FIRM TECHNOLOGICAL RESPONSES TO REGULATORY CHANGES: A LONGITUDINAL STUDY IN THE LE MANS PROTOTYPE RACING

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[FORTHCOMING IN RESEARCH POLICY]

ABSTRACT

Despite the critical role of regulations on competition and innovation, little is known about firm responses and related effects on performance under regulatory contingencies that are permissive or restrictive. By longitudinally investigating hybrid cars competing in the Le Mans Prototype racing (LMP1), we counter-intuitively suggest that permissive regulations increase technological uncertainty and thus decrease the firms' likelihood of shifting their technological trajectory, while restrictive regulations lead to the opposite outcome. Further, we suggest that permissive regulations favour firms that innovate their products by sequentially upgrading core and peripheral subsystems, while restrictive regulations—in the long term— favour firms upgrading them simultaneously. Implications for theory and practice are discussed.

Keywords: regulations; environmental change; technological innovation; system complexity; technological trajectory; knowledge; performance; hybrid vehicles; Le Mans Prototype racing; LMP1.

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1. INTRODUCTION

A traditional stream of research in management literature investigates how firms respond to environmental changes and competition by exploring different innovation opportunities (Andriopoulos and Lewis, 2009; Blind et al., 2017; Dosi, 1982; Gupta et al., 2006; March, 1991; O'Reilly and Tushman, 2007). Firms' responses are indeed critical in competitive settings, particularly when winning or losing is driven by technological innovation (Ansari and Krop, 2012; Jenkins, 2010; Marino et al., 2015; Rothaermel and Deeds, 2004).

One essential aspect for a firm's success in a competitive environment is striking the optimal degree of exploration to maximize performance (Posen and Levinthal, 2012). In technological arenas, a firm's exploration has been traditionally defined as the level of innovation—in products, technologies, solutions—that the firm advances beyond the knowledge baseline of its competitive setting (Benner and Tushman, 2002; Marino et al., 2015). Scholars have identified in many cases curvilinear returns from exploratory innovation, so that beyond an optimal point returns might plateau, or even turn negative (Gupta et al., 2006; Posen and Levinthal, 2012). Research highlights that this optimal point is a "moving target" that varies as environmental changes occur (Posen and Levinthal, 2012). Striking such a moving target by deploying the right amount (and type) of innovation to maximize performance is particularly difficult, particularly in dynamic contingencies (Bourgeois and Eisenhardt, 1988; Davis et al., 2009; Jansen et al., 2006). To overcome this challenge, it is thus necessary to fully understand the structure and nature of environmental shifts (McCarthy et al., 2010).

According to previous studies, environmental change can arise from a variety of different sources (Bourgeois and Eisenhardt, 1988; McCarthy et al., 2010) and may involve different dimensions, such as distinctive frequencies (Posen and Levinthal, 2012) or divergent magnitudes (Tushman and Anderson, 1986). Among other environmental changes, regulatory frameworks (Amable et al., 2016; Blind, 2012; Blind et al., 2017; Mahon and Murray, 1981; Porter and Van der Linