests, but it is perceived as a delicate balance. A senior member of a UK government transport department stated that it was a question of how aggressively CO_2 reductions in transport emissions were set by government. In his opinion there is a 'sweet spot' in regulation, where you are forcing manufacturers to innovate and to bring the vehicle to market, without unreasonably driving up the price of the vehicle, and causing the OEMs to incur financial losses. What is evident is that the entire industry recognises EU regulation targets as the ultimate goal. According to a representative of the Advanced Propulsion Centre:

> If I'm being completely honest, I'll go back to the classic quote 'necessity is the mother of all invention', it's been EU regulations, in my opinion, that drives everything. I mean now we've got to hit a certain level of CO_2 for cars and that drives OEMs.

This sentiment is particularly interesting as it was expressed before the European Referendum vote, and it remains to be seen how influential EU regulations will be in the 'post-Brexit' UK domestic market. Brexit is especially relevant since the UK imports 59% of the components used for vehicle assembly from the EU. Of the vehicles manufactured in the UK, 77% are exported, 57% of which are destined for the EU continent (SMMT, 2016a).

3.5.2.1. Lack of stringency

Lack of stringency also emerged as a theme alongside that of regulatory stringency among respondents. Based on the data, lack of stringency or lax regulation appears to have an inverse relationship with the technology-forcing effects of CAC policies, which has been echoed in previous research (Schot et al., 1994). The following quote from an EU regulator illustrates the problem:

> Everything else being equal, pollutant emission standards for diesel have been laxer than for petrol in the past. That was a political choice that was made by people setting those standards. And, on top of that, the real world pollutant performance of diesel engines was much worse than was established in the tests. And that is something that has been well known for quite some time.

In speaking with regulators, the issue of political will to amend EU legislation regarding the preferential treatment of diesel was also apparent. While the implications of political will on EU regulation setting is not within the purview of this article, it has certainly flagged itself as worthy of further academic consideration. The consequences of lax regulations are severe, not only for environmental and human health, but at the regulatory level, it encourages a type of behaviour from firms that goes beyond what has generally been discussed in environmental policy literature. This behaviour endangers the entire framework and can only be described as exploitive. Here is an EU regulator discussing these actions in the context of 'Dieselgate':

> To go back to the mantra about deregulation and light-touch regulation and so on. What you see with the Volkswagen case is how damaging it is to not have effective regulation. I mean, the cost of this single incident to Volkswagen is going to exceed I would imagine any estimate of what proper regulation would have cost the industry.

3.5.2.2. Exploitation of flexibilities

When firms face an incentive to reduce pollution, this simultaneously creates an incentive to find the cheapest way to reduce that pollution (Jaffe et al., 2005). So it was expected that faced with lax regulations, firms would adopt a ‘strategy of least compliance’ where the regulatory requirements are met ‘at as low a level of compliance as the regulation allows’ (Wells and Nieuwenhuis, 2012, p. 1685). This usually meant a decrease in innovative efforts, however, this study began to uncover a previously obscured form of industry behaviour, incited by lax regulations. This quote from a senior executive of a UK automotive trade association describes the situation:

> You probably noticed that the emission figures that are being sold by automotive companies are false, the tests that they’ve created were weighted to make them sound better than they really were; those things conspire to change government opinions because once your electorate is dying of emissions, you know particulates, suddenly the government are not on the side of automotive.

It became evident that automakers had taken a step beyond the ‘strategy of least compliance’ and were actively exploiting regulatory allowances in the testing procedure, known as flexibilities, to their benefit. (Regulatory) flexibility has been defined as an important degree of room for manoeuvre in the implementation of laws and regulations in order to establish a viable technological base (WIPO, 2010). The following comments are from an EU regulator concerning the current state of flexibilities in EU automotive emissions legislation:

> The fact that you have a system where firstly the manufacturer comes along, he declares the results of his test, he shows them to the technical service who approves it or not, the technical service is paid by the manufacturer, so they have no incentive to disagree. The manufacturer can shop around to another one if he doesn’t get the results he wants with the people he’s working with, there’s no verification by anybody else of these results, the conditions of the vehicle are secret, so nobody else can actually find out the values to check themselves whether the vehicle complies. I mean it is completely, fatally flawed. And this of course has led the industry to believe they could happily ignore the rules, because nobody was ever going to find out. And this is exactly what you see, and this is the result – and now this is my political interpretation – you’ve had this deregulatory push for the

> last 10 years, everyone was like ‘regulation, bad thing’ you know ‘light touch, leave the industry, they’ll sort it out’, and this is what happens. They don’t sort it out, they cheat.

3.5.3. Policy Interaction

Policy interaction as a theme emerged when stakeholders began to discuss what they described as the vilification of diesel. In no uncertain terms, many respondents from industry indicated that they felt as if the government had encouraged them to produce and sell diesel vehicles given the policies put in place, and now diesel was suffering a tremendous backlash. Events in 2015 such as the UK Supreme Court’s ruling that government must take immediate action to curtail air pollution and the ‘Dieselgate’ scandal conspired to bring diesel technology as a whole under severe scrutiny. During this study, policy interaction was found to compound the air quality problem in the EU. The major source of this policy interaction came from EU emissions legislation interacting with technology-specific economic instruments, implemented by EU member states, to specifically favour the low-carbon benefits of diesel technology. An EU regulator explains the problem as follows:

> The reason many people buy diesel cars is because they’re cheaper to run, one of the reasons they’re cheaper to run is because diesel is undertaxed, that’s a decision by member states, the EU has tried to reform fuel taxation and the member states have rejected that, despite the commission’s proposals saying ‘this is not right’.

The discussion of these national economic incentives is often associated with political interests. In the opinion of EU regulators, diesel should be more expensive because it has a higher energy density than petrol. However, respondents pointed out that in most member states, diesel is taxed at a much lower rate than petrol and, in their opinion, there was no obvious justification for that choice. They acknowledged that in the past, the under-taxation of diesel was driven by the economic logic that diesel was primarily being used in heavy goods vehicles and that taxes should not be applied an intermediate product, which was economically inefficient. Given that diesel is now as much used in cars as in commercial vehicles, regulators believe that argument has lost its validity. Regulators find it rather difficult to amend these preferences at the EU level, because member states choose to leave them in place. Respondents found these subsidies to be ‘a fundamental problem.’

The preferential treatment of diesel through economic incentives such as the under-taxation has created a market pull effect and explains their popularity in Europe. Thus at the EU regulatory level, automakers were producing cars with widening real-world emissions gaps, while at the national level, the EU member states had created a significant demand for these same vehicles, creating a lock-in effect to a sub-optimal technology (Dolfsma and Leydesdorff, 2009).

3.6. Discussion: How were automakers able to skirt the EU's strict performance standards for reducing emissions in road cars?

This article has examined policy design and policy interaction to understand the possible causes of the real-world performance gap in EU road emissions, as it is well-established that these are key determinants of effective technology-forcing regulations within the automotive industry (Bergek and Berggren, 2014; Flanagan et al., 2011; Gerard and Lave, 2005; Lee et al., 2010). I have argued that the main cause of real-world emissions performance gaps was a structural failure in the policy to enforce strict adherence by OEMs. Several key factors contributed to this legislative breakdown, notably the lack of stringency via exploitation of flexibilities by automakers. There was also an unforeseen compounding effect on air quality caused by policy interaction between diesel under-taxation, which created a national market pull effect and a flawed regulatory push for lower CO_2 at the EU level. This began to initiate a lock-in effect (Dolfsma and Leydesdorff, 2009; Witt, 1997), which in this case was the mass diffusion of over-polluting diesel engines in European Domestic Market (EUDM). Diesel, which at one time seemed promising, is now crowding out more potent technologies which had not previously been considered (Bergek and Berggren, 2014; Jaffe et al., 2005).

While exploitation of the rules by firms has not been given much attention by transition scholars, I believe this article sufficiently demonstrates that it becomes an inevitability when environmental policies contain too much 'wriggle room' in the form of flexibilities. Whilst not all manufacturers fitted defeat devices into their vehicles, no manufacturer has been able to meet its emissions targets in real world driving conditions. Interestingly, some OEMs have been seeking alternatives the official regulatory regime: PSA in a collaboration with NGO T&E, jointly developed an independent CO_2 testing procedure, which they claimed was more representative of real world emissions than the upcoming WLTP testing standard (Transport & Environment, 2016). It should be noted that the European Environment Agency published a report in 2016 mirroring the core findings in this article, however, they came short of using the term 'exploitation' and chose to describe the automakers' behaviour as 'optimising testing procedures' (EEA, 2016).

This article found that flexibilities in regulations erode the second 'law' of stringency, which states that compliance with existing technologies should be either impossible or too costly (Oltra and Saint Jean, 2009). Flexibilities in EU legislation revolves around the type-approval test procedures and an EU regulator describes his revelation in the following manner:

> It was only when we did our study on the test procedure flexibilities that we realised what was actually more important was *how* you carry out the tests rather than *what* the test itself is, and that's where all the flexibility was and where the car industry probably intended for there to be a whole load of new flexibilities in the new test procedures.

The result is that these flexibilities effectively render the policy instrument benign. Interestingly, the literature warns that if regulations are too stringent, there is the potential for hostility between OEMs and regulators (Schot et al., 1994; Vogel, 2003). Ironically, in the case of the EU real-world emissions gap, it was the absence of stringency that resulted in hostilities between parties. These hostilities stem from automakers exploiting flexibilities to their maximum legal limits at best, and engaging in purposeful deception at the worst, as was the case with VW. A point of interest is that over the years, cars have been 'loaded' with various amenities aimed at the consumer, which are not mandated by regulation. By adding weight, many of these non-essential extras are inconsistent with other key performance metrics such as acceleration, fuel economy, weight reduction and energy efficiency, thus it would appear that part of OEMs' difficulty in hitting emissions targets is self-inflicted.

There have been occasions where these flexibilities could have been decisively corrected upon the recommendation of the EC. As early as 2011 the Commission raised concerns about 'unexplained progress' in one of its reports assessing the revision of Regulation (EC) No 443/2009 (European Commission, 2011). A year later, a pair of reports detailing the Commission's findings on CO_2 test flexibilities (European Commission, 2012a) and their recommendations on actions to be taken (European Commission, 2012b) were published, but there has been no visible evidence of reform to date. Respondents often suggested that national interests and lack of political will among EU member states have resulted in the continuation of the status quo, but further analysis is required to support these assertions. Political red tape highlights one of the cited criticisms of CAC regulations, which is that policies must be constantly revisited in order to set new targets and influence new levels of innovation (Santos et al., 2010). This political wavering on the behalf of the legislators potentially dilutes the potency of the next round of performance standards. While the effects of national interests on EU legislation falls outside of this study's research mandate, the correlation between political will and exploitation by industry is fertile ground for future study, particularly if it were approached from the perspective of regulatory capture (Dal Bó, 2006).

In the aftermath of the 'Dieselgate', Germany, Austria, Spain, Italy and most Eastern member states remained reluctant to support stricter limitations on diesel vehicle emissions. Eventually a compromise deal was reached between the EC and member states, and as of 2017, new diesel cars will be allowed to exceed the NO_x pollution limit by no more than double and as of 2019, that excess amount would be further reduced to no more than 50%. US EPA regulators, in consultation with the European Commission and MEPs ahead of the European Parliament's vote, are quoted as saying that 'a standard and rigorous set of test cycles is also meaningless unless you have the authority, the resources and the will to enforce'(Stupp, 2016a).

Simultaneously, the EC proposed a draft that would give them new powers to oversee the manner in which national authorities go about approving new vehicles, akin to the EPA's powers in the US. Under the new proposal, offenders could be fined up to €30,000 per offending vehicle found in the EU. This petition came amid reports (Stupp, 2016b) that the Commission felt limited in its ability to enforce, as member governments are primarily responsible for the implementation of legislation, as compared with the more autonomous EPA in the US. Despite being beyond the scope of this article, the theme of regulator legitimacy arises here and rightfully merits further academic investigation, in particular the relationship between regulator legitimacy and regulatory stringency. The EC's technical proficiency had been called into question by some (Stupp, 2016c), while the EPA was praised for uncovering the 'Dieselgate' scandal in the US. For the record, it should be noted that 'Dieselgate' was uncovered by independent scientists at the University of West Virginia (Thompson et al., 2014) who were conducting research on real-world emissions and subsequently handed their findings over to the EPA. Therefore, the EPA's failure to uncover VW's wrongdoing should also be a cautionary tale to the EC, that even enhanced organizational autonomy does not safeguard against chronic regulatory failure.

This study also found that EU member states failed to maintain a competitive balance by subsidising diesel (Dolfsma and Leydesdorff, 2009), and encouraged increasing returns to adoption that favoured the technological lock-in to diesel vehicles (Oltra and Saint Jean, 2009; Sandén and Azar, 2005). Aside from crowding out more optimal technologies (Dijk and Yarime, 2010), this increase in adoption of diesel vehicles, incentivised by the state, had the unforeseen effect of compounding air quality degradation in Europe.

3.7. Conclusion and Policy Implications

The successful regulation of road transport emissions in the EU has faced major challenges recently and while many of the highlighted issues in this article have been ongoing for years, the 'Dieselgate' emissions scandal has brought the entire EU legislative framework under sharp scrutiny. The role of academia and civil society must also be acknowledged, as several damning reports on the industry exposed how performance gaps were being created by the exploitation of flexibilities in the regulations by automakers. This resulted in deception and damage to the environment's air quality, which has significantly contributed to the deterioration of public health in the EU (Walton et al., 2015). The growing backlash against diesel in Europe now appears to be an attempt by policymakers to reverse the longstanding preferential treatment that diesel has received from EU member states.

This study identified the major contributing factors of policy failure to be lax regulation and the exploitation of flexibilities by automakers, resulting in the EU being at risk of being locked-in to a suboptimal, diesel engine technology. One of the obvious solutions to the problems plaguing the EU regulatory landscape would be to simply close all known flexibilities in future test procedures. In reality, however, several member states, with vested interests in supporting their domestic automakers, would have to agree to any such revision of the regulations. Even if a member state retroactively eliminated preferences of a particular technology like diesel, it would ultimately punish millions of consumers who bought into the government's economic incentives to buy diesel vehicles. Granting the European Commission additional oversight powers to intervene at the national level would also go a long way towards resolving some of these problems, but that too would require sponsorship from the European member states. Therein lies the fly in the ointment.

From an industry perspective, future EU emissions targets will be modulated down to a point where achieving targets with an internal combustion engine will become virtually impossible, which is the whole point of the regulations. However, innovation is not free and thus the ‘costs’ of these regulations are of perpetual concern to OEMs. As the EC continues to conduct detailed cost studies, research has shown that between 1995 and 2010, regulations have not increased the per unit cost of new cars and that on average, their quality-adjusted price has remained unchanged (Wells et al., 2013). With regards to present-day technology, EU regulators’ cost curves estimate that another 50% to 60% efficiency can potentially be extracted from the internal combustion engine compared to 2013 technology (European Commission, 2008).

At a higher level of abstraction, some contend that merely swapping propulsion technologies is insufficient to bring about meaningful change, much less sustainable mobility to society at large (Banister, 2011; Geels and Kemp, 2012). While cleaner propulsion fails to address the larger issue of private ownership of automobiles, I maintain that technology (radical or incremental) is the main element of present-day sustainable mobility. Another overarching concern is the current EU emissions legislation regime, which has arguably been focused on lowering CO_2 emissions to the exclusion of other issues. This is apparent in statements from respondents, and the ‘backpedalling’ by several EU policymakers, in response to the impact that diesels are having on air quality. While the low-carbon regulatory approach has been critiqued by some (Hawkins et al., 2013), the policy framework and government-industry shared vision on low-carbon innovation remains unchanged. This article contributes to the burgeoning literature demonstrating that the EU’s low-CO_2 policy focus suffers from bounded vision and that it needs to be reformed to embrace a more holistic energy-efficient outlook on innovation.

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Chapter 4

Paper Title: 'Racing improves the breed': The obscure link between Motorsport and Low-Carbon Innovation

Submitted manuscript under review in the *Journal of Cleaner Production* (ISSN: 0959-6526)

Abstract

Motor racing conjures many images – fast cars, celebrity drivers, cheering crowds – but few involve environmental benefits/protection. Yet one aspect of the motorsport industry that is rarely discussed is its significant contribution to low-carbon innovation in the automotive sector. This article argues that innovations in motorsport have, perhaps counterintuitively, influenced the development of low-carbon technologies in the passenger car industry. Historically, motorsport has been credited for many technological innovations that were eventually adapted to road cars, but as technologies matured, the contributions from motorsport lessened. However, post-2008, the motorsport industry came to the rescue of automakers tasked with rapidly developing low-carbon technologies in order to meet emissions targets set out by the European Union. With an expertise in rapid prototyping and access to engineers already skilled in electrification, hybridisation and other energy efficient techniques, the motorsport industry has once again become highly relevant in the knowledge transfer of innovation. A major theoretical contribution of this article, therefore, is an explanation of how innovation derived from FIA motorsport has assisted automakers in developing low-carbon technologies compliant with newly implemented EU regulations.

4.1. Introduction

Motorsport racing teams have always been on the bleeding edge of innovation and have consistently sought to exploit technology in their quest for victory. So great is each team's investment in technology, that observers have jokingly dubbed the sport 'the search for the unfair advantage' (Amey, 1995). Motorsport, for the purposes of this article, refers to two of the world's largest racing series: Formula One Grand Prix (F1) and the World Endurance Championship (WEC), known for its famous '24 hour Le Mans' race. Both series are governed by the Fédération Internationale de l'Automobile (FIA). Historically, innovation in motorsport has come in all shapes and sizes. After the First World War, F1 benefited from advances in fuels, materials, component design and forced induction which had been lifted directly from the aircraft industry. Later, 1958 proved to be a pivotal year when, through the successful petitioning of oil companies, commercial petrol replaced nitro-methanol as the only fuel allowed in F1 race cars (Foxall and Johnston, 1991). As teams approached the technical limits of their engines, however, they understood that failure to explore promising new technologies in other areas could result in missed opportunities (Foster, 1985). This recognition pushed teams to pursue other technical avenues for a competitive advantage in areas such as tyre design, electronic systems, fuel injection, chassis design and aerodynamic efficiency (Foxall and Johnston, 1991). For example, the 'tyre wars' of the 1960s between Firestone, Goodyear and Dunlop gave birth to the 'slick' (un-treaded) tyre in 1971 (Foxall and Johnston, 1991).

The relationship between motorsport and commercial automobiles has been traditionally portrayed as a process of radical innovations developed on the racetrack, transferred and adapted to road-going vehicles and marketed to the general public. While technological transfer might once have been a straightforward proposition, some have argued that in reality, modern motorsport rarely produces genuine breakthroughs, and that technological innovations have become more incremental in nature (Foxall and Johnston, 1991). Innovation in motorsport is driven by two groups of stakeholders: sponsors from inside and outside the industry, and the constructors (teams) that participate on the track. Industry sponsors are automakers and related organisations that primarily seek to capture innovative products and knowledge acquired from racing. They also often seek to acquire complementary assets which serve the purpose of marketing their primary products more efficiently (Foxall and Johnston, 1991). A common industry saying illustrating this point is: 'Win on Sunday, sell on Monday' (Oldham, 2000). Non-industry sponsors on the other hand, are solely interested in the acquisition of complementary assets used for their corporate marketing campaigns, which are projected through televised race coverage. Foxall and Johnston argued that while the racetrack was still used as a test bed for technological innovations, involvement in motorsport as part of a firm's marketing strategy, had become the major rationale

(1991). This article suggests, however, that within the last 8 years, the opposite has proven to be true.

In 2015, the three fastest passenger cars available on the market were hybrids, and coincidentally, all made by automakers synonymous with motorsport: Ferrari, Porsche and McLaren. This article's aim is to revisit academic arguments about motorsport, and present a refreshed account of the EU automotive sector, with a focus on UK-based industry contributions, specifically in the areas of low-carbon technology. In doing so, this article's main theoretical contribution will be to demonstrate how climate change and the challenge of carbon reduction - along with the subsequent introduction of EU emissions legislation - has reignited motorsport's significance as a unique contributor of low-carbon technologies to the automotive industry. Section 2 provides an overview of the relevant theories upon which this article builds and Section 3 lays out the methods of analysis used herein. Section 4 presents the main findings and discusses their significance and Section 5 concludes with a summary of the major findings and limitations of this research.

4.2. Theoretical overview

This section briefly reviews relevant literature and establishes the theoretical platform upon which this article is based. The following sub-sections specifically cover the theoretical relationship between regulations and innovation, the non-governmental regulation of innovation in motorsport, empirical studies on knowledge transfer within the automotive industry, and their theoretical foundations.

4.2.1. Regulations in motorsport

The types of rules (regulations) set by the FIA in their racing championships are technology-forcing strategies, where the regulator sets an objective for the future that cannot be met by employing existing technologies (Nentjes et al., 2007; Santos et al., 2010; Tarui and Polasky, 2005). Therefore, an understanding of technology-forcing policies is important, as they explain the innovation dimension of rule-setting (Lee et al., 2010), and support the arguments made below by linking regulations in motorsport to the innovation of low-carbon technologies by its participants.

Motorsport incurs frequent and sudden rule changes that affects all competitors simultaneously, and this repeatedly alters the balance of power between teams during a championship (Hoisl, 2011). The frequency of rule changes in F1, for example, is approximately nine rule changes per season. These are usually specification changes, which can be bodywork or engine specification changes (Mastromarco and Runkel, 2009). Some of these rule changes are for safety reasons, while others are to redress unfair advantages some teams may have gained with a particular piece of technology (Hoisl, 2011). This latter type of policy change serves to prevent one team from establishing a disproportionate number of victories during the season. Beyond the desirability of competitive balance (Judde et al., 2013), scholars have recognised that in motorsport, regulations play a critical role in the technological development of the race cars involved (Foxall and Johnston, 1991). The regulatory bodies in motorsport orchestrate the pace and direction of technological development, which means that the quest for speed and victory must be conducted within the framework of these regulations (Foxall et al., 1992; Foxall and Johnston, 1991). This is mirrored in commercial automotive industry research and development, where studies have shown that technological innovation is driven by stringent command-and-control regulations (Lee et al., 2010; Schot et al., 1994), which are described as ‘technology-forcing’.

Technology-forcing is not a simple matter, however, because it involves interactions between industry and governing bodies, in this case, between teams and the FIA. While technology-forcing can lead to innovation, studies in the automotive industry urge caution regarding the degree of stringency enforced, as outright hostility between industry and regulators is best avoided (Schot et al., 1994). The FIA and its F1 teams are no different, and their relationships often become publicly strained over regulatory disputes. In 2015, Renault, Red Bull and Ferrari all threatened to leave the F1 series at one point or another over various disagreements about regulations.

Generic regulation theory also tells us these kinds of technology-specific regulations force the diffusion of entirely new vehicle architectures and components, effectively inducing radical innovation (Collantes and Sperling, 2008; Sperling and Gordon, 2010). There is generally no flexibility built into these kinds of regulations, which makes it impossible to gradually develop or test the technologies, as they must be presented as a complete package (Bergek and Berggren, 2014) at the beginning of the racing season. In F1 for example, teams are currently allowed to carry out no more than 15,000km of testing within a calendar year (FIA, 2015). Inevitably, the engineering of these cars tends to be similar, reflecting a uniformity of technical thinking (Foxall and Johnston, 1991). This is described by scholars like Nelson and Winter (1977), and Dosi (1982) as a technological paradigm, where in the case of motorsport, teams will tend to converge on a limited set of design configurations, better known as a dominant design (Windrum and Birchenhall, 1998). Therefore, from the literature it is reasonable to argue that the regulations set by motorsport's governing bodies - in this case the FIA - dramatically influences the technologies seen on the track.

4.2.2. Knowledge transfer from motorsport to automotive

The history of motorsport is inextricably linked to innovation in the automotive industry and the focus of this article is to examine the implications of those linkages, within the contemporary context of low-carbon innovation. Over the years, there have been many instances of direct carry-over technologies from motorsport to the automotive industry, some of which are considered to be fundamental to the modern road car, like adaptive suspensions derived from F1 in the 1930s (AIO, 2015). In 1953, Jaguar in collaboration with Dunlop in the UK were credited with developing the first reliable calliper disc brake, which was initially fitted to their Jaguar C-Type Le Mans race car and can now be found on all modern road cars (Fearnley, 2013). The introduction of reinforced carbon fibre in race car construction in 1981 by Lotus and McLaren was one of the most significant developments in the history of F1 racing. The use an advanced material like carbon fibre made it possible to build lighter, faster, safer race cars - benefits that were also passed on to today's private road cars (Amey, 1995).

The engine management system (EMS), which is the car's computer that controls various functions like on-board electronics, fuel injection and ignition, is another prime example of knowledge transfer from motorsport to the automotive industry. The EMS is significant because it is one of the few ways in which automakers have managed to simultaneously attain the seemingly contradictory goals of increased power, lower emissions and increased fuel economy. In 1983, Honda entered F1 racing with its engine controlled by a Bosch licensed EMS. Further updates to the EMS allowed for a 13% increase in fuel economy and an additional 180 horsepower (HP). In the 1998 F1 season, the Honda-McLaren team won 15 of the 16 race events, thanks to the increasing sophistication of Honda's EMS technology. Soon after, Honda transferred this technology to its production vehicles; initially the F1-derived EMS only appeared in Honda's top-of-the-line NSX model, but eventually it was adopted by Honda's entire fleet. By the mid-1990s, EMS technology was best practice throughout the automotive industry (Amey, 1995). In the 1980s, Honda F1 engineers also pioneered 'drive-by-wire' technology, whereby the movement of the throttle pedal is transmitted to the engine electronically rather than mechanically. Today, this technology is also considered best practice throughout the industry (Stanton and Marsden, 1996; The Guardian, 2011).

Non-automaker race teams have also successfully carried over their services and applied their technological know-how to the automotive industry, based on their racing expertise, knowledge assets and performance reputation. One famous example of this happening was when the Williams F1 team opened the Williams Advanced Engineering (WAE) facility, an engineering consultancy firm in Oxfordshire, UK. Since then, WAE has been known to assist automakers including Renault, Jaguar, Porsche and Nissan, in their road car development (Joseph, 2014).

Amey (1995) highlights two significant caveats concerning the transfer of knowledge and technology from motorsport to the automotive industry: First, not all new technologies making their way into consumer automobiles can be attributed to the utilisation of racing programmes as R&D platforms. Sometimes, there are other external influences at work, for example advances in ignition technology were related to other advances in electronics. Similarly, developments in automotive microprocessor technology represented a maturation and convergence of several core technologies unrelated to motorsport. Secondly, even when the transfer of technology is a result of racetrack innovation, there are multiple actors involved. The direct racing involvement of automakers accounts for only a portion of in-house research and development programmes which have resulted in technologies transferred to the production line. The indirect involvement of external source technologies and component suppliers such as Bosch and Motorola must be acknowledged, as it has become increasingly difficult for automakers to sustain the R&D necessary to be both innovator and early adopter of all current dominant design technologies. Amey (1995) also argues that auto racing is no longer a unique source of R&D for production automobiles, and that on the contrary, there is increasing upstream movement of innovation from production engineering to racing programs. While this may be perfectly reasonable in very general terms, this paper will argue that in fact, the global climate change agenda has serendipitously promoted the use of motorsport engineering as a potent tool within the automotive industry's carbon mitigation strategy. Having discussed the limited literature on knowledge transfer from motorsport to the automotive industry, I now draw on broader theory to supplement the discussion about the knowledge transfer process.

4.2.3. Knowledge transfer in theory

The question of how exactly the majority of innovation-relevant knowledge circulates across sectors, and the primary means, channels and mechanisms of diffusion has been the focus of many studies (Cao and Wang, 2017; Fritsch and Franke, 2004; Karlsson and Manduchi, 2001; Nieto and Quevedo, 2005). One major academic consensus about knowledge transfer is the role of geographic proximity (Cheng et al., 2017) in the sense that it favours and facilitates inter-industry transmission of knowledge or productive specialization. An abundance of localised activity therefore contributes significantly to innovation (Audretsch and Feldman, 2004; Paci and Usai, 1999). Geographic proximity plays an important role in knowledge transmission because tacit knowledge is inherently non-rival (Audretsch and Feldman, 2004). The concept put forward is that social interactions have economic value and the exchange of highly contextual, uncertain knowledge in particular, is best conveyed face-to-face through frequently repeated interactions (Von Hippel, 1994). Glaeser et al (1991, p. 1126) argue that 'intellectual breakthroughs must cross hallways and streets more easily than oceans and continents.' Geographical proximity is relevant to this study because the spatial concentration of the UK's automotive and motorsport development facilities suggests that many of the above arguments may be applicable (AIO, 2015).

Knowledge spillover occurs when knowledge is unintentionally transmitted beyond its intended audience(Hojnik and Ruzzier, 2016; Jakobsen and Clausen, 2016), and a knowledge externality is created when it is used by those beyond that intended boundary (Costantini et al., 2017; Fischer, 2001; Guo and Fan, 2017). Knowledge transfer, however, is the intended exchange of knowledge between people or organisations. The transfer of knowledge can be either tacit or explicit. Tacit knowledge is exchanged exclusively at the individual level while explicit knowledge can be transacted among individuals, firms and even across borders. Tacit knowledge is knowledge conveyed by an individual based on their own interpretation, thus giving that knowledge a 'personalized' quality when articulated by that individual (Fallah and Ibrahim, 2004). Explicit knowledge is the codified transmission of knowledge in an orderly and formal manner. Firms can exchange explicit knowledge via technology, documents, products and processes. Nations can also exchange explicit knowledge in the form of multilateral agreements on technology transfer, education and through the trade of goods and services. Tacit knowledge can be turned into explicit knowledge by a process called 'externalization' and the reverse process is called 'internalization' (Fallah and Ibrahim, 2004).

4.3. Methods

Research in the transport sector frequently makes use of qualitative methods for inductive purposes, as it permits the identification of concepts and interpretations from the respondent's perspective (Gardner and Abraham, 2007; Steinhilber et al., 2013). This article applies qualitative methods with the intent to capture relevant themes from the perspectives of automakers, regulators and other industry stakeholders based on their experiences. It then becomes possible to establish linkages between collections of different sets of knowledge within the automotive industry.

This study took place between 2014 and 2016 and the primary sources of data were recordings of semi-structured elite interviews with senior industry decision-makers within the automotive (industry and government) and motorsport sectors. These respondents were based in the UK, US, Germany and Belgium, and were selectively targeted for their opinions on the role of the motorsport in low-carbon and energy-efficient innovations within the UK and European automotive industry. **Table 2.** lists the elite respondents interviewed during this study.

Interviewees were specifically selected (non-probability sampling), and in this case, a combination of purposive and chain-referral sampling which allowed for the inclusion of key institutional actors in the data gathering process (Tansey, 2007). In accordance with the ethics approval guidelines of this study, express permission was granted before the recording of each interview, participants were guaranteed anonymity and were assured that recorded data would be destroyed in accordance with the UK's Data Protection Act 1998.

Recorded interviews were transcribed and thematically coded using the Template Analysis method, which gives an account structured around central themes that have emerged, and draws on examples from interview transcripts as required (King, 1998). The conclusions of this study are meant to provide a robust overview of the role of established firms in low-emissions transitions within the automotive industry.

Table 2.

List of interviewees

Institution / Organisation	Title / Department
UK Motorsport Industry Association (MIA)	Senior Executive, Leadership
UK Automotive Investment Organisation (AIO)	Senior Executive, Leadership
Mercedes-Benz	Senior Executive, AMG High Performance Powertrains
Ferrari	Former F1 Chief Aerodynamicist
World Endurance Championship (WEC)	Senior Executive, Leadership
BMW	Senior Executive, Powertrain Research
Williams Advanced Engineering (WAE)	Senior Executive, Programmes and Commercial
Nissan Motor Co.	Senior Executive, Global Motorsport
Audi	Senior Executive, Audi Sport Engine Technology
Ricardo	Senior Executive, Transmission Systems
Formula E	Senior Executive, Leadership
Porsche	Senior Executive, Porsche Motorsport
UK Motor Sports Association (MSA)	Former Technical Director
Renault	Former F1 Technical Director
European Commission	Policy Analyst, Directorate-General for Climate Action
Qualcomm	Senior Executive, Business Development
GKN Drivelines	Executive
Cosworth Group	Development Engineer
Delta Motorsport	Engineer

4.4. Results & Discussion

4.4.1. The Motorsport-Automotive industry connection

In 2008-2009, not only were automakers facing bankruptcy, but they were also under pressure to meet the first round of outstanding EU emissions targets by 2015, which was considered relatively short in the automotive industry. Respondents explained that in 2008, the global automotive industry faced several crises, and consequently the motorsport industry trailed in the wake of whatever fate awaited the automakers (OEMs). Many F1 and WEC teams feared that sponsorship and patronage would end as the automotive companies began to focus on the newly agreed EU emissions targets, but that did not come to pass. As the OEMs shifted their attention to low-carbon technologies, this period of transition unexpectedly provided an opportunity for motorsport to become a valued asset to the automotive industry. Meanwhile, respondents from the motorsport industry revealed that over the decades, they had become experts in the efficient use of energy and one chief executive from the motorsport industry argued that the simple reason for this is that 'there's never been a race won inefficiently'. Despite accumulating several decades of knowledge in the deployment of efficient technologies, motorsport had become less relevant to the automotive industry over the years. Many respondents believed that the increasingly restrictive regulations in motorsport subsequently limited the scope of possible innovations, and ultimately rendered motorsport technologies less relevant to the automotive industry. But some respondents from the motorsport industry recalled predicting that someday, energy would become important. As one senior UK motorsport executive tells it:

> We always felt that one day, energy efficiency may become valuable, one day we may be able to sell our knowledge and capability, and that day came in 2008 - 2009.

The connection between the motorsport and automotive industries makes little sense without first understanding the background context of the relationship that had developed between these two industries. In this instance, the relationship between the FIA motorsport and the UK automotive value chain is used to illustrate this point. In the UK, the New Automotive Innovation and Growth Team (NAIGT) was a project, comprised of experts from across the industry, government and academia, that was launched by Shriti Vadera, then Minister for Business at the Department for Business Enterprise and Regulatory Reform (BERR) in 2008. The purpose of the NAIGT was 'to develop recommendations to help secure the future of the [automotive] industry' (SMMT, 2016b), and this project was the forerunner to the Automotive Council and their industrial strategy. This industrial strategy was based on a year's worth of research and discussions on the future of the UK's automotive industry, which set out to create a completely different business model for the island's automotive industry. Respondents recalled that at that time, industry stakeholders reviewed the assets of Britain in the face of the 2008 financial crisis and struck a comprehensive deal with government which has endured for nearly a decade. The automotive strategy laid out in the industry's various technology roadmaps focused particularly on low-carbon innovation. The relevance of motorsport to the mainstream automotive sector however, became increasingly clear, as the capability of motorsport organisations to rapidly engineer solutions for testing and demonstration was recognised as a significant asset to the UK's automotive industry. This was how motorsport in the UK was afforded the opportunity to develop energy efficient, low-emission technologies in collaboration with automakers throughout the region. This newfound synergy emerged not only at the technical level, but also at the policy level. For example, the motorsport trade association leaders in the UK now sat on various industry councils (Automotive and Technology), where they could provide input on national technology roadmaps and strategies related to the UK automotive sector. So, a much closer and intentional alignment developed between these related industries. According to a former OEM CEO, the sentiment among OEMs about the potential to collaborate with the motorsport industry was as follows:

> Well we've got a world beating, world leading [motorsport] subsector here, how do we put it to good use?

Thus, according to respondents, in a time of great difficulty, the automotive sector found an ally in the motorsport industry and together, they would go on engineer their way past the 2008 crisis.

4.4.2. Knowledge Transfer from Motorsport to the Automotive industry

The theme of knowledge transfer from motorsport to the automotive industry was immediately observable from the data collected. For example, according to Porsche executives, the company has been racing as long as they have been manufacturing streetcars, and thus they describe the organization as having motorsport is in their DNA. Indeed, there has always been a very close link between their experience in racing and their experience in building road cars. Additionally, models like their GT car are very close to their race cars while being street legal, and in those cases, they are able to carry over, one-to-one, a lot of technology from the race cars. This includes materials such as carbon fibre, titanium, high-strength aluminium, magnesium etc. These models are often top of the line, meaning they are usually the most expensive and very often, the most exclusive (limited production numbers). Commonly referred to as 'halo cars' by the press, OEMs like Porsche classify these models as 'technology carriers'. A technology carrier is described as a low volume, highly priced car where the sole focus isn't on the production costs of the car but rather the 'product experience.' Engineers also have a lot more freedom to try new ideas, where they can make things more extreme like full carbon fibre skin or advanced navigation systems, which is only possible on a limited-edition car. Technology carriers are significant not only for the innovations that they bring over from motorsport, but also for the eventual cascade of technology that diffuses downstream throughout the OEM's entire product line.

Japanese automaker Toyota with its 24 Hours Le Mans race car, the TS040, has hinted that some of the its technologies will probably be used in future versions of the world's bestselling hybrid, the Toyota Prius (King, 2014). The TS040 uses supercapacitors which allows the race car to efficiently store energy generated under braking, and then quickly redistribute that power on demand, to assist with acceleration. According to a Toyota spokeswoman:

> [The TS040] represents an advanced vehicle laboratory for hybrid vehicle and component development. The supercapacitor technology used in this vehicle with its fast charge and discharge capability offers great possibility for production car use.

German manufacturer Audi, is even more aggressive and intentional when it comes to capturing technologies developed on the racetrack. In a published interview (Ramsey, 2015), Chris Reinke, head of Audi's Le Mans Prototype development, offered the following:

> Not one single euro is spent on a separate motorsports program. We [Audi Motorsport] are part of the Technical Department [of the road car company]. We are a pre-development lab for road-relevant technology.

The sentiment throughout the interview was that Audi did not race for philosophical reasons, but rather, for the sole purpose of improving its road cars. In the same interview, Dr. Wolfgang Ulrich, head of Audi Motorsport, signalled that Audi was in fact not a racing brand, but a technology brand:

> Instead of components, look at technologies – not lights, but lighting technologies, not engines, but engine technologies, like injection pressure technology is the same from the race car to the road car.

Finally, when asked why Audi focused most its racing efforts and resources on the WEC (as opposed to other championship series), Reinke retorted that Audi was primarily interested in competing in a series with ‘road-relevant’ technologies. The concept of ‘relevant’ technologies is important, and will be discussed later in this paper.

4.4.2.1. Rapid Prototyping

When discussing the transfer of knowledge between sectors with respondents, the theme of rapid prototyping featured very strongly in their narratives, and thus is discussed in its own section. One example given was when a car is built for the Le Mans race, it is built solely to last the length of that race, and is not intended for use afterwards. It may look like the same car to the average spectator, but actually, in the six-hour race that follows, the car on the track is, for all intents and purposes, a new car. This is an example of the motorsport industry’s expertise in the rapid production of prototypes. Here, a senior motorsport executive discusses the value of fast production to mainstream the automotive sector:

> In a world that is going to need stunning levels of R&D, the speed of prototype development is critical to a company’s financial efficiency. In the automotive industry, it could take two years to develop a prototype, but consumer trends now demand much faster production times.

According to OEMs, the value of motorsport is its process, capability, speed and rapid adoption of innovation. The areas in which OEMs are finding a value in transfer of knowledge from motorsport is in the actual processes that enable OEMs to react quickly to changes in technology, which has been a weakness in the automotive industry. ‘Motorsport races prototypes, not production vehicles’ is a common mantra, which means that motorsport tends to push the technological boundaries further than automotive companies are accustomed to. OEMs still prefer to approach development safely and in a conservative manner, given the size of their operations, but OEMs also recognize that the ‘time to market’ is a desirable metric that can be improved by the cross-border flow of knowledge from motorsport. According to one industry respondent, ‘time is money in an innovative world', especially when the automotive industry is facing threats from 'white goods manufacturers' - newcomers the likes of Apple, Google and Tesla. Stakeholders say that motorsport provides a way to develop technology faster than most other methods while gaining a level of acceptance through marketing that can lead to automotive production programs and the sale of cars.

So, a major aspect of technology transfer is the '*modus operandi*' of the motorsport industry, or their applied methods and processes. This is especially relevant to the processes of rapid prototyping coming from motorsport and applying those techniques to road car production. Short development times also mean being able to make quick decisions, and this is something that is learned in motorsport as well. For example, if a car must be optimised between races, there is usually a gap of only a few weeks. In cases like this, teams must not only develop the product very quickly, but also make quick analyses and decisions, and these kinds of transferable skills enhance an OEM's capability in the production of passenger cars. In motorsport, the goals, objectives and frameworks that teams operate in are very clear and precise. They know when the first race is going to be, how many races, what the rules are and they know that they must win. By nature, motorsport is very competitive, very efficient with time, and very effective in turning ideas - in the shortest possible time - into reality by maximising performance per unit of time. So aside from the marketing and technological transfer, OEMs involved in motorsport also enjoy the benefits of accelerated development cycles, improved critical thinking and a faster time to market.

4.4.2.2. Innovating to Win

Nested within the theme of rapid prototyping; the sub-theme of 'winning' and the desire for ultimate victory began to emerge as a strong motivation for rapid innovation among respondents. In this article, the theme of winning is distinguished from competitiveness by the binary nature of racing, where the outcome of each race is based on positions and the most valued of these is the easily identifiable and measurable 1st place. A former lead F1 designer for Ferrari puts it as follows:

> Because fundamentally, when you have to get a job done, or something absolutely needs to happen, then motorsport is very good at that because the performance benefit and the competition is so intense. What you see on the track is one thing, but behind the scenes it's a development battlefield, and it's a war you have to win. So that approach is very useful and very interesting to all sorts of business sectors.

This theme of winning has been described by some OEMs as a ‘soft factor’ for innovation; the very basic concept of going out to race and competing, where the first car to cross the chequered flag wins. OEMs insist that competitive motorsport keeps their engineers and their organisations sharp. Respondents from the motorsport industry saw motorsports as providing a platform and environment for innovation to happen, where people needed to be motivated to innovate. For them, winning is the most sought-after reward in motorsport. In their opinion, there is a significant relationship between innovation and the desire to win. In the words of a senior FIA regulations official:

> What you need to understand is that two years of development in Formula One is the equivalent of about eight years of normal research. There is nothing like war and competition to accelerate the development of technology.

4.4.2.3. Engineers and Tacit Knowledge

We have already established from previous research on knowledge transfer (Glaeser et al., 1991; Von Hippel, 1994) that tacit knowledge can be one of the most efficient means of transmitting highly contextual and uncertain knowledge. Respondents from within the industry confirm that this is also the case in the automotive industry. A senior executive within NISMO (Nissan’s motorsport division) describes his career experiences as follows:

> I myself started [working as an engineer] in racing, then spent over a decade in production, and I’ve been involved with pretty much every passenger vehicle launched in [the region] over the last eight years. I am now moving back to racing and I am sure that eventually, I will go back to production. So, there is a great value in that for the OEMs. For example, our engineers working on the Le Mans racing team in the fields of hybrid integration, deployment and development, will eventually return back [sic] to the production line and work in the software development of those systems, so there is an absolute transfer. Again, it’s not necessarily transferring part *A* in motorsport to part *B* in automotive, but the knowledge that is gained. It would be a waste not to use it to be honest with you.

In the same vein, a senior executive within the Williams racing organization estimated that with regards to the nature of knowledge transfer, ‘it is 95% philosophy and 5% actual intellectual property’ that is carried over to the automotive industry. This theme of engineers and tacit knowledge goes hand in hand with the speed of innovation and prototyping. Engineers who have worked in both motorsport and automotive become more focused on finding solutions and are not impaired by ‘typical mental barriers’ according to a senior Audi Sport executive. Teamwork and integration helps engineers that participate in motorsport to return to the production line with diversified and enhanced skillsets that can be deployed within the OEM’s production process. For example, Williams have used a combination of motorsport and automotive engineers to push the boundaries of power and energy density in electric batteries, and have developed the first thermodynamic management system (battery heat management). This indicates that while engineers benefit from knowledge transfer by moving back and forth between motorsport and automotive production, they also benefit from jointly working on projects with other engineers from different backgrounds.

In the past, Honda have often said publicly that they use motorsport to improve the knowledge and skills of their people. Otmar Szafnauer, Vice President of Honda Racing Development from 2001 to 2008 was quoted as saying:

> Honda has many engineers working on the F1 programme who subsequently return to road car manufacture. By having engineers on the F1 programme for three years before they go back to designing and fitting, say, engine control on Honda's road cars, we hope we can bring the meticulous attitudes of F1 engineering into every aspect of our road cars. We think it gives our engineers the right attitude (The Guardian, 2011).

In 2015, two former Renault F1 engineers left the motorsport industry and founded Flybrid Systems in the UK. With the help of a government-industry innovation scheme, they developed a Kinetic Energy Recovery System (KERS) based on the one used by F1 race cars, and these units are now operating in buses and excavators across the country. While motorsport can be a great showcase for a company’s ultimate engineering capabilities, it is the access to higher levels of technology which allows engineers to apply that tacit knowledge to mainstream automotive applications.

4.4.3. Low-carbon Innovation in Motorsport

If the proposition, that winning races is about being as efficient as humanly possible is accepted, then the logical connection between motorsport and low-carbon innovation can be made.

Historically speaking, motorsport has been quietly contributing to lower emissions technologies for many years and one example is the Audi R10 TDI, which was the first diesel-powered car to win the 24hr Le Mans race in 2006. Back then, diesel cars were perceived to be ‘industrial’ and slow, with oil burning, noisy engines. Fast forward to the present day and there are currently three racing series that incorporate electrification into their regulations: Formula One, WEC, and more recently Formula E. In Formula One, the first hybrid KERS was introduced in 2009, and when the regulations were changed in 2014, all race cars had to have hybrid-electric power units, which resulted in a 30% increase in fuel efficiency over the previous year. These regulation changes have gained a high level of acceptance and have also aggressively accelerated the development of motor-battery systems integration. Developments in aerodynamics and light weighting are also key in terms of driving the future of low CO_2 innovation and those are two areas in which motorsport excels. Often the perception of high performance innovation in motorsport focuses on engine technology, but motorsport’s contribution to light-weighting and aerodynamics have also had major impacts on automotive innovation in general. For instance, the use of composite materials which replaced sheet metal was pioneered in motorsport and is now being used in mostly in high-end automotive applications. Respondents expect these types of technologies to eventually be deployed throughout entire production lines in the coming years, even to the least expensive automobiles. Not all low-carbon innovations are valuable to the automotive industry, however, because some of the materials used in motorsport are extremely expensive and hence are not considered for production by automakers. One example of this is the use of titanium in ‘supercars’. While titanium is as strong as steel but only half the weight, the alloy is much too costly to use in the production of low profit margin, high volume economy vehicles.

Stakeholders in motorsport and the automotive sector perceive the areas of hybridisation and electrification to be fertile ground for development and knowledge transfer. Respondents considered Formula E, the world’s first all-electric championship, to be an ideal platform for showcasing electrification by ‘fast-tracking’ some of the technologies while showcasing electric vehicles performing at very high levels. This falls squarely in line with the automotive strategy published in 2013 by the Automotive Investment Organisation (AIO), where one of the stated aims was for much greater alignment between motorsport and the mainstream automotive sectors. While a breakthrough in electric car batteries is not guaranteed, the Formula E series has structured its regulations in a manner that ‘forces’ increasing amounts of innovation from the teams each year.

Even now, in the early stages of Formula E's development, knowledge transfer is already occurring. F1 team and supercar manufacturer, McLaren developed the electronic control systems for the series, while F1 team Williams developed the championship's electric batteries. Incidentally, based on their work in Formula E, Williams is now also developing an electric battery for a leading OEM.

As it stands, many OEMs are already officially involved in Formula E, including the Peugeot Citroen group (PSA), who are partnered with Virgin, as well as Volkswagen who has jointly entered the series with the ABT Audi Sport team. Mahindra, which is a major Indian OEM, has also entered Formula E. While there are other OEMs who have made alliances with current Formula E teams, they are not publicly acknowledging involvement in the series at this time. As a final example of low-carbon knowledge transfer, respondents at Porsche conveyed the compelling story of how the automaker took their series winning, hybrid 919 Le Mans race car, and transferred much of that technology into their critically acclaimed 918 Spyder hybrid road car. The technological cascade from the 919 race car to the 918 road car is as explicit as it gets when demonstrating low-carbon technology transfer from motorsport to automotive, where both cars share much of the same architecture. A respondent directly involved in the development of the 918 confirmed that Porsche plans to expand further on their success in electrification by putting their acquired expertise into the upcoming 'Porsche Mission E', the company's very first fully electric vehicle.

4.4.4. Motorsport Regulations

In the process of examining the primary mechanisms of knowledge transfer between motorsport and the automotive industry, the theme of regulations in motorsport was also shown to be significant from the respondents' perspective. In contrast to most research about the role of regulation in innovation, very few areas of motorsport are regulated by the government, because most of its usage is on private land and on racetracks. The only major areas where government policies apply to motorsport are health and safety issues in factories, and employment laws. While government legislation affects motorsport in a limited manner, the actual racing is governed by a separate entity in the form of sport legislation, in this case, the FIA. In Formula One, there is a constant effort to balance commercial pressures between primary funders, currently five OEMs, who manufacture power plants (engines) for the championship, along with other OEMs who've decided not to manufacture engines. Every season, these very influential manufacturers sit in the same room to decide the future of the championship and invariably, they have diverging interests and thus have disagreements, because they don't all have the same ambitions. For some, it is to sell cars, for others, it is a matter of better public perception of their brand. The FIA must mediate between all parties as well as the commercial rights holder who is selling the sports package on television, and trying to attract maximum interest and viewership. Hence, there is pressure from various stakeholders, and sometimes the FIA makes policy decisions that are less pleasing to manufacturers, but cater more to the audience, and vice versa. For example, with the introduction of fully hybrid race cars in the 2014 F1 season, the quieter engines which produced a 'less pleasing sound' caused some discontent among spectators, but ultimately benefitted the manufacturers' interests by improving fuel efficiency.

4.4.4.1. Relevant regulation

While exploring the theme of regulations in motorsport, the sub-theme of relevant regulations emerged as being especially important to respondents, and thus is laid out in greater detail here. When car manufacturers invest money into a motorsport programme like Formula One, they must be able to demonstrate that there is a value to the company that goes beyond marketing. According to respondents, if an OEM is developing a 'road relevant' technology within their Formula One budget, then it is viewed as an element of research and development rather than just pure marketing. Engineers can then be moved back and forth and ultimately this helps the OEM in their innovative production efforts. This rationale makes it much easier for manufacturers to justify their racing budget by capturing additional value from racing, and for this reason, motorsport comes under tremendous pressure from OEMs to promote emission-lowering technologies, as was conveyed by the directors of two racing series covered in this paper.

In motorsports where powertrain hybridisation and electrification plays a crucial role, the regulations that govern those championships have a significant driving impact on the technologies that are developed. Thus, the regulations in those championships become very important to stakeholders interested in capturing and transferring that knowledge to the automotive industry. This can be observed at the top tier of the automotive industry, where high-performance supercars are mimicking many of the technologies seen in motorsports series like F1 and Le Mans. OEMs also understand that if they are going to benefit from being involved in motorsport, it very much depends on the class of motorsport chosen and whether the regulations are relevant to their engineering efforts in the manufacturing plant. According to one senior BMW engineering development executive, there are some championships with ‘a lot of freedom’ or permissive regulations like Le Mans and even Formula One, where involvement in these series can speed up innovation in low-emission technologies. But for the moment, BMW has chosen to involve itself in Formula E, as ‘it is a good place to develop technologies for serious production’. In this case, it benefits an OEM like BMW to engage in a motorsport like Formula E in the hopes of being able to transfer some of those electric technologies back into their production line. If the regulations are relevant in a given class of motorsport, OEMs will benefit not only from technical transfer of knowledge but also knowledge transfer between engineers. According to one of Mercedes Benz’s F1 development chiefs:

> While motorsport is a great platform for providing focus and accelerating innovation, those involved in the regulation setting for motorsport must keep a keen eye on the big picture, and put regulations in place that accelerate the right technologies, that follow that big picture.

Mercedes benefits from motorsport because the regulations in Formula One focus on efficiency; more specifically, the conversion efficiency within Energy Recovery Systems (ERS) and the thermal efficiency of the internal combustion engine, which is exactly what occurs in road cars. So again, the benefit of Mercedes-Benz being a ‘fast moving, high paced, R&D centre’ is that the technologies developed in F1 can potentially be transferred into their passenger road cars.

Another aspect of relevant regulation is that the automotive industry is actually moving ahead of motorsport in several areas, for example, adaptive aerodynamics for braking or cruising conditions. In Formula One, it is prohibited to have moving or adaptive parts with respect to aerodynamics, and in the opinion of a former F1 aerodynamics chief:

> If motorsport wanted to guide or become more relevant, they could look at regulation design as an opportunity to contribute more thoroughly.

Lastly, respondents made the additional point that relevant regulations improved safety technologies in addition to low-carbon technologies. In the WEC championship, for example, technical regulations are constantly improved and put in place to provide a platform for new technologies to develop with regards to OEMs. While the championship is ideal for accelerating hybrid technology development, the WEC simultaneously works very closely with many safety organisations involved in motorsport and the automotive industry. According to a WEC chief executive:

> OEMs are happy that regulations are encouraging the relevant technologies, not only in the area of low-carbon innovations, but also safety technologies, which are of great importance to the FIA organization.

4.5. Conclusion

Over the years, FIA motorsport has contributed directly and indirectly to innovations in the automotive industry, but as these technologies matured, the motorsport industry became less relevant as a source of innovation. With the advent of the 2008 financial crisis, however, and in its immediate aftermath, the UK automotive industry was in real danger of collapsing just as the Labour Government was in the midst of overhauling domestic climate and energy policy (Carter, 2014; Carter and Jacobs, 2014). It is under these circumstances that the automotive industry struck a comprehensive deal with the government, under the guidance of the UK Automotive Council (AIO, 2015), and significantly revised its technology roadmap. This extensive restructuring focused on two key components: low-carbon innovation, and a much closer alignment between the motorsport and automotive sectors, which fell squarely in line the Labour Government's climate change agenda at that time. I argue that the convergence of these circumstances is characteristic of how FIA motorsport became highly relevant once again to the EU automotive industry.

Crucially, the focus on low-carbon innovation, brought on by stringent EU emissions regulations, meant that much more research and development in the areas of electrification and systems integration (hybridisation) would be required. Fortunately, not only had the FIA motorsport industry already been developing energy efficient solutions for many years, they had also acquired key competencies that were highly relevant to low-carbon innovation in the form of rapid prototyping and highly skilled engineers. The FIA motorsport further accelerated its contribution to low-carbon innovation by encouraging the 'right technologies' on the racetrack with the implementation of relevant regulations. Thus design followed regulation (Foxall and Johnston, 1991), and the imposition of energy-efficient regulations within the FIA stimulated the development of low-carbon innovations that eventually got transferred to mainstream automotive production lines in the EU.

A limitation of this paper is that the empirical support for the arguments made is largely based on data from UK and European industries within the framework of EU emissions control legislation. While this may limit some of this paper's conclusions to the UK and the wider European Union, other arguments can be extended beyond those borders due to the multinational status and operations of the automakers examined. Thus, the overarching theoretical contribution of this article is that public policy governing passenger car emissions in the EU automotive industry has indirectly influenced the setting of 'relevant regulations' in FIA motorsport. These relevant regulations forced the development of low-carbon technologies on the race track, which eventually found their way back into passenger cars through a series of causal mechanisms involving tacit knowledge transfer. While the analysis presented in this article is thorough, it is has not addressed every relevant issue and some questions remain unexplored due to various constraints. One possible avenue for future research would be the examination of the motorsport industry as a competence enhancing asset for established automakers (OEMs). This is relevant because sustainable transition scholars (Geels et al., 2012) generally argue that niche actors (industry newcomers) are the most likely sources of discontinuous innovation. However, in this case, the motorsport industry appears to enhance incumbent OEMs' capacity to aggressively innovate and integrate these technologies into the private vehicles that are sold today.

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Costantini, V., Crespi, F., Marin, G., Paglialunga, E., 2017. Eco-innovation, sustainable supply chains and environmental performance in European industries11We gratefully acknowledge the support by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 649186 – ISIGrowth. The comments and suggestions by three anonymous referees are also acknowledged. The usual disclaimers apply. J. Clean. Prod., Making, Buying and Collaborating for More Sustainable Production and Consumption 155, 141–154. doi:10.1016/j.jclepro.2016.09.038

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Chapter 5

Paper Title: Remapping discontinuity: Established firms as change agents in the automotive industry

Submitted manuscript under review in *Research Policy* (ISSN: 0048-7333)

Abstract

In sustainable transition scholarship, industry newcomers are most often portrayed as innovators-extraordinaire, unencumbered by archaic industry dogma, and the bounded vision of established firms. Ideally, these newcomers bravely introduce their technological inventions to the marketplace, where they gather momentum in protected niches, before maturing into radical innovations that disrupt industries. This article challenges that stereotypical characterisation of sociotechnical transitions in complex capital goods markets by interrogating one of the major theoretical propositions in transition scholarship: the incumbent-newcomer dichotomy. Based on a template analysis of the UK automotive industry, this article argues that established firms lead the industry in low-emissions innovations by deploying an array of strategies and assets at all levels of the sociotechnical system. It also discusses previously obscured variables such as evolving government-industry relations, the motorsport sub-sector, component suppliers and the notorious 'valley of death'. These concepts are all key to understanding present day low-emissions transitions in the automotive industry. By scrutinising the creative and innovative capacity of established firms as multi-level actors, this article goes beyond the 'attacker's advantage' in explaining the forces behind sustainable industry transitions.

5.1. Introduction

Over the past two decades, new models of technological change have risen to replace older neo-classical growth theories (Mulder et al., 2001). Among these, the multi-level perspective (MLP), developed by Geels, has become one of the most widely used theoretical frameworks in contemporary transition scholarship (Markard and Truffer, 2008). The MLP provides a means of investigating the core debate in transition studies: (dynamic) stability vs. (radical) change. This interaction occurs across multiple tiers of an industry (Geels, 2012; Smith et al., 2010), particularly between the regime and niche levels (Berggren et al., 2014). Like much of the work that followed Schumpeter's concept of creative destruction (Schumpeter, 1942), contemporary transition scholarship often focuses on 'the attacker's advantage' (Christensen and Rosenbloom, 1995). For clarity, Schumpeter's concept proposes that 'creative' innovation is effected by the invaders - new firms or entrants to the industry - while 'destruction' is the fate of entrenched industry incumbents (Bergek et al., 2013). This characterisation of technological discontinuity is also often invoked by MLP adherents in their explanations of sustainable transitions (Markard et al., 2012), frequently focusing on the dismantling of existing regimes. The result is the emergence of new technological systems (Sandén and Azar, 2005; Steinhilber et al., 2013; Turnheim and Geels, 2012) as a means of reducing industrial society's impact on the environment (Faber and Frenken, 2009).

Despite being well suited to examining sustainable transitions, the MLP has been accused of intellectually monopolising innovation studies and some scholars (Smith et al., 2010) have suggested that future research should explore other social scientific and systemic theories of change (Shove and Walker, 2007). Due to the MLP's foundations in evolutionary economics and technological innovation, it has been critiqued for the way it explains change, where 'consumption becomes a substitute for the genuine development of the self' (Hanlon and Carlisle, 2009, p. 28). Scholars have also challenged the MLP on the grounds of conceptual vagueness (Whitmarsh, 2012) and lacking granular analysis (Markard et al., 2012). Geels himself concedes that the empirical application of the MLP is an interpretive assessment, where breadth and depth must be balanced. He explains that while the MLP broadly addresses the various dimensions of transitions in transport systems, many real world nuances are backgrounded for the sake of 'the big picture' or larger patterns (Geels, 2012). The broad nature of the MLP, however, is also its strength, and even some of its harshest critics (Markard and Truffer, 2008) have praised its contributions and paid homage (Cohen, 2010) to the rich body of literature it has inspired in the field of sustainable transition research (Berggren et al., 2014).

Recently, transition scholars have begun calling for innovation studies to move beyond the attacker's advantage characterised by regime-niche antagonism, and instead explore alternative conceptual understandings of the innovation process (Bergek et al., 2013; Berggren et al., 2014). This paper responds to that call by building upon recent Creative Accumulation literature, and examines the role of established firms within the context of the UK automotive industry. This UK sector is interesting because on the surface, it appears to defy some of the MLP's typical assertions (Geels, 2012), and gives the impression that established automakers are (a) the most likely sources of radical innovation and (b) preserve their primacy by leading the industry in disruptive innovation. One only need consider the 'Holy Trinity'[7] as evidence. While the MLP has been a reliable framework for examining multi-actor processes, Geels invites researchers to further analyse the multi-dimensional determinants involved in low-emissions transitions towards sustainable transport (Geels, 2012). This article will demonstrate how incumbent firms aggressively deploy various strategies and assets to influence transitions which, until now, have been underestimated or under-hypothesized in previous transition literature. Section 2 of this article provides an overview of the relevant theories upon which this study builds and Section 3 lays out the methods of analysis employed. Section 4 presents the main findings, Section 5 discusses their significance and Section 6 concludes with a summary of this study's findings, limitations and opportunities for future research.

5.2. Theoretical Framework

5.2.1. The classic regime-niche actor dichotomy in literature

Transition scholars recognize that in the automotive industry, the acceleration and diffusion of niche innovations depends on the involvement of regime actors (established firms) and, more specifically, relies on collaborations between these firms and newcomers for the development of

[7] In 2015, Porsche, McLaren and Ferrari released 3 hyper-cars; the 918 Spyder, the P1 and the La Ferrari respectively. All three were petrol-electric hybrids, and more importantly, were three of the fastest, most sophisticated production cars to date. They became known in the media as the 'Holy Trinity'.

‘green technologies’ (Geels et al., 2012). Established automakers (OEMs) possess complementary assets such as specialised manufacturing capabilities, distribution channels and service networks that are otherwise unavailable to industry newcomers (Sushandoyo and Magnusson, 2014). Despite this recognition of the important role played by OEMs, the MLP portrays these regime actors as defensive in nature, constantly protecting their entrenched technologies and avoiding collaborations that could endanger their core markets (Berggren et al., 2014). The incumbent strategy toward new technologies is often perceived as a hedge against the possibility of shifting market conditions in an attempt control the pace of technological change, without ever genuinely committing to resolving fundamental environmental issues (Geels et al., 2012). A common MLP argument is that industry incumbents are burdened with ‘core rigidities’ of the old technological regime (Leonard-Barton, 1992) and thus when technological discontinuities occur, new entrants may gain access to the industry through various modern-day versions (Bergek et al., 2013; Christensen, 2006) of Schumpeter’s creative destruction (1942) (See Chapter 1 section 3.1. for more details).

5.2.2. Automakers, innovation and the policies that drive them

The MLP adopts a broad analytical approach to understanding sustainable transitions in an attempt to bridge the dichotomy between technological solutions and behavioural change (Geels and Kemp, 2012). This article, however, focuses on technological solutions, which is justified by the argument that technologies - and the policies that drive them - are the main elements of present-day sustainable mobility. I contend, like others (Beirão and Sarsfield Cabral, 2007; Lane and Potter, 2007; Schwanen et al., 2011; Whitmarsh et al., 2011), that demand-side considerations such as public outreach and change in personal values are unlikely to result in meaningful sustainable transitions. Thus, if technology is the means by which sustainable transitions are achieved, then stringent regulations are the primary driver behind motivating firms to innovate (Gerard and Lave, 2005; Yang et al., 2012). Ideally, low-emissions regulation ‘forces’ a measurable reduction of harm to the environment (e.g. volume of pollutants generated) and increased levels of R&D among firms, resulting in new innovations (Oltra and Saint Jean, 2009). These kinds of ‘technology-forcing’ policies require governments to interact with firms and the markets in a manner that revolves around regulators trying to influence firms to invest in R&D. Subsequently, research has found that firms are more likely to invest in R&D when regulators are committed to enforcing stringent regulations (Nelson and Winter, 1977; Nentjes et al., 2007).

In this article, low-emissions technology-forcing occurs via command and control (CAC) policies, which are deployed by EU regulators in the automotive sector and are classified as general regulatory instruments. These instruments are specifically performance standard regulations (Bergek and Berggren, 2014) for Nitrogen Oxides (NO_x) and Carbon Dioxide (CO_2) tailpipe emissions, and they mandate that automakers must meet a certain level of emissions based on a fleet average (European Commission, 2016). CAC regulations are a technology-forcing strategy where the regulator sets an objective for the future that cannot be met by employing existing technologies (Nentjes et al., 2007; Tarui and Polasky, 2005). CAC policies generally regulate in two different ways: performance-based regulations (performance standards) and technology-based regulations (technology standards). A performance standard is usually the preferred approach when the goal is to induce technological innovation, because the only requirements are target performance outputs and how they are achieved is up to the individual firm (Jaffe et al., 2005; Lee et al., 2011). In this case, emission standards for the automotive industry are based on CO_2 and NO_x emissions, and are therefore technologically 'agnostic', because in theory, petrol, diesel, electric and hybrid propulsion technologies all have the opportunity to meet the specified regulations. For the practical reason that the EU does not use technology-based policies to regulate road transport emissions, they are not considered in this article.

MLP theory, however, cautions that while governments can stimulate innovation with CAC policies, there is a risk of too narrow a technological focus and inward-looking technical learning. We are also reminded that policy makers are beholden to the electorate, public opinion and the automotive industry for jobs, taxes and economic growth. For these reasons, it is argued that policy makers can only govern from within the confines of 'the cockpit' as they are in fact part of the system and are constrained by their dependence on other actors (Geels, 2012). Despite these caveats, transition scholars recognize the effectiveness of automotive emissions regulations, and EU legislation in particular, citing that while initial emissions targets could be met incrementally, longer-term targets would probably require radical innovations (Geels, 2012). MLP studies remain sceptical of EU policymaking, however, arguing that its measures are oriented towards a green technology path rather than a more holistic system-wide transition path (Wells et al., 2011).

5.2.3. Beyond the MLP: An alternate theory of change

Alternatively, there is an argument that creative incremental accumulation has been occurring in recent times rather than radical waves of creative destruction, where new paradigms do not destroy old ones, but rather extend and complement them, offsetting the attacker's advantage (Andersen, 1998; Patel and Pavitt, 1994). Transport studies looking at powertrain competition in the car industry (Bergek et al., 2013) and multi-level actors in the heavy vehicle industry (Berggren et al., 2015), seem to align with this view. They describe the automotive industry as a routinized regime, characterised by conditions of high variability and cumulative resources, which allows incumbents to accumulate technological knowledge and innovative advantages over industry newcomers. This results in technological leadership among incumbents, which explains the concentration of innovation and hierarchical stability among them and the low rate of entry typically observed in the automotive industry (Oltra and Saint Jean, 2009). Thus, complex systems regimes like the automotive industry are characterised by high entry requirements in knowledge, scale and persistence of innovation (Marsili, 2001). Another distinctive feature of established firms is their high levels of knowledge diversification, particularly in upstream technologies coupled with access to external sources of knowledge. These firms are 'active in a wide range of technological fields along similar search trajectories' (Oltra and Saint Jean, 2009, p. 569) and possess the ability to exploit opportunities with high degrees of relevance within their network of R&D activities. A good example of this variation in knowledge assets is the motorsport industry, discussed in later sections, which is identified as an important feature of the automotive regime and their innovative strategy. The central argument here is that the complex knowledge-base is a fundamental barrier to entry for newcomers in the automotive industry. However, aside from this complex technical knowledge-base, there exists a sophisticated network of actors that must also be taken into consideration. For example, the long-standing relationship between OEMs and component suppliers in the development of new technologies is crucial to the analysis of low-emissions innovations in the automotive industry. This high degree of cumulativeness of innovation gives way to incremental innovations along a particular technological trajectory, which in turn can encourage low-emissions innovations if such innovations can be integrated into the regime's current trajectory (Oltra and Saint Jean, 2009).

5.2.4. The new school: Creative Accumulation

Bergek et al. (2013) expand on the concept of cumulative innovation by observing that creativity is difficult for incumbent firms in complex capital goods markets. While previous literature presents cumulative innovation as incremental, step-by-step refinements, Bergek et al. (2013) put emphasis on the tensions between creativity and accumulation. Creativity implies responses beyond the range of existing practices and can be manifested through improvements in cost, performance or quality over previous iterations. Accumulation, on the other hand, implies knowledge creation based on existing practices, rather than making them obsolete. Creative accumulation closely resembles a concept Geels refers to as ‘competence-expanding’ innovation (Geels, 2006), which builds on previous competence-based models of innovation (Tushman and Anderson, 1985). Firms in complex product industries involved in creative accumulation therefore must seek a balance between deep component related knowledge and broad systems related architectural knowledge, implying the added challenge of balancing and using existing knowledge with new knowledge (Bergek et al., 2013). This perspective explains why potentially competence-destroying or disruptive innovations have thus far failed to supplant OEMs in the automotive industry and why automakers have managed to survive and even increase their competitive capabilities. The main reasons given by Bergek et al. (2013) are that (a) attackers are unable to match incumbents’ accumulated knowledge and experience; (b) this expertise allows incumbents effectively to develop solutions at a much faster rate; and (c) competition between established firms means that new entrants are constantly trying to hit a moving target. In addition, I suggest that the evolving industrial standards guiding the regime’s technology roadmap, like the EU’s emissions regulations, represent an additional ‘moving target’ for newcomers. It must be noted that Tesla leapfrogged these changing regulations by going straight to EVs. Creative accumulation therefore highlights the significance of accelerated development, technological exploration and the integration of new competencies, which explains some of the challenges facing new entrants competing in complex capital goods industries (Bergek et al., 2013). The arguments made in this section, therefore, are based on the MLP’s broad analytical framework, while incorporating the concept of creative accumulation when defining the processes by which established firms maintain a competitive advantage in knowledge assets and speed of innovation. The rationale for adopting the Bergek’s concept of creative accumulation over the MLP’s ‘newcomer advantage’, is because prior to data collection and analysis, the innovation processes within the automotive industry appeared to be more accurately represented in Bergek et al. (2013).

5.3. Methods

Research in the transport sector frequently makes use of qualitative methods for inductive purposes, as it permits the identification of concepts and interpretations from the respondent's perspective (Gardner and Abraham, 2007; Steinhilber et al., 2013). This article applies qualitative methods with the intent to capture relevant themes from the perspectives of automakers, regulators and other industry stakeholders based on their experiences. It then becomes possible to establish linkages between collections of different sets of knowledge within the automotive industry.

This study took place between 2014 and 2016 and the primary sources of data were recordings of semi-structured elite interviews with senior industry decision-makers within the automotive sector (industry and government). These respondents were based in the UK, US, Germany and Belgium, and were selectively targeted for their opinions on the role of established firms in the process of low-emissions innovation. **Table 3.** lists the elite respondents interviewed during this study.

Interviewees were specifically selected (non-probability sampling), and in this case, a combination of purposive and chain-referral sampling which allowed for the inclusion of key institutional actors in the data gathering process (Tansey, 2007). In accordance with the ethics approval guidelines of this study, express permission was granted before the recording of each interview, participants were guaranteed anonymity and were assured that recorded data would be destroyed in accordance with the UK's Data Protection Act 1998.

Recorded interviews were transcribed and thematically coded using the Template Analysis method, which gives an account structured around central themes that have emerged, and draws on examples from interview transcripts as required (King, 1998). The conclusions of this study are meant to provide a robust overview of the role of established firms in low-emissions transitions within the automotive industry.

Table 3.

List of interviewees

Institution / Organization	Title / Department
Qualcomm	Senior Executive, Business Development
AVL Powertrain UK	Senior Executive, Leadership
Ricardo	Senior Engineer
Ricardo	Senior Executive, Transmission Systems
UK Government's Office for Low Emission Vehicles (OLEV)	Senior Executive, Leadership
Motorsport Industry Association (MIA)	Senior Executive, Leadership
Ford Motor Company UK	Former Chairman
Advanced Propulsion Centre (APC)	Senior Executive, Business Development
Audi	Senior Executive, Powertrain Development
Jaguar Land Rover	Senior Executive, Engineering
Transport Systems Catapult	Senior Executive, Leadership
Williams Advanced Engineering (WAE)	Senior Executive
Formula E	Senior Executive, Leadership
European Commission	Policy Analyst, Directorate-General for Climate Action
Tesla Motors	Senior Executive, European Leadership
Torotrak Group	Senior Executive, Leadership

5.4. Results

5.4.1. The Post-2008 UK Automotive Industry[8]

Respondents describe the UK automotive industry as having gone through significant changes since 2008, where it transformed itself into a sector that is led equally by industry and by government. A key moment was 2008, frequently described as a period of transition, when the UK automotive industry was adjusting to several crises, the first of which was the ‘hollowing out’ of the UK automotive supply chain, which had started in the 1970s. Hollowing out refers to a gradual reduction in the locally sourced content for vehicles built in the UK, involving the flight or dissolution of many automotive supply chain companies, or their rationalisation within bigger groups. OEMs were partly complicit by encouraging supply chain companies to achieve low-cost sourcing in overseas territories. This loss of productive capacity reduced the local content in UK-built vehicles to approximately 35% in 2008, compared to Italy, Germany and Spain who typically achieve local sourcing content of approximately 60% (Automotive Council, 2014). A second, more immediate, crisis was that several OEMs were in danger of bankruptcy as a result of the global financial crisis (Muller, 2016). The final major problem for the industry was that OEMs were also in the midst of readjusting their corporate strategies to meet CO_2 emissions targets that had just been re-negotiated with the European Commission that same year. The first target to be met was a fleet average of 130g CO_2/km by 2015 (European Commission, 2016), which was considered a relatively short time in the automotive industry.

The New Automotive Innovation and Growth Team (NAIGT) was formed in 2008 and was tasked with developing a comprehensive strategy that would navigate the industry past the difficult times ahead. After a year’s worth of research and discussions on the future of the UK automotive industry, one of the major results was the creation of the Automotive Council in 2009 and the publication of its industrial strategy in 2013. At the heart of the strategy was the UK’s decision to transition to a completely different business model for the island’s automotive industry. One of the major impacts was the establishment of the Catapult network, which has been described by respondents as the UK’s equivalent of the German Fraunhofer Society. After the Second World War, Germany established a nationwide network of technology innovation centres, part-funded by

[8] For the purposes of this study, the ‘Automotive Industry’ refers exclusively to the Light Duty Vehicle market, defined by the UN as passenger cars and commercial vans (IPCC, 2014a).

the federal government, and part-funded by local state funding and regional banks. Their mission was to help small and medium-sized businesses develop their products, processes and commercialisation capabilities in the marketplace. That network, built upon relationships between academia, industry and government, is the German Fraunhofer Society. During interviews, a few senior respondents were of the opinion that within the last 7 to 8 years, government policy in the UK had been influenced by the success of the Fraunhofer network in ushering in innovation and commercialisation of R&D capabilities. The UK Catapults, for example, are testimony to the UK's adoption of this innovation partnership. There are eleven centres in the Catapult network and fundamentally, these organisations have been part-funded by the British government to accelerate the development and production of early technologies in the UK, while attracting industry funding to match the government's contributions. It is important to note that a crucial element of the Catapults' endeavours is to attract the involvement of Small and Medium-sized Enterprises (SMEs), as they are a vital part of the domestic value chain. The UK government's hope is that the Catapults will become successful models of innovation and a means of introducing new technologies into the marketplace, while making the UK more competitive against other car manufacturing nations like Germany, Japan and the USA.

5.4.2. The UK's innovation approach: consolidated research and development

The automotive strategy set out in the industry's 2013 technology roadmaps[9] is heavily focused on energy efficiency and technological innovation, specifically low-emissions innovation. These areas are perceived by industry respondents as their opportunity to significantly reduce CO_2 emissions from road transport. What stood out in the UK's new industrial strategy was the highly integrated approach that was kick-started by the NAIGT, and is now prevalent throughout the UK automotive industry. Take for example the UK Office for Low Emission Vehicles (OLEV), which is made up of representatives and ministers from the Department of Transport (DfT), the Department of Business, Innovation & Skills (BIS) and the Department of Energy & Climate Change (DECC). OLEV's day-to-day operations are overseen by ministers within those three departments in a collaborative mission to reach 'zero emissions' in the UK, and it can be argued

[9] For more details see (The Automotive Council, 2013).

that this collaborative approach speaks to the integrated outlook the UK has adopted for its automotive industry.

Another prime example of integration and the use of complementary assets is the way the motorsport[10] industry is used by the automotive sector to accelerate low-emissions innovation. The relevance of motorsport to mainstream automotive became increasingly clear as the capability of motorsport companies to rapidly engineer solutions for testing and demonstration was recognized as a potentially significant asset to the UK and its automotive industry. The focus on low-emissions innovation, brought on by stringent EU emissions regulations, meant that much more research and development in the areas of electrification and systems integration (hybridisation) would need to be undertaken. Fortunately, not only had the motorsport industry already been developing energy efficient solutions for many years, they had also acquired key competencies that were highly relevant to low-emissions innovation in the form of rapid prototyping and highly skilled engineers. The European motorsport industry further supported its contribution to low-emissions innovation by encouraging the ‘right technologies’ on the racetrack. This was achieved with the implementation of ‘relevant regulations’, such as the rule changes that mandated Formula One’s switch to hybrid-electric propulsion in 2014. There was also integration at the administrative level where the UK’s Motorsport Industry Association (MIA), for example, was on the Automotive Council, as well as the Technology Council and each had their own technology roadmaps. So, a much closer and intentional alignment developed between these related industries, and in a time of great difficulty, the UK automotive sector found an ally in their motorsport industry and together they would go on engineer their way past the economic crisis.

Within the UK automotive industry, the current funding for propulsion technology over the next 10 years is set at £1 billion, which is split 50-50 between government and industry, each contributing £500 million with a total budget of £100 million a year for 10 years (Foy, 2013). This funding is not for production costs; it is strictly allocated to the development of future powertrain concepts. Respondents also noted that the industry’s language has transitioned from ‘engine’ to ‘propulsion’, which more accurately reflects their low-emissions R&D agenda. According to one industry executive, ‘everything on the drawing board is up for consideration’.

[10] Specifically, Formula One racing and the World Endurance Championship

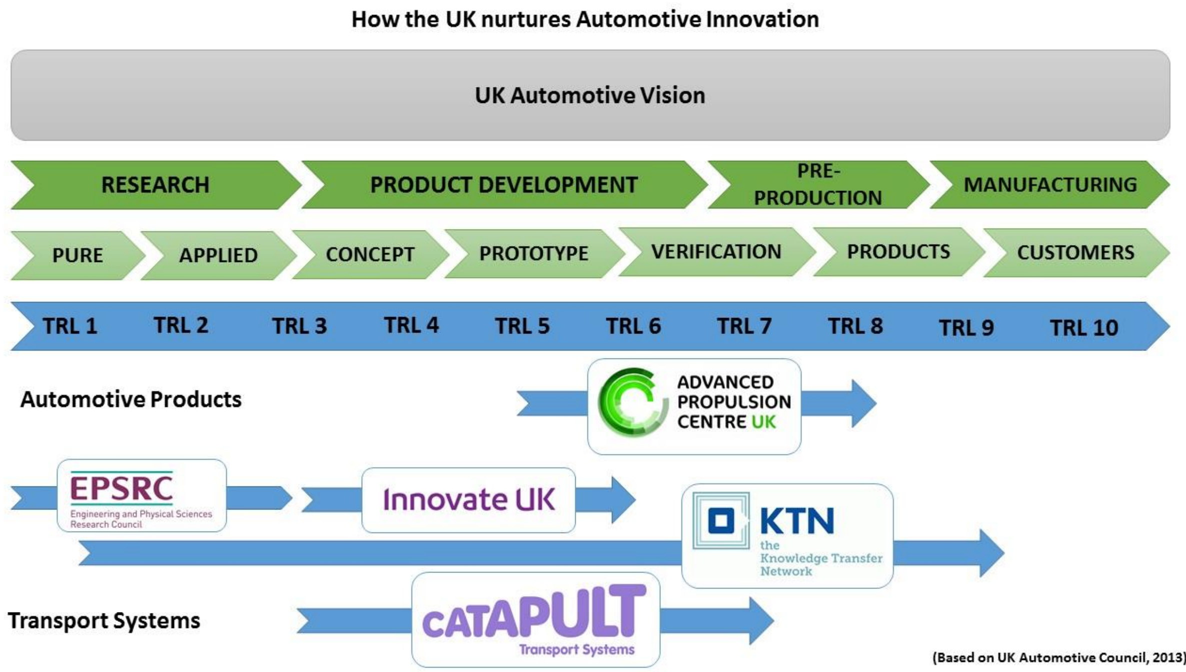
Among the many organizations observed in this study, the UK's Advanced Propulsion Centre (APC) most aptly embodies the theme of collaborative effort within the context of low-emissions innovation. The APC was formed in 2013 as a government-industry collaboration orchestrated by the Automotive Council in an effort to position the UK as a global leader in low-emissions powertrain development and production. The APC hosts biannual competitions where entrants compete by submitting low-emissions technology project proposals. These competitions are completely technology agnostic, meaning that any type of propulsion system (electric, diesel, etc.) is considered as long as its CO_2 emissions are in line with EU regulations. Very importantly, the submission must be part of a collaboration between a SME - generally a university and/or a supply chain company – and an OEM or Tier 1 supplier, because the point of the competition is to advance those types of projects through the 'valley of death'.

5.4.3. The 'valley of death'

The valley of death is an industry term that indicates a specific point in an innovation's lifecycle that is underpinned by an empirical industry measurement: the Technology Readiness Level (TRL). TRL is a method by which the technological maturity of a particular innovation can be estimated on a scale from 1 to 10, and was originally developed by the National Aeronautics and Space Administration (NASA) in the US (NASA, 2015). In the UK automotive industry, the valley of death refers specifically to TRL 4-6, which is perceived as the most perilous phase of any technology's development. A project that is TRL 1 or 2, usually seeks out organizations like the Engineering and Physical Sciences Research Council (EPSRC), which mainly funds university projects that are just starting off. Once an innovation reaches TRL 5, then project leaders may approach an organisation like the APC, where they come with a pre-arranged partnership or the APC can help them find one. At this stage, the project has a working prototype but the innovators don't know how to commercialize it. This is where the APC is able to assist the project in finding solutions, build collaborations and help the project enter the APC competition. **Figure 1.** illustrates the various productive phases and technological typology of the TRL, as well as some of the appropriate agencies involved throughout the development cycle (APC, 2014). A related concept of equal importance in assessing an innovation is the Manufacturing Readiness Level (MRL). MRL measures the maturity of the manufacturing supply chain, which is highly relevant to the automotive industry in assessing factors like the capabilities of suppliers, quality assurance and the production costs of an innovation that is being considered for mainstream deployment. While newcomers may come forward with innovative technological proposals, TRL and the MRL are very good tests for an innovation's chances of achieving production. According to one senior engineer of a leading Tier 1 supplier:

> Unless newcomers can actually get their innovations into production state, it just sits on a shelf at home. So, while newcomers may dream up superb innovations, they cannot practically get them as an effective change in the market without knowing how to do that, mastering the game of scale.

Figure 1. Technology Readiness Level



Therefore, a newcomer (small innovator / SME) to the automotive industry may have a working prototype, but lack the required funds, effort and know-how to get that innovation through to the open market. Industry respondents refer to that phase as the 'valley of death', the place where many new and innovative ideas perish.

5.4.4. Component Suppliers

The role of component suppliers, particularly Tier 1 suppliers (T1s), in automotive innovation has been seriously undertheorized and mostly neglected in transition studies. According to the chief engineer of one of the UK's largest component suppliers:

> A Tier 1 supplier is a company that can supply a component or module that is fit for purpose for primary assembly onto a vehicle. It is delivered into the production facility of the OEM and it meets all of their specifications and requirements. All validation (if necessary) has already been done on that component and it is fully approved, certified and ready to be assembled onto the vehicle.

The first important fact to consider is that according to all respondents in this study, T1s are responsible for between 75%-90% of the technological content in any given passenger car. This fact indicates that OEMs are increasingly becoming systems integrators rather than actual manufacturers, and that T1s are doing the majority of the R&D and production of new technologies. Tier 1 suppliers have become comfortable with being the R&D departments of OEMs, and some have stated that they are simultaneously aligning themselves with research partners such as universities or small-companies that can feed into their business model by providing the research capacity while they focus on the development end. In general, suppliers have been calling for better cooperation between themselves, universities and OEMs. For example, in Germany, the component supplier FEV works very closely with Aachen University (FEV, 2015), while AVL, another supplier, also works closely with Graz University (TU Graz, 2017). This type of cooperation has been seen as an area of weakness in the UK by German supplier respondents, where greater engagement with academics as well as engineers is needed, and was expressed by a senior executive of AVL as follows:

> I just think honestly, if the UK wants to stay producing wonderful cars like JLR does, we need R&D companies. We need companies like ourselves and FEV as well as smaller R&D companies, and what we need honestly is a better cooperation between universities, OEMs and companies like ours. We have great universities in the UK, but what we're missing in the UK – sorry I'm German – [is] more engineers educated in the UK, which [is] more practical, and not [just] academics. This is the thing I would say we have to put emphasis on in the UK, because this is done much better, sorry to say, in my own country [Germany].

UK industry respondents are especially keen to establish partnerships between universities, SMEs, OEMs and suppliers; facilitating the appropriation of intellectual property (IP) at the academic level. This framework would allow OEMs to more easily spot very good but undeveloped ideas that they wouldn't usually entertain, and translate them into production through an existing, known and proven supply chains. One such example is the recent long-term commitment between Jaguar Land Rover (JLR) and the University of Warwick, with the establishment of the National Automotive Innovation Centre (NAIC) on the university's campus (University of Warwick, 2016). While interesting for various reasons, the commercialization of academic research in this context is beyond the scope of this article, but is certainly worthy of future academic attention.

5.4.4.1. Supplier relationships

Among respondents, a strong sub-theme concerning the nature of the various relationships that suppliers maintain with other actors began to emerge when discussing the role of component suppliers in the industry. Hence, this sub-theme is isolated and given further consideration here.

Tier 1 suppliers develop technologies that they sell to the automakers, hence they are considered as part of the industry lobby. They understand, however, that EU emissions regulations forces money to be spent on the development of new technologies, which results in reduced emissions and better fuel economy for consumers. Hence a lot of the companies that provide hardware and software emission control equipment, like BOSCH for example, are T1 suppliers and therefore pay close attention to the legislation and maintain close contact with regulators. So, it is in the interest of technology suppliers that regulations exist because it means that they are able to develop new technologies to sell to manufacturers. During this study, it was apparent that the good working relationship between EU policymakers and component suppliers, particularly Tier 1 suppliers, has proven to be a valuable resource to the European Commission in bolstering their credibility as regulators. The Regulator-Supplier relationship is an important one because suppliers are keenly aware of what is technically possible in the context of providing regulators with feedback on future regulations. This relationship helps to compensate for the technical knowledge asymmetry between regulators and OEMs, allowing regulators to better approximate the real emissions targets that OEMs are capable of achieving. There is a balance that must be preserved, however, and suppliers are careful to remain neutral because they must balance their relationship with the OEMs who are their primary customers, with the demands and requirements of the legislators. Suppliers therefore, try to keep a ‘low profile’ in their interactions with regulators.

On the other hand, the relationship between Tier 1 suppliers and OEMs can be contentious at times, for a variety of reasons. One popular point of contention among respondents was the issue of open book pricing. Open book pricing (or costing) is a parts-buying program where the OEM forgoes conventional supplier bidding. Instead, the OEM inspects the suppliers' factories, analyses their internal cost data and makes them an offer based on that analysis. Suppliers who agree may be privy to an exclusive contract with that OEM for periods ranging up to the life of a vehicle. Open book pricing has been difficult for suppliers as they perceive it as OEMs ‘flexing their muscles’. According to one senior executive, when OEMs use open book pricing, they are in effect saying; ‘Tell us exactly how you’ve priced this component, otherwise you won’t get the business’.

In the past, suppliers have perceived this practice to be quite ruthless (Sedgwick, 2015), but some supplier respondents now believe there has been some softening and leniency from the OEMs. These respondents are of the opinion that OEMs realise their success is becoming increasingly reliant on good relationships with their suppliers. Recently Tier 1s have also been partnering together, creating a larger, more stable and commercially robust presence in the marketplace.

5.4.5. Established firm advantage in scale and scope

We have already seen that the ability to rapidly develop and deploy innovation is one of the crucial differences between incumbents and newcomers. Not only are OEMs able to deploy their upscaling capabilities in their R&D and innovations, but they are also able to use this same concept of scale when sourcing from suppliers as a cost cutting measure. A senior executive of a major OEM gave the example of grouping together with other OEMs to procure electric batteries at a significantly reduced price. This tactic was not only an exercise in cost cutting, but also a strategic move to keep overall costs down in the face of incoming competition from industry newcomers. According to one industry executive:

> The expertise of the OEM lies in their ability to get an innovation into production and make 20,000 cars of it.

Another strategy frequently employed by OEMs is economies of scope, in the form of platform sharing. Due to the modular architecture of the automobile, OEMs can share many design components between themselves and then apply their own branding to the finished product. Respondents admitted that they know, and have already proven, that consumers buy brands not engines. The example given by a senior automotive executive of the UK's Automotive Council to illustrate this was that the Bentley Continental and the Volkswagen Phaeton share the same chassis, yet one demands £250,000 and the other £60,000. Respondents argued that the platform, ride quality and many other features are comparable, yet consumers are content to continue buying both Bentleys and Volkswagens. There is already extensive platform sharing going on between rival automakers, and respondents have signalled that this practice is moving towards collaborative technology development and is bound to accelerate in the face of challenges from outsiders[11]. One example of this is the collaboration between BMW, Nissan, Renault and Volkswagen on the Rapid Charge Network (RCN) where they are jointly developing a multi-standard, rapid charging network for electric vehicles throughout the UK and Ireland.

5.4.6. Newcomers in the UK automotive industry

Conversely, respondents indicated that a major barrier to entry for small firms in the automotive industry was the challenge of scale. Taking a technology developed at a university, building a functional prototype, and then fitting it into a car that will be driven for 15 to 20 years without the expectation of failure is often beyond the capabilities of new industry entrants. According to one T1 executive:

> Quality assurance is an expensive, long part of the development cycle that no start-up or small-company is able to achieve, so they necessarily need to partner with the companies that focus on scaled up production like Tier 1 suppliers.

According to all three senior OEM respondents, newcomers may enter the industry with radical innovations because they cater to niche markets and consumers with higher levels of tolerance for reliability issues that would otherwise be unacceptable from brands like Mercedes or BMW. Mainstream manufacturers submit their cars to such rigorous levels of validation, that – in the opinion of respondents - if any small car company tried to do the same, the process would bankrupt them. Thus small scale or 'boutique' manufacturers have small customer bases, which makes it easier to control quality issues. Large manufacturers, on the other hand, must have much stricter

[11] Newcomers to the industry were referred to as outsiders by most respondents

quality controls as recalls have severe consequences on their share prices. Recalls are also hugely expensive as OEMs must pull every affected vehicle off the road, find an effective fix and pay all affiliated garages for carrying out the appropriate repairs. Alternatively, niche market manufacturers supplying cars in the hundreds, can more easily manage quality issues due to their smaller scale of operation. Nine out of twelve respondents asked were of the opinion that many automotive start-ups often tend to underestimate the complexity in engineering.

Another important fact, which began to emerge, was that the types of technologies newcomers were bringing to the marketplace were significantly shaped by regulation. As one APC executive observed:

> I'll go back to the classic quote 'necessity is the mother of all invention'. It's been EU regulations in my opinion, that drives the innovation. We've got to hit certain CO_2 targets for cars and that drives the OEMs which in turn affects the SMEs' ideas and innovations.

This quote is quite telling, and is in line with the underlying sentiment of all respondents, which was that emissions legislation had to be a primary concern for industry newcomers if they were to find any relevance for their product in the UK market.

While it is acknowledged that SMEs will struggle to traverse the valley of death without the help of an established firm, there are some exceptions. For example, some newcomer respondents noted that it is was easier initially to push certain types of innovation into alternative markets, such as technologies being used in excavators and buses, which they referred to as 'off-highway applications'. But when a niche innovator gets to the point where they need to set up a production line and invest millions in machinery and production line equipment, then it quickly becomes prohibitive. Hence if an SME wishes to continue the transition into the car market, the support of a Tier 1 supplier becomes essential, because considerable effort and capital is required to 'de-risk' the proposition for OEMs who might be interested. Newcomer respondents, who were owners and engineers, viewed the acquisition of SMEs by established firms (T1s or OEMs), and the sale of their intellectual property as a desirable financial transaction. Some SME owners were even kept on as non-executive directors within the incumbent organization after the sale, as was the case when the small firm Flybrid Automotive, was bought by the Torotrak Group in 2013.

The other recent exception to the valley of death has been Tesla Motors. In the media, this premium electric vehicle (EV) manufacturer has been praised as an industry ‘disruptor’ due to the popularity of its Model S and the pre-order success of its 2017 Model 3. However, established firm respondents point out that despite Tesla’s rapid success, CEO Elon Musk had to invest vast amounts of capital to get the Model S to market. They also noted that the parts for the Model S are sourced from over 300 component suppliers globally. In Tesla’s case then, it can be argued that their EV technology was within the capabilities of mainstream OEMs, but their ‘disruptiveness’ actually stems from the business model they chose to pursue. The Model S occupies a unique space in the automotive market by combining a premium tier automobile with electric propulsion, which, to date, no other OEM has offered. Despite its success, Tesla is a testament to the significant amounts of capital required to develop a passenger car as a newcomer.

5.5. Analysis and discussion

5.5.1. The UK’s transition pathway

The UK’s automotive sector is a longstanding, stable industry that is characterized by deeply entrenched isomorphism and powerful landscape determinants that reinforce the existing regime (Wells and Nieuwenhuis, 2012). However, in 2008, the landscape shifted and threatened to usher in an era of de-alignment or breakdown in the regime (Geels, 2012). Faced with several challenges, the automotive industry quickly assessed and restructured itself in a manner that fully integrated the efforts of policymakers and industry stakeholders into one common vision. The new partnership between government and industry was built around a development framework of vertical integration, where the common vision transcended from the landscape level down to the niche levels of the industry. The transition pathway chosen by the UK was one of incremental low-emissions innovation which, at the technological level, was agnostic in its approach, as was demonstrated by the establishment of the Catapult Transport and APC development centres. At a higher level of abstraction, however, it can be argued that post-2008, the UK set aside agnosticism in favour of overt industrial policy intervention, effectively picking the automotive industry as ‘a winner’ by considering it ‘too big to fail’. For the UK, the automotive sector is considered a ‘pillar’ industry and therefore an era of technological transformation (Geels and Schot, 2007) was introduced in alignment with the newly conceptualized technology roadmaps. This new era, however, was not led by 'niche-innovations', but instead was driven by industry incumbents; a trend also seen in recent research into the heavy vehicle industry (Berggren et al., 2014). This new wave of technological transformation, spurred by the expansion of incumbents' existing knowledge, is arguably an instance of creative accumulation (Bergek et al., 2013). In this scenario, the independent innovative efforts of niche actors are either completely suppressed or absorbed by established firms with their mastery of complex knowledge in the capital goods market.

This paper focused on the crucial role of established firms in order to gain a deeper understanding of the cooperation and support involved in initiating meaningful technological change. The cooperation between government and industry in the UK effectively acts as a translator (Smith, 2007), or a bridging construct (Sushandoyo and Magnusson, 2014), for the rapid development of new technologies beyond incubators or niches and into broader market spaces (Berggren et al., 2014). In this particular case, established firms engage in innovation at all levels of the sociotechnical system and use the 'bridging construct' to support the steady development of promising technologies. I argue that the valley of death, or TRL 4-6, is the most significant barrier to entry into the industry. I also argue that transition scholarship could potentially benefit from embracing the industry's TRL and MRL scales, as a much more accurate method of assessing a technology's maturity. Taken a step further, the TRL and MRL of a given technology can then be cross referenced with the industry's roadmap (if available) for a much deeper and contextual understanding of where that technology lies in a given industry's transition pathway.

5.5.2. Established firms as multi-level actors

In this paper, I primarily argue for a reassessment of established firms in the automotive industry, based on the observation of two major attributes not accounted for in mainstream transition literature: first, that established firms are multi-level actors in the innovation process; and second, that they possess an uncanny reflexivity in response to shifting regulatory and competitive pressures. Regarding the first attribute, the MLP in sustainable transition scholarship traditionally defines industry newcomers as operators at the niche level, while established firms' activities are relegated to the regime level. In this article, I revise this somewhat simplistic arrangement of actors by demonstrating that industry incumbents are driving innovation at both the regime and the niche levels of industry, while competing with other incumbents as well as newcomers in these sociotechnical spaces. This dynamic behaviour – or creative accumulation - displayed by established firms, further supports recent calls to reconsider traditional static representations of the incumbent-niche dichotomy within the multi-level framework (Bergek et al., 2013; Berggren et al., 2014). The conceptualisation of established firms as multi-level actors also contributes to the academic understanding of the component supplier. Component suppliers are arguably the most innovative, yet the most obscure, ‘class’ of established firm within the automotive industry. They conduct the majority of R&D and maintain equally good relationships with OEMs and regulators. Thus, their expertise makes them indispensable to any size firm interested in manufacturing an automobile. Relationships with them are not only unavoidable, but also mutually beneficial, especially to newcomers, who are trying to move their innovations across the valley of death, and into the mainstream. OEMs, however, use component suppliers to reinforce their innovative and productive capacity - and by proxy - their dominant position within the automotive regime.

The second major attribute of established firms observed by this study was the overall level of reflexivity demonstrated by OEMs and suppliers. Post-2008, not only did incumbents restructure themselves fiscally, but as this paper has shown, they also had to adopt a radically different R&D framework while implementing sufficient technological change to meet their emissions target obligations for 2015. These high levels of reflexivity contradict the typical characterization of ‘regime actors’ as being slow to react to changing market conditions. At the very least, this article has sufficiently demonstrated that these traditional theoretical propositions (Sandén and Azar, 2005; Wells and Nieuwenhuis, 2012) are not applicable to today’s automotive industry.

This paper has also observed how established firms leverage strategic relationships (procurement), and economies of scale and scope (platform sharing) against competitors, which further reinforces their dominant position in the industry. The deployment of the motorsports industry as a specialized and complementary asset is a further example of OEMs’ disproportionate access to complex knowledge (Berggren et al., 2014), which effectively acts as an insurmountable advantage over new entrants to the industry. Another major barrier to entry for newcomers identified here is the issue of quality assurance, as automotive certification is prohibitively costly for small newcomer firms, who are also unable to manage defect recalls at scale. An important reality for newcomers that is alluded to throughout this article is that niche development in the UK is now primarily being driven by government-industry partnerships. While newcomers can often signal new technological opportunities, their cognitive search for innovation is ultimately guided by the post-2008 low-emissions agenda. While these EU low-emissions regulations are reasonably broad and technologically agnostic, they are still very much set within a selection environment (Nelson and Winter, 1977) created by the common vision of the government-industry partnership.

5.6. Conclusion

The interaction between the niche and regime levels of the sociotechnical framework has been the primary mechanism by which scholars using the MLP have sought to explore various pathways towards sustainable transitions. In doing so, operators within the multi-level framework have been stereotypically assigned the role of either 'niche-actors' or 'regime-actors' with regards to their industrial behaviour. According to Nelson and Winter (1977, p. 41) 'Any useful and coherent theory of innovation must recognise explicitly the factors that differ across industries'. Therefore, the sector specific analysis conducted in this paper represents an attempt to deliver operational insights into the role of established firms in sustainable transitions within the automotive industry. The resulting theoretical contribution of this article is to challenge the conceptualization of established firms as entrenched 'regime actors', whose default course of action is to either defend against, or reluctantly engage with newcomers and their disruptive innovations. On the contrary, I argue that industry incumbents, supported by their creative accumulation of complex knowledge, are keenly sensitive to low-emission futures and highly reflexive in their pursuit of innovation across all levels of the sociotechnical system. This high-resolution analysis of the automotive industry is a differentiated step away from the simplistic incumbent-niche dichotomy, and a step towards a more capable framework of analysis that better reflects the complex and nuanced mechanisms of change within the automotive industry. At this point, it is important to note that nearing the end of this study, Geels et al (2016) published a reformulated typology of sociotechnical transition pathways originally conceptualised by Geels and Schot (2007) nearly a decade earlier. In redefining the Transformation pathway, they acknowledged that established firms were also capable of pursuing radical innovations, contrary to what is commonly assumed in the MLP. By going beyond the dichotomy of 'incremental incumbents' and 'radical newcomers', Geels et al (2016) embrace the contemporary scholarship of creative accumulation (Bergek et al., 2013; Berggren et al., 2015), and by proxy, the theoretical foundations of this research. Given the insights set out in this paper, it may be possible to apply some of these ideas to better understand technological transitions in other highly regulated, complex capital goods industries such as the energy, aerospace or construction sectors.

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Chapter 6

Paper Title: Level 5 autonomy: The new face of disruption in road transport

Submitted manuscript under review in *Technological Forecasting & Social Change* (ISSN: 0040-1625)

Abstract

Over the past decade, the gradual transition away from internal combustion engines (ICE) to battery electric vehicles (EVs) has been perceived, from a theoretical perspective, as the best pathway available out of the petroleum industrial regime, and towards more sustainable mobility. In 2017, however, the EU road transport sector is poised to deploy a host of advanced intelligent transport systems (ITS), including connected and autonomous vehicles (AVs), which are expected to be more 'disruptive' than any other technology to date. This vision of the future is also fuelling a virtual 'arms race' among automakers (OEMs), who are forging unconventional alliances and investing heavily in R&D, to ensure their competitiveness in anticipation of a radically changing industry. Car travel seems set to undergo a paradigm shift, evolving from a privately-owned asset into a mobility service; a metamorphosis that will have huge implications for policymakers and industry stakeholders alike. Currently, academic discourses on autonomous driving are still very technically focused, and how the sociotechnical transition is likely to unfold remains uncertain. Similarly, the integration of autonomous technology into the wider framework of sustainable mobility lacks analytical scrutiny. This paper therefore seeks to address these gaps in knowledge, by using primary qualitative interview data from industry and government elites to analyse the early-stages of the AV revolution within the EU automotive industry. This paper also assesses the major policy challenges facing the industry regulators tasked with underwriting this radical and dynamic transition to autonomous driving.

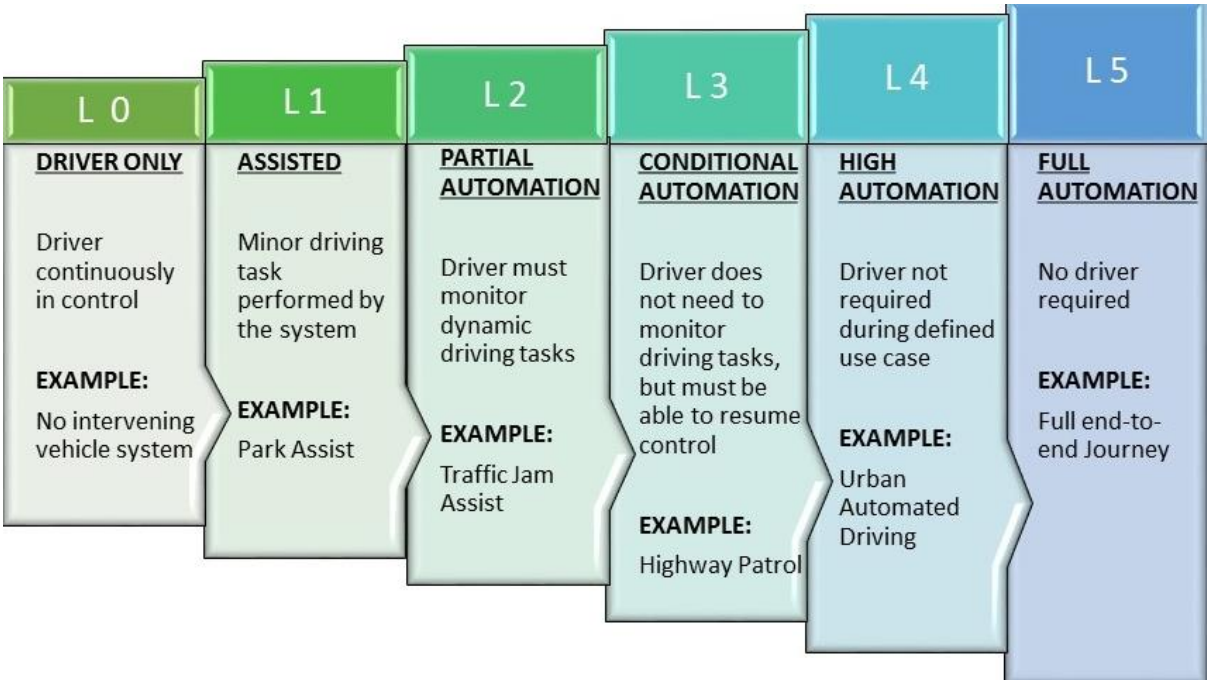
6.1. Introduction

The focus of this paper is the autonomous vehicle (AV), or more precisely, the 'connected *and* autonomous' vehicle, which integrates connectivity *with* autonomy. These are distinct, yet related technologies, and should be treated as such (GOV.UK, 2015). Automation of the driving task is a significant leap forward in technology, but its full benefits are realized when the vehicle is also capable of being aware of other vehicles (vehicle to vehicle connectivity; V2V) and its physical surroundings (vehicle to infrastructure; V2I). Not only does V2V and V2I provide the AV with additional data for more efficient operation, but connectivity also acts as a redundancy system if the AV ever loses its 'over-the-air' signal (Dey et al., 2016). In such a scenario, it would retain its ability to make sense of its surroundings thanks to connectivity. As one senior official from the UK's Centre for Connected and Autonomous Vehicles (CCAV) put it:

> Autonomous vehicles on their own operate quite well, but putting several autonomous vehicles together begins to cause certain issues, therefore collaborative communication [i.e. connectivity] between them has been one way to solve some of those problems.

In 2014, SAE International, the multinational automotive standardization body, published a classification system based on six increasing levels of autonomy (SAE, 2016), ranging from Level 0 which represents no autonomous driving function to Level 5, where no human intervention is required. It is useful to understand this scale, as industry insiders often use it to reference technological milestones within a given timeframes (e.g. Level 5 autonomy by 2030). See **Figure 2**.

Figure 2. Defined levels of automation (for road vehicles)



In general, industry developers believe that driverless cars are still quite an abstract concept to society at large, and perceive the advances being made in autonomous technology to be taking place in somewhat of an industry 'bubble'. The average industry expectation, however, is that Level 4 autonomy will be widely available in 3-5 years (Etherington, 2017), and for this reason, stakeholders from Transport Systems Catapult (TSC)[12] in particular, continually advocate the need for much wider public awareness. With the aim of contributing to public awareness, this paper presents autonomous driving as an immediate sociotechnical concern, which has arguably caught policymakers flat-footed, forcing them to reconsider the laws governing the sector much sooner than anticipated. This paper therefore seeks to (1) identify the major disruptive implications of the AV sociotechnical transition and (2) ascertain the early legal concerns surrounding the technology. Given that we are in the infancy of the driverless transition, these two aims will highlight the most salient areas of concern, and provide academics and policymakers alike with the major rationales for appropriate policy intervention. Section 2 begins with a brief overview of relevant and

[12] The Transport Systems Catapult is one of eleven elite technology and innovation centres established and overseen by the UK's innovation agency, Innovate UK (TSC, 2017).

overlapping literature between Innovation Policy and Transition literature. Section 3 lays out the methods used in this research and Section 4 presents the main findings. Section 5 discusses the most pressing challenges regarding the driverless transition, the regulation of the technology, and concludes by posing several theoretical questions, while suggesting areas for future research.

6.2. Theoretical Underpinnings

6.2.1. Information and Communication Technology (ICT) and Intelligent Transport Systems (ITS) in the automotive sector

ICT and ITS are both precursors to autonomous vehicle technology, hence it is worth briefly discussing here how they are conceptualised in academic literature. Location-aware technology in the transport sector traditionally refers to ICT, which has been gathering momentum since the 1990s (Geels, 2007) and its societal impact, especially in urban settings, has been extensively discussed in academic literature (Batty, 1997; Beecham and Wood, 2014; Graham and Marvin, 2001; Shen et al., 2013; Steenbruggen et al., 2015). More interestingly and relevant to this paper, is the burgeoning research on ITC issues concerning the security, ownership, access and ethics of data usage (Cottrill and Thakuriah, 2011), which as we shall see, has become highly relevant to the autonomous vehicle debate. In recent years, the automotive industry has become increasingly bullish on the integration of ICT with automobility, especially automakers, map digitization firms and telecom providers (Geels, 2012). This technological phenomenon has become known as ITS, and is characterised by advanced information gathering, accident reporting and traffic flow management (European Commission, 2017).

6.2.2. Sociotechnical Transitions

The incoming paradigm shift within the automotive sector, where personal mobility evolves into a shared transportation service, is viewed in this paper through the theoretical prism of the Multi-Level Perspective (MLP) (Geels, 2012). This sociotechnical transition theory offers significant insight on how societal actors form networks of interdependencies within a given sector (Geels and Kemp, 2007). The MLP develops the concept of socio-technical systems as a cluster of aligned elements including science, technology, regulations and user practices (Geels, 2012). This paper however adopts a derivative view of the MLP, which suggests that creative incremental accumulation has been occurring in recent times, rather than radical waves of creative destruction. Proponents of this view argue that new paradigms do not destroy old ones, but rather extend and complement them (Andersen, 1998; Patel and Pavitt, 1994), therefore offsetting the 'attacker's advantage'. Transport scholars of this persuasion describe the automotive industry as a routinized regime, characterised by conditions of high variability and cumulativeness, which allows incumbents to accumulate technological knowledge and innovative advantages over industry newcomers (Marsili, 2001). This results in technological leadership among incumbents which would explain the concentration of innovation and hierarchical stability among them and the low rate of entry typically observed within the automotive industry (Bergek et al., 2013; Berggren et al., 2014; Oltra and Saint Jean, 2009).

Relevant to this paper, it would appear that the MLP has correctly anticipated some of the evolutionary phases that ITS is currently undergoing. Most notable among these are the emergence of the 'cybercar', 'digitally enacted environments' and automated vehicle guidance (Geels, 2012). The MLP has also correctly estimated that these kinds of technologies would be stimulated by national innovation policies, as is currently the case in the UK (Skeete, 2017). However, it is the 'post-MLP' literature discussed above that is largely responsible for explaining the role of established firms as lead innovators of autonomous technology in the automotive industry (Bergek et al., 2013; Berggren et al., 2014). Understanding these concepts of systemic change allows for a textured interpretation of the industry data collected throughout this study, and a more considered assessment of the initial sociotechnical implications of autonomous technology. I argue therefore that by understanding these processes of change, transition scholars can (a) more accurately assess the disruptive potential of AV technology and (b) identify evolving policy concerns that will continually challenge the development and diffusion of this technology.

6.2.3. Regulating innovation

One of the integral groups of actors within the MLP are policymakers, or regulators, and discussed in this section are the common ways in which they approach technological innovation within the automotive sector. Since the 1960s, OECD countries and emerging economies have sought ways to encourage the development of new technologies that benefit society (Bergek and Berggren, 2012). The two most widely used policy instruments are strict command-and-control (CAC) regulations and market-based instruments (MBI). CAC policies are regulations that force consumers and producers to change their behaviour, while MBIs provide financial incentives to stakeholders in exchange for shifts in their behaviour (Santos et al., 2010). Traditionally, technological design has followed regulation (Foxall and Johnston, 1991), and the imposition of regulations in the automotive industry has stimulated the development of the ‘right kinds’ of innovation (Nentjes et al., 2007; Tarui and Polasky, 2005). Regulators establish legitimacy by having a sound technical understanding of the industry, eliminating information disadvantages (Gerard and Lave, 2005; Pindyck, 2007), and having good regulatory programmes and robust political support (Kleit, 1992). These qualities are key for any regulator seeking to accurately assess the technological capabilities within their industry, and just as importantly, estimate the implications of future technologies.

While the MLP adopts a broad analytical approach and attempts to bridge the dichotomy between technological solutions and behavioural change (Geels and Kemp, 2012), this paper is more influenced by the ‘technology fix’ end of the MLP spectrum, and in fact argues that cars and technology (and the policies that drive them) are the main elements of present-day sustainable mobility. Within the automotive industry, CAC regulations have proven to be effective (Brown et al., 2010; Lee et al., 2010; Santos et al., 2010) and research has shown that several low-carbon technologies have been successfully driven by technology-forcing policies (Clerides and Zachariadis, 2008; Schot et al., 1994) and performance standards (Atabani et al., 2011).

6.2.4. Private car ownership

This section concludes by briefly discussing the academic debates surrounding private car ownership, because the concept of private ownership, and the deviation from it, serves as the theoretical platform from which several of this paper’s central arguments are made. Private car ownership facilitates personal mobility, enabling distance to be easily overcome and thus making available a wider selection of activity sites such as work, shopping and recreation. One could argue that the automobile has altered national geographies unlike any other mode of transportation (Moon, 1994). In the UK, for example, between 1976 and 2001, distances travelled per person using all modes of transport increased by 44%, while car use increased by 67% (Knowles, 2006). Thus the environmental and social consequences of mobility have also increased with the advent of mass motorisation (Knowles, 2006; Lyons and Urry, 2005) and is compounded by the fact that 70 to 80% of the world’s population lives in cities (Banister, 2008). It is also true that the majority of urban transport infrastructure such as parking space allocation is given a high priority in cities compared to the space demands of other more sustainable modes of transportation, and comes at a significant cost to society (Gössling, 2016). It is estimated that drivers searching for parking spaces account for as much as 8% of total city traffic in the United States (Shoup, 2005). The reality is that increasing car dependency and decentralisation of cities (and the negative externalities that accompany them) will be difficult processes to reverse in a transport-led future (Banister, 2008).The core questions then becomes: How much mobility does society need? How much can the planet sustain (Thomsen et al., 2005)?

In an attempt to address the increasing demand for mobility, transport scholars have recently been focusing on the individualized, flexible nature of personal mobility (Kent and Dowling, 2013; Urry, 2012). Of interest has been the growing trend of car sharing in urban areas, where ridesharing company Uber, for example, reported 1 million rides per day by the end of 2014 (Huet, 2014). Ridesharing challenges the subjectivity that is implied in car ownership as a means of self-expression by ‘selling mobility instead of cars’ (Firnkorn and Müller, 2012). The ridesharing modal shift away from private ownership is peculiar in that it emerges from within the existing automobility regime, rather than exogenously attempting to supplant it (Shove and Walker, 2010). Researchers argue that ridesharing confronts the hegemony of the private car (Banister, 2011; Kent and Dowling, 2013) by turning the fixed costs of owning a car into variable (lower) travel costs (Duncan, 2011), thereby decreasing or at least deferring car ownership (Sioui et al., 2013). Other benefits of ridesharing include travel time reduction, lower traffic congestion, fuel efficiency and reducing air pollution (Furuhata et al., 2013). Ridesharing also carries a public good value where in reducing the dominance of the private car, it also reduces negative externalities, and thus reinforces sustainable mobility (Watson, 2012), which is appropriate (Thomsen et al., 2005), given that climate change is the over-arching issue for most transport research agendas (Hall, 2010). However, shared mobility also gives rise to regulatory questions (Guerra, 2015) surrounding liability (Leibson and Penner, 1994), privacy (Chaube et al., 2010) and data protection (Amey et al., 2011).

Nested within the concept of private ownership, is the related issue of shifting perceptions (Kent and Dowling, 2013). While the expenses involved in purchasing and maintaining a vehicle are a barrier to ownership, at least of equal significance is society’s declining interest in owning automobiles (Cohen, 2012; Foster, 2003; Seiler, 2009). In particular, fewer young people seem to perceive cars as aspirational purchases (Dowling and Simpson, 2013). An indicator of this has been the declining percentage of young people acquiring driving licenses since the beginning of the 1990s, which has continued to stagnate since 2000. This trend can be seen in the UK, Germany, France, Japan, the USA, Canada and Australia (Hjorthol, 2016), and in that same period, car travel among young adults has also declined in several developed nations (Oakil et al., 2016). These trends have led researchers to argue that there is an emerging norm whereby young people are increasingly willing to share transport (Hopkins and Stephenson, 2016).

Underpinning the concept of shifting perceptions is a wider phenomenon occurring in modern economies; the transition from ownership to access (Rifkin, 2000). The automotive sector is keen on integrating this new business model (including financing) of shared services (Wingfield, 2017), alongside traditional private ownership (Kent and Dowling, 2013), where consumers can benefit from the usage of a car without the need to own one outright (Botsman and Rogers, 2010). Sustainability scholars (Hopkins and Stephenson, 2016) hope that this emerging, shared consumption paradigm results in a significantly reduced rate of car use, and serves as a catalyst that incites a transition away from the long-standing and self-reproducing culture of automobility. One of this paper’s arguments is that AVs are a technology driven solution that facilitates ridesharing, and deviates from the current regime of privileged car ownership. Automation will have the inevitable impact of making mobility easier, more flexible, more reliable and more like owning a private vehicle (Kent and Dowling, 2013).

6.3. Methods

Research in the transport sector frequently makes use of qualitative methods for inductive purposes, as it permits the identification of concepts and interpretations from the respondent’s perspective (Gardner and Abraham, 2007; Steinhilber et al., 2013). This article applies qualitative methods with the intent to capture relevant themes from the perspectives of automakers, regulators and other industry stakeholders based on their experiences. It then becomes possible to establish linkages between collections of different sets of knowledge within the automotive industry.

Transport studies often follow the epistemological trend of using quantitative methods with a positivist world view (Curl and Davison, 2014; Vowles, 2006), which at times, has been critiqued as being archaic (Goetz et al., 2009; Hall, 2004). On the other hand, it has been argued that qualitative approaches have been steadily contributing to fuller understandings of transport practices and policies (Aldred and Jungnickel, 2014; Clayton and Musselwhite, 2013; Hall, 2010; Preston and O'Connor, 2008). Hence, there has been an appeal for more critical (qualitative) analysis in transport studies, to compliment the already well-established technical (quantitative) scholarship (Pangbourne and Alvanides, 2014). While comparing the merits of qualitative versus quantitative approaches is a false dichotomy, there have been calls for the application of more varied methodologies and holistic approaches, that offer more robust theoretical underpinnings from a wider range of disciplines (Curl and Davison, 2014). One such example is the multi-level perspective (MLP) used in this paper, which seeks to explain sociotechnical transitions as a systemic theory of change (Geels, 2012). Thus, this paper makes appropriate use of the MLP and qualitative methods to examine the implications of the increasing integration of location-aware technology within the automotive sector.

This study took place between 2014 and 2016 and the primary sources of data for this article were collected through recordings of semi-structured elite interviews with key industry decision-makers within the automotive sector (industry and government). These respondents were based in the UK, US, Germany and Belgium, and selectively targeted for their expertise and opinions on the impacts of connected and autonomous technology on the automotive industry and society at large. **Table 4.** lists the elite respondents interviewed during this study.

Interviewees were specifically selected (non-probability sampling), and in this case, a combination of purposive and chain-referral sampling, which allowed for the inclusion of key institutional actors in the data gathering process (Tansey, 2007). In accordance with the ethics approval guidelines of this study, express permission was granted before the recording of each interview, participants were guaranteed anonymity and were assured that recorded data would be destroyed in accordance with the UK's Data Protection Act 1998.

Recorded interviews were transcribed and thematically coded using the Template Analysis method, which gives an account structured around central themes that have emerged, and draws on examples from interview transcripts as required (King, 1998). The conclusions of this study are meant to provide a robust assessment of the early sociotechnical implications of autonomous technology, and the associated challenges facing EU automotive industry regulators.

Table 4.

List of interviewees

Institution / Organization	**Title /Department**
Transport Systems Catapult	Senior Executive, Leadership
Transport Systems Catapult	Senior Executive, Programmes
Transport Systems Catapult	Senior Technologist
HORIBA MIRA	Senior Executive, Strategy
PROFORGED	Senior Executive, Leadership
Qualcomm	Senior Executive, Business Development
Ford Motor Company UK	Former Chairman
Motorsport Industry Association (MIA)	Senior Executive, Leadership
RICARDO	Senior Engineer
Society of Motor Manufacturers and Traders (SMMT)	Senior Executive, Leadership
Visteon	Senior Management, Global Telematics & Connectivity
European Commission	Policy Officer, DG Climate Action
European Commission	Senior Officer, Intelligent Transport Systems: Innovative and Sustainable Mobility
Milton Keynes Council, UK	Senior Executive, Transport Innovation
Centre for Connected and Autonomous Vehicles - Department for Transport UK	Senior Executive, Leadership
Office for Low Emission Vehicles (OLEV)	Senior Executive, Leadership
BMW Group	Senior Executive, Governmental and External Affairs

6.4. Results and Discussion

6.4.1. Disruption of the private ownership business model

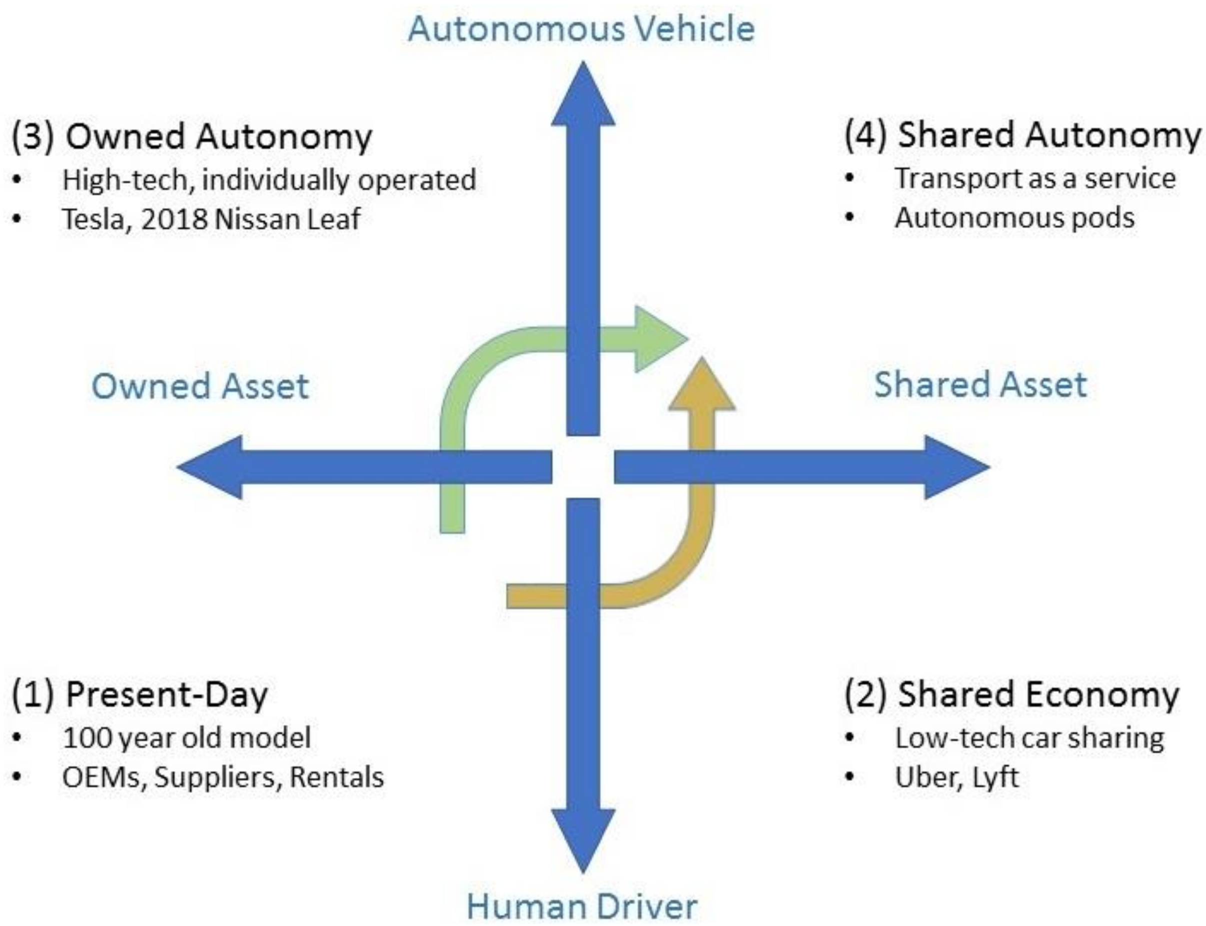
The primary aim of this paper is to examine whether autonomous technology might force a paradigm shift within the automotive industry, where private automobiles are replaced by a transport service, and this section discusses the findings related to this query. The shift away from the traditional private ownership model to a shared platform model, is potentially the most disruptive implication of AVs because it creates a scenario where traditionally privately owned mobility is abandoned in favour of a transportation service. Automakers are not taking the threat of this radical transition lightly as all of them, in some form or fashion, are developing autonomous capabilities, while also simultaneously exploring ridesharing business models. BMW, for example, has established I Ventures, which is a venture capital subsidiary that invests in small and medium sized companies who specialise in ITS and with whom BMW collaborates. BMW also invests in different ownership model and mobility programmes unrelated to their vehicles like “DriveNow” and “Life360” (BMW UK, 2017). OEMs acknowledge the high probability of the ownership model changing, particularly in cities, and differentiate the transport needs of urban dwellers from those of non-urban dwellers as two distinct demographics. All industry respondents expect there will be a slower rate of adoption among non-urban dwellers, but the fact remains that 80% of the EU’s population lives in an urban environment. The disruption of private ownership within the automotive regime is also highly regarded among transport technologists, to the point of being considered a metric of success. One senior autonomous systems planner expressed the following sentiment:

> If we end up having the same numbers of people in autonomous private vehicles as we did in manually driven private cars, then we’ll have achieved nothing.

Without exception, and regardless of their disposition, each respondent considered the move towards a shared mobility platform as a near inevitability.

Reinforcing the move away from private ownership is an evolving perception of personal mobility which is migrating away from the concept of owned assets, and towards that of on-demand and shared transportation services. This is evidenced by the industry’s keen focus on delivering services to generation Y and Z, who are the purchasing generation of the future. Industry respondents have stated that they believe young people are more willing to share data and assets, which contrasts with the privately-owned car, being one of the most underutilized assets of all (on average 4% utilization). The gross inefficiency of private car ownership only reinforces the fact that purchasing and maintaining a vehicle is prohibitive and unattractive for many. Respondents believe that the current automotive business model will be increasingly interrogated for value and appeal in comparison to emerging ITS alternatives. A final theme concerning the move away from private ownership is the public's willingness to embrace AV technology. While some technology development respondents believe that public awareness of AVs is woefully lacking, the largest traveller experience survey in the UK was recently conducted by Transport Systems Catapult (TSC, 2015). The results revealed that 39% of people surveyed would be willing to use AVs immediately, were they available. The following chart (**Figure 3.**) illustrates how leading industry analyst for Morgan Stanley, Adam Jonas (Lavrinc, 2015), expects the automotive industry to evolve alongside autonomous technology levels 0 – 5.

Figure 3. Morgan Stanley financial services' vision of the autonomous future



6.4.2. Wider restructuring of the industry

In addition to the transition from private ownership, respondents made it clear that the very nature of the industry was also undergoing a transition, and that the core membership of industry stakeholders was also changing. The diffusion of AV technology throughout the sector necessarily invites the increased participation and presence of new, non-traditional, organizations. These new entrants primarily consist of network operators from the telecom sector. Some respondents believe that they may become the main actors in the industry if the AV transitions into a highly-commoditized product. As one senior automaker executive explains:

> The delivery of data services will be the way in which the traveller interacts with the transport system. This will happen through data and technology providers, and thus the emphasis will shift from engines to the delivery of service through electronic platforms.

Regarding the shift in value from sheet metal to digital content, some respondents remain sceptical about the wholesale commoditisation of AVs, arguing that certain levels of differentiation will still be possible. A senior executive of a major UK automotive trade association explains his position in the following manner:

> If we take the mobile phone industry as an example, the value used to be in the handsets, but that transitioned to the content and services provided by the phone; the apps. So the question is, where does the value go in AVs? Yes, there will be a degree of commoditization, but automakers have a long and distinguished reputation of differentiating their products from one another. Again, using the same example of mobile handsets, the transition in the mobile industry doesn't preclude Apple from charging a premium for their top of the line model, when its functionality is not tremendously different from other brands and competitors on the market.

Other respondents believe that data and service providers will be regarded as equals among Tier 1 suppliers and OEMs. These respondents believe that data that will be used to improve products, back warranties, and provide services and updates, and will be shared equally between Tier 1s, OEMs and mobile network operators.

While there was an initial expectation that some 'white goods manufacturers' (Apple) and other non-traditional industry newcomers (Google) were going disrupt the conventional supply chain, these firms have since also began partnering with OEMs on various AV projects (Webb and Chang, 2017; Welch and Webb, 2017). Even firms like Uber and Lyft who specialize in new business models which offer alternatives to car ownership in cities have partnered with OEMs to deliver urban mobility services, car sharing services and community based ridesharing.

6.4.3. The EU's regulatory approach to Intelligent Transport Systems

Regardless of the nature and pace of AV R&D and deployment, it must be underpinned by parallel public policies which preserve the public interest. It is from this normative principle that the second focus of this paper emerges, which is to examine the public policy changes required to accommodate rapidly developing AV technologies. According to a senior European Commission (EC) policy maker, Intelligent Transport Systems (ITS) at the EU level is mainly concerned with mobility for passengers and the transport of goods. ITS at this regional level is broad in scope and includes areas such as approval legislation for technology, road safety, the revision of the Vienna Convention, cross-border testing of technologies, and road-traffic rules to name a few, and these activities are funded principally by the Horizon 2020 mechanism. The Cooperative Intelligent Transport Systems (C-ITS) Platform is a working group of European automotive industry stakeholders from across the value chain (OEMs, telecoms operators, Tier 1 automotive suppliers, motorcycle industry etc.), coordinated by the EC, and focuses on connectivity and autonomy. For the EC, enhancing cooperation across the sector with a 'common vision' is crucial to the successful deployment and follow up development of ITS. European regulators primarily perceive AVs as a tool with which they can capture potential benefits such as improvements to public transport and dynamic traffic management. This is primarily because infrastructural capacity is a fixed variable in Europe. According to EC respondents, there is no option of building a significant number of additional roads, therefore the 'intelligent use of the current infrastructure' is crucial and may include flexible or dynamic measures to ensure reliability and safety. It should also be noted that some of the relevant regulations for ITS are set at the international level (Brussels, Geneva-UNECE).

Standardisation is also an important issue for EU regulators regarding ITS, specifically, the benefits that standardisation brings to the emerging issue of access to data, which will be discussed later in this section. Interoperability is an equally important issue for EC respondents, as the potential benefits of AV technology will require it. Interoperability is the ability of ITS to maintain functionality across national borders by seamlessly integrating with systems in different countries, e.g. freight operators using sophisticated telematics systems. According to respondents, these two issues will require international dialogue, and conversations at the national levels as well.

6.4.4. AV policy hurdles

6.4.4.1. Liability

A common theme, which began to emerge from interviews, was that certain policy issues regarding autonomous technology deployment had become rather significant, given the implications of inevitable change within the industry. One such policy hurdle facing regulators is the question of liability. Who is liable in the event of accidents involving AVs? A C-ITS working group (WG) estimated that initially, the driver will always remain in control of the vehicle, therefore there will be no initial changes concerning insurance liability. The WG did concede, however, that as higher levels of automation are reached (Levels 0 – 5), information provided by the environment, such as lane markings is expected to trigger subsequent actions from the vehicle, and thus the information provided can no longer be considered as just information. Eventually traffic signage is expected to migrate from the physical infrastructure to being provided digitally (only) inside the vehicle. At such a time, this would require the question of liability to be re-evaluated. Respondents throughout the industry eventually expect liability to shift from the vehicle occupant to the manufacturer. An industry which is expected to be greatly impacted by this is the insurance industry, which revolves around liability. Insurance industry stakeholders estimate that AVs will reduce private automotive insurance premiums by as much as 80%, which is significant if we consider that in the US, private auto insurance accounts for 34% the industry's total revenue (Scism, 2016).

6.4.4.2. Data

Who has access to what data? Ownership of data is another major concern for regulators. AVs in Europe will enable information and communication technologies to share information across the road transport network by broadcasting and receiving large amounts of data vehicle to vehicle (V2V) and vehicle to infrastructure (V2I). This data can be usefully converted to assist with AV decision-making and optimize transport operations such as congestion, parking and safety. This is in addition to the host of applications and end-user services that AV occupants are expected to access over the course of a journey. This volume of broadcasting also raises concerns as how to guarantee privacy and data protection. A C-ITS WG has already concluded that many of these communications will be considered 'personal data' due to the possible indirect identification of users, and thus the European legislation on Data Protection 95/46/EC is considered applicable. Closely related to the theme of privacy is concern about data security. One industry insider estimates that AVs will eventually host 150 million lines of computer code, which has the statistical probability of being vulnerable to approximately 750 exploitable bugs, which represents a real threat to the vehicle and its occupants in addition to any personal data or financial details. A Senior Technologist describes below, the data-related policy hurdles his organisation was currently facing:

> [Data regulatory concerns] are pretty much killing some of the work we are doing at the moment. To become compliant with the GDPR [General Data Protection Regulation – EU Regulation 2016/679], we need a system whereby all of the data is secured because the penalties for breaches are astronomical, even for mostly small organizations. So, the whole concept of whether or not you can record data in a public space and gather information about the identity of people inside and outside the vehicle is a big issue. While people inside the vehicle can give their consent, the people outside the vehicle who are identified by their image or by the number plate on their vehicle and so on, obviously, you cannot gain their consent, and if this [testing] is to work, a [solution] is needed, one way or the other.

6.4.4.3. Type approval

The preceding quote also indicates the most immediate challenge for policy makers, which is the testing and use of AVs on public roads. The laws in many counties state, for example, that when a car is in gear and the engine is running, a person must be in the driver's seat, or that a foot must be on the pedal. This is exactly why the Vienna Convention on Road Traffic was amended in 2014 to allow drivers take their hands off the wheel of self-driving cars. Many of these laws defeat the purpose of technologies that are currently available in cars today such as adaptive cruise control and self-parking. Car manufacturers like Tesla, Mercedes and Audi currently offer vehicles with some autonomous function, which are considered 'grey areas' in terms of legislation and legality. The speed and manner in which these functions are made available to drivers are also problematic for policymakers, as demonstrated in the following real-world example: Traditionally, vehicle models change on an 8-year rotation, but Tesla famously launched an 'over the air' update (much like a smartphone update), which over-night, bestowed Tesla Model S owners with access to autonomous functionality. It is not hard to see how the nature of this technology is disruptive to a 100-year-old industry not used to such a rapid pace of development and shifting perceptions of the vehicle itself. Regarding testing on public roads, there is currently a 1-million-kilometre drive cycle being suggested by EU legislators as the foundation for testing and validation of AV technology. Industry respondents argue, however, that such an escalation of cost is unacceptable and that they are considering simulation driving as a possible alternative to some of the real-world testing, as this is a common practice with other technologies such as crash tests.

With regards to whether AV technology is currently ahead of policy makers; some stakeholders do believe that policy makers and standards bodies are a step behind. For example, automotive emissions and safety equipment in the US and EU markets are regulated by type approval testing. Type approval is granted when a product has met a specified minimum set of regulatory, technical and safety requirements. Currently, there are no type approval tests for autonomous vehicles, or more significantly, for vehicles with autonomous capabilities that are on public roads today (Tesla, Mercedes, Audi). Connectivity (V2V and V2I) standards appear to have been in place for a while, but the technology had not quite reached maturity, as confirmed in the latest C-ITS platform report. So, regarding the ability of policy makers to regulate AV technology, it depends on the technology, where some areas are completely unregulated and unstandardized, while in other areas, the opposite is true. These issues are becoming increasingly urgent, as the very first autonomous-related road fatality occurred in May of 2016, with other fatal incidents occurring since then. As one transport regulator explains:

> The more you lean towards the autonomous side of AVs, the fewer standards and regulations there are in place.

The UK government has been quite responsive to AV technology. Chancellor George Osbourne allocated £100 million to AV development in early 2015 along with the establishment of the new Centre for Connected and Autonomous Vehicles (CCAV) whose aim is to promote the development of these technologies by encouraging collaboration between industry and academia, facilitated by government, which reflects the UK's 'Fraunhofer-like' R&D model throughout the industry. EC respondents believe that if regulators wait too long to craft policy, the technology becomes 'settled', production at scale gets underway and the market becomes established. At this point, regulators will likely find themselves trying to retroactively address certain issues such as interoperability, which ensures continuity of services throughout the transport network. EU regulators argue that the timing of legislation also has to do with addressing the entire value chain, the private sector, the public sector, states, regions, and even sometimes local authorities to ensure the most efficient deployment of the 'shared vision' that caters to the needs of all parties. For the EC, regulating AVs 'has to be a process of learning by doing', to ensure that they are not legislating too early or too late in the process. This rationale can be seen in how the EU has allocated all its ITS funding through the Connecting Europe Facility (CEF), which is an infrastructure funding mechanism that allows for the cross-border pilot deployment of AVs. EU regulators maintain that only after rigorous testing and data collection has been carried out will they consider bringing ‘legal certainty’ to the sector.

6.5. Discussion and Conclusion

Previous studies have approached the phenomenon of autonomous vehicle research from various perspectives, from conducting quantitative impact assessments (Fagnant and Kockelman, 2015), to macro-sociotechnical analyses of possible transition pathways (Fraedrich et al., 2015). Most studies, however, conduct micro-technical examinations of specific technologies deployed in autonomous vehicles (Azimi et al., 2014; Gerla et al., 2014; Janai et al., 2017; Menze and Geiger, 2015). This paper has differentiated itself by delivering a mid-level, sector-specific, sociotechnical analysis of the EU automotive industry, while highlighting the most important and identifiable challenges presently associated with the incoming transition to autonomous vehicles. This paper also makes use of public policy scholarship to explain how various sociotechnical actors affect - and are affected by - regulatory uncertainty, and the likely policy adjustments that will be required.

AVs are set to trigger a deep and transformative sociotechnical transition unlike any other, and it will certainly be the most significant event to occur in road transport since horse-drawn carriages were replaced by the automobile. The first aim of this paper was to assess the process by which privately-owned vehicles are likely to be replaced by shared transportation services. Within the automotive industry, we see that OEMs have begun to set these events in motion with the development and integration of connected and autonomous technology in vehicles sold today. This initiation of radical innovation by the OEMs defies classic MLP theory and is more in line with creative accumulation scholarship, where incumbents, not newcomers, are the architects of sustained innovation. Another interesting observation is how the industry will inevitably be restructured with the entry of telecoms companies and network operators. While they are technically newcomers to the automotive industry, they continue to play increasingly crucial roles within the value chain that is rapidly becoming more digital-based. Whether intentional or not, the disruptive nature of driverless technology will necessarily reconstruct the modes of consumption and systems of use of private mobility, and future research must address these changes.

Why would you own a self-driving car that is parked 95% of the time, if you could access one, on-demand, for less money? Why would you continue to pay road taxes, repairs and maintenance, parking fees, fuel costs, driver's insurance, or even learn to drive if you didn't have to? These legitimate questions inevitably cause automakers to rethink their value-creation logic in delivering mobility to customers, and are likely to give birth to new business models (Teece, 2010). This also raises some interesting theoretical questions. I argue that business models are constructs that mediate the value creation process, implicitly mapping between technical and socioeconomic domains (Chesbrough and Rosenbloom, 2002). Can it be argued then, that new business models (Wells, 2013) - spurred by technological innovation - can induce a form of systemic behavioural change in society (e.g. online shopping)? If so, how does it compare to the individual, discretionary behavioural change that is often argued for by sustainability scholars (Hanlon and Carlisle, 2009; Whitmarsh, 2012)? Is behavioural change (in society) then, a prerequisite for; or a consequence of, sustainable transitions? Modes of mobility and behavioural reconfigurations have long been considered as non-technical concepts, and solutions outside of the technology fix (Whitmarsh, 2012), how then can AV technology be reconciled within traditional scholarship? These questions speak to the very core of the long-debated dichotomy between the 'tech fix' (technological solutions) and behavioural change (Upham et al., 2013; Wells and Xenias, 2015), and should be high on future research agendas geared toward sustainable development.

The secondary aim of this paper was to discern the policies that would be required to begin accommodating the deployment of autonomous technology within society. The findings in this paper indicate that in the short term, policy makers are faced with three major legal categories of concern which are: (1) the broad question of liability, (2) data access and security, and (3) the type approval of autonomous technologies that are currently operating in an unregulated environment. It is also interesting to note that traditionally, regulators deploy command-and-control legislation to force certain technological outcomes such as performance standards and thus these policies are appropriately known as technology-forcing policies. In this case, however, it appears that the reverse is true, where certain aspects of autonomous technology have developed faster than most anticipated, and thus policymakers are having to play catch up. Could autonomous vehicles in this case then be said to be inducing 'technology-following' policies (Faiz et al., 1996; Hascic et al., 2008; Santos et al., 2010; Vieira et al., 2007)?

The biggest impact that driverless technology can potentially achieve is changing the ratio of owners to cars, especially in urban areas, where based on simulations, one self-driving 'Uber' can potentially replace between 6 to 10 privately owned cars (Hars, 2016). Therefore, it would appear the dilemma for automakers is either to learn to become transportation providers by the time Level 5 autonomy is mature and ubiquitous, or hope that the 100-year-old private ownership business model proves once again impervious to the march of time (and innovation). As the transition to AVs is recorded by social scientists, many other questions will need to be answered, such as impacts on climate (congestion, emissions), transport-related social exclusion (increased aggregate travel), road safety, and new-found productive time during commutes.

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Chapter 7

Conclusion

In this chapter I shall summarize the key findings and limitations of this thesis, and discuss the results of the four paper chapters as representative of a coherent body of work. I shall also suggest avenues for future research derived from all four paper chapters. The main function of this final chapter is to tie the four paper chapters together by demonstrating their contribution to knowledge in sociotechnical transition scholarship.

The knowledge contribution of this thesis advances the understanding of performance standard 'command-and-control' (CAC) regulations as a powerful tool in the pursuit of mobility transitions via energy-efficient innovation (EEI) and automation. In this thesis, CAC regulations have also demonstrated their ability to negatively affect society and the environment when they are ill-conceived, abused, or are the source of unintended consequences. While there are a variety of well-studied approaches to mobility transitions (Geels et al., 2012; Whitmarsh, 2012), the findings in this thesis support the claim that regulation forces technological innovation, which holds great potential for incremental change towards sustainable mobility. At a macro level, the effectiveness of technological innovation – or 'the technology fix' – lies in its ability to incrementally decouple negative externalities from economic development. This is important, because it gradually removes the persistent tension between catering to the mobility needs of today's society, and mitigating against further environmental degradation for the sake of future generations. This decoupling can occur though sociotechnical transitions, which are either incremental or radical, with the latter often being accompanied by significant shifts in behaviour.

Thus, CAC regulations are the common denominator in all four of the papers in this thesis. These analyses of CAC regulations provide a platform for testing various social theories, and observing the implications of those policy interventions - via technological innovation – on sociotechnical transitions. Throughout this thesis, CAC regulations have been used as the unit of measure to test hypotheses underpinned by the concept of 'technology-forcing', where the premise is that technological innovation by firms is predominantly influenced by stringent 'command-and-control' regulations. While the industry background and context remains the same across all four papers (EU automotive industry 2008-2017), the technological innovations being analysed vary (low-emissions technologies, motorsport technologies, connected and autonomous technologies). The findings from all four papers indicate that organisational allocation of innovation R&D, industrial behaviour and, by proxy, EEI, are not independent of command-and-control regulations.

Paper 1 - Examining the role of Policy Design and Policy Interaction in EU Automotive Emissions Performance Gaps

Paper 1 builds upon and expands prior conceptualizations of policy design and policy interaction where previous studies have investigated the impact of policy design features on inducing innovation and effectively regulating automobile emissions (Bergek and Berggren, 2014; Dijk and Yarime, 2010; Kemp and Pontoglio, 2011; Kleit, 1992; Lee et al., 2010; Oltra and Saint Jean, 2009; Rogge et al., 2011). The coordinated use of multiple policy instruments - or 'policy mixes' - has also been the subject of previous academic investigations, which have sought to understand and refine the process of integrating and synergising policy instruments (Flanagan et al., 2011; Foxon and Pearson, 2008; Holweg, 2014; Veugelers, 2012). Past findings identify stringency (Oltra and Saint Jean, 2009), predictability (Lee et al., 2010), and legitimacy (Gerard and Lave, 2007) as the most significant elements of policy design that affect technological innovation. However, existing literature on effective 'policy mixing' is vague at best (Whitmarsh, 2011) and limited in scope, focusing mainly on the processes of successfully implementing innovation-inducing policies. The policy analysis undertaken in this study explores fresh perspectives on how industrial regulations can 'fail', and the unintended consequences that can emerge in such scenarios.

The results of the investigation conducted in Paper 1 enhances an understanding of how policy design and policy interaction have contributed to the exploitation of EU regulations by automakers, and, in the process, further degraded air quality in EU urban centres. This study identified structural flaws within the policy – known as flexibilities – that encouraged automakers to exploit EU emissions legislation by not strictly adhering to them, which in turn led to significant real-world performance gaps. The performance gap is the difference in emission levels reported by automakers during type approval testing, and actual real-world driving emissions. This paper's findings also showed additional unforeseen negative effects on air quality caused by policy interactions between the under-taxation of diesel at the national level, and the flawed regulatory push for lower CO_2 emissions at the EU level. This created a market-pull effect, and initiated a lock-in to - and mass diffusion of - over-polluting diesel engines throughout the European Domestic Market (EUDM). While exploitation of the rules by firms is severely under-explored by transition scholars, this paper sufficiently demonstrates that misbehaviour by several firms was a consequence of EU regulations containing too much 'wriggle room' in the form of flexibilities.

Having identified the major contributing factors of policy failure to be lax regulation and the exploitation of flexibilities, this paper did not explore the role of regulator legitimacy, which is also a crucial determinant in technology-forcing policymaking (Kemp, 1995; Kleit, 1992; Rogge et al., 2011). Instead, it focused solely on the endogenous aspects of regulatory design (stringency and predictability) as the main determinants in influencing industrial activity and policy outcomes. Given that the European Commission recently proposed a draft that would grant it additional oversight powers to intervene at the national level (akin to the EPA's powers in the US), future research could benefit from comparatively examining regulator legitimacy, and their ability to independently enforce compliance. Lastly, respondents often expressed the opinion that national interests and the lack of political will to amend EU legislation had resulted in the continuation of the status quo regarding diesel's preferential treatment within the EU. This kind of bureaucratic impasse is one of the cited criticisms of CAC regulations, which is that policies must be constantly revisited in order to remain effective (Santos et al., 2010). One of the obvious solutions would be to simply close all known loopholes or flexibilities in present and future legislation, however, EU member states with vested interests would have to agree to any such revision of the regulations. While the effects of national interests on legislation fell outside of this study's research mandate, the relationship between political will and exploitation or 'rule-bending' by an industry is worthy of further academic investigation, particularly from the perspective of regulatory capture (Dal Bó, 2006).

Paper Chapter 2 - 'Racing Improves the Breed': The obscure link between Motorsport and Low-Carbon Innovation

In the world of FIA[13] motorsport, specifically Formula One (F1), the World Endurance Championship (WEC) and Formula E, there are at least a dozen major automobile manufacturers (OEMs) competing in all three championships. These championships also share similar technologies such as hybrid battery-electric propulsion systems, or kinetic Energy Recovery Systems (ERS). An issue that has been overlooked in scholarly work, however, is how, and to what extent, does being involved in motorsport benefit OEMs in the process of developing 'cleaner' technologies for the purposes of complying with present and future EU emissions performance standards. As OEMs develop energy-efficient technologies in motorsport, do these innovations have any use to the automotive sector? If so, by what processes do these technologies crossover from one industry to another? Moreover, previous research shows that while technological transfer from motorsport to the automotive industry was commonplace in times past, that knowledge transfer has become relatively rare or even non-existent (Foxall and Johnston, 1991). Thus, a sociotechnical analysis of knowledge transfer is used in the second paper to investigate the processes by which technologies developed on the racetrack influence energy-efficient innovations in today's UK automotive industry. Paper 2 also investigates the roles that motorsport regulations and EU emission policies play in facilitating such knowledge transfer.

The findings of the paper reveal that knowledge transfer was occurring between motorsport and the UK automotive industry both generally, in terms of performance innovation, and specifically, in terms of energy-efficient innovations. This investigation was specifically interested in the carryover of technologies from motorsports to road cars, and found that there were two main factors responsible for this exchange. The first factor was the motorsport industry's proficiency in rapid prototyping, which was driven by participants' motivation to win races, and the second was the exchange of tacit knowledge between engineers 'crossing over' between industries. During the period of this study, 'low-carbon' or energy-efficient innovation had become especially relevant in motorsport, and this was mainly due to regulation changes implemented by the FIA. Subsequently, it was found that these rule changes resulted from petitioning by OEMs seeking to develop more 'road-relevant' technologies within their motorsport budgets. This could be

[13] The Fédération Internationale de l'Automobile (FIA) is the governing body for F1, WEC and Formula E.

therefore justified as dual-use R&D for winning races, and simultaneously helping road cars meet stringent EU standards.

The results show that in the wake of the 2008 financial crisis, and freshly negotiated EU emissions standards, the automotive industry and UK government entered a close partnership brokered by the UK Automotive Council. This organizational restructuring focused on low-carbon innovations, and much closer alignment between the motorsport and automotive sectors, both of which complemented the then Labour government's climate change agenda. The convergence of these circumstances created a 'perfect' scenario where motorsport once again became highly relevant to EU automakers, and by extension the automotive industry's transition to more sustainable mobility. Being an EU sector specific study, however, implies that some degree of variability in results can be expected in countries where stringent "EU style" CAC performance standards are absent. This is important when considering technology-forcing mitigation strategies at the global scale for sustainable mobility. Despite the global operational nature of OEMs, and the fact that nations without strict regulations can free-ride on cleaner technologies developed for EU markets via trade; care must be taken when conducting similar sociotechnical work in other countries. In short, the measurement of technology-forcing regulations in a project designed to assess the value of the 'techo-fix' in Chinese sustainable mobility is not likely to be accurate for the same project in California.

Paper Chapter 3 - Remapping Discontinuity: Established Firms as Change Agents in the Automotive Industry

In the last decade, sociotechnical transition research has arguably been dominated by the Multi-Level Perspective (MLP) (Markard and Truffer, 2008), which is Schumpeterian in spirit, in that the 'attacker's advantage' is one of its core tenets. The concept of the attacker's advantage proposes that new and radical innovations are brought to market by 'invaders' - new firms or entrants to an industry – who destroy established firms (Bergek et al., 2013), in a process Schumpeter described as 'creative destruction' (Schumpeter, 1942). Recently, however, there have been several critiques of the MLP (Shove and Walker, 2007) and calls for innovation studies to move beyond the 'attackers advantage' and subsequently, beyond the characterisation of industry incumbents as guardians of the old technological regime. The research conducted in Paper 3 draws upon insights from Creative Accumulation scholarship, which is based on the MLP, to explore alternative conceptual understandings of the innovation process. This study also critically re-examines the role of established firms, and how they maintain a competitive advantage in knowledge assets and speed of innovation.

The results of a thematic analysis of qualitative data from the automotive sector revealed that established firms are in fact multi-level actors in the innovation process, which is reinforced by their high levels of organizational reflexivity in response to regulatory and competitive pressures. Established firms' ability to leverage strategic business relationships (procurement) and proven supply chains (quality assurance), capitalise on economies of scale and scope (platform sharing), and deploy specialized and complementary assets (motorsport industry), fortifies their dominant position in the industry. These distinct advantages are further multiplied by the fact that niche development in countries like Germany and the UK is predominantly driven by government-industry partnerships that are guided by a post-2008 low-emissions agenda. This reiterates the importance of command-and-control regulations in encouraging sustainable transitions, because the EU's low-emissions agenda is implemented at the regional level by CAC performance standards, as the preferred means of government intervention. However, the degree of importance that each EU member state places on stringently enforcing these regulations may vary, and can be a source of bureaucratic inertia.

This paper therefore challenges the MLP's characterisation of established firms as entrenched 'regime actors', who continually defend against - and reluctantly acknowledge - disruptive innovations at their own peril. I argue instead, that industry incumbents creatively accumulate complex knowledge, which is integrated into their pursuit of innovation across all levels of the sociotechnical system. Another finding, which contradicts classic MLP theory, is that industry newcomers find it either technically or financially impossible to advance an invention beyond the 'valley of death without the support of established firms, usually Tier 1 or 2 component suppliers or OEMs. Given the revelations in this paper; I suggest that other highly regulated, complex capital goods industries may also benefit from similar sociotechnical explorations in pursuit of clearer conceptual understandings of the innovation process.

Paper Chapter 4 - Level 5 Autonomy: The New Face of Disruption in Road Transport

The final paper is an early exploration of driverless car technology, and joins a first wave of contemporary sociotechnical research being conducted on this technology in relation to sustainable mobility. Currently, the clear majority of academic discussions surrounding connected and autonomous vehicles (AVs) are focused on the technical aspects of the technology, as it begins to make its way into the marketplace. However, there exist significant gaps in knowledge as to how AVs will be embedded into the existing road transport system, which is expected given the early stages of the technology's deployment. There is also little in the way of contemporary research relevant to this kind of transition because, until now, autonomous personal mobility has not been possible, and the sheer scale of disruption that is expected to occur is still unknown. The sociotechnical analysis conducted in this study affords the opportunity to explore not only the most easily identifiable disruptive implications of AV technology, but also the legal clarity that regulators will be required to provide to facilitate this radical transition.

The results of Paper Four's inquiry provide a robust initial understanding of the disruptive nature of AVs in the sociotechnical context, as the industry prepares to adopt this technology at scale. Probably the most significant finding is that the automotive industry unanimously expects AVs to transform personal mobility, where what was previously a personally owned asset (automobiles) will become a mobility service (on-demand AVs). The shift away from the private ownership model is even more interesting from an academic standpoint, given the fact that every established OEM is currently developing an autonomous mobility platform, which, on the face of it, defies classical sociotechnical transition theory. Another reality uncovered by this study was that the industry's members were changing, or at least being reorganized in order of importance, with network operators (telecoms companies) assuming a much more prominent role in the sector. First-timers to the automotive industry are also expected to enter the marketplace, but they would do so via partnerships with established firms. The policy-related findings of this study indicate that in addition to standardization concerns such as interoperability, the major regulatory concerns related to AV technology are liability in the event of an accident, data ownership and security, and the implementation of type approval standards. Policymakers also consider the timing of policy interventions in the marketplace as important.

Although a significant portion of this paper's findings is based on the present-day attitudes of industry stakeholders towards future scenarios that remain largely uncertain, the conclusions of this early exploratory research remain valuable. This is particularly true in the case of transition scholarship, which is largely a framework for pattern recognition, and thus, early assumptions and predictions remain useful for generating more accurate prescriptions for the future. Regarding future research, this paper represents the tip of the iceberg in chronicling the sociotechnical transition to driverless vehicles. However, this paper has raised several empirical questions about the impact of AVs on climate and sustainable mobility (congestion and emissions), transport-related social exclusion (elderly and disabled), and the productive time of vehicle occupants. Several other theoretical concepts will need clarification, such as: Can AV technology shed new light on the relationship between policy, innovation, business models and behavioural change? Given the nature of AV technology, can modes of mobility still be considered as a non-technical concept? If not, where do AVs lie on the spectrum between technological solutions and behavioural reconfigurations?

Conclusions

The work presented in these four paper chapters provides a richer understanding of the role of command-and-control regulations in the process of influencing sociotechnical transitions via technological innovation. CAC regulations not only guide technologies in the automotive sector, but they also influence firm behaviour positively or negatively depending upon their stringency and predictability. CAC regulations can also affect firm behaviour in other industries via knock on effects, and encourage collaborations with government. The most powerful implication of CAC regulations, however, is the potential to affect broad swaths of society's behaviour via new technologies and the new systems of use (business models) associated with them. Researchers from the political sciences, business management and sustainable development disciplines should consider the consequences of these findings in future studies to more accurately measure the effects of policy changes on innovation, and to predict the effectiveness of regulatory pressures on sustainability pathways.

List of Abbreviations

AIO	Automotive Investment Organization
APC	Advanced Propulsion Centre
AR5	Fifth Assessment Report
AV	Connected and Autonomous Vehicle
BERR	Department for Business Enterprise and Regulatory Reform
BIS	UK Department of Business, Innovation & Skills
C-ITS	Cooperative Intelligent Transport Systems platform
CCAV	UK Centre for Connected and Autonomous Vehicles
CAC	Command-and-Control
CEF	Connecting Europe Facility
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DECC	UK Department of Energy & Climate Change
DfT	UK Department of Transport
EC	European Commission
EMS	Engine Management System
EPA	Environmental Protection Agency
EPSRC	Engineering and Physical Sciences Research Council
ERS	Energy Recovery System
EU	European Union
EUDM	European Domestic Market
EV	Electric Vehicle
F1	Formula One Grand Prix
FIA	Fédération Internationale de l'Automobile
GDPR	EU General Data Protection Regulation
GHG	Green House Gas
ICE	Internal Combustion Engine

ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
ITS	Intelligent Transport Systems
KERS	Kinetic Energy Recovery System
MBI	Market-Based Instrument
MEP	Member of the European Parliament
MIA	UK Motorsport Industry Association
MLP	Multi-Level Perspective
MOT	Ministry of Transport
MRL	Manufacturing Readiness Level
NAIC	National Automotive Innovation Centre
NAIGT	New Automotive Innovation and Growth Team
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
NO_x	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturers
OLEV	UK Office for Low Emission Vehicles
PM	Particulate Matter
PSA	Groupe PSA Peugeot Citroën
R&D	Research and Development
RCN	Rapid Charge Network
RDE	Real Driving Emission
SMMT	Society of Motor Manufacturers and Traders
SO_2	Sulphur Dioxide
T1	Tier 1 Supplier
T&E	Transport and Environment
TRL	Technology Readiness Level
TSC	Transport Systems Catapult
UK	United Kingdom

US	United States
V2I	Vehicle to Infrastructure connectivity
V2V	Vehicle to Vehicle connectivity
VW	Volkswagen
WAE	Williams Advanced Engineering
WEC	World Endurance Championship
WG	Working Group
WLTP	World-harmonized Light-duty vehicle Test Procedure

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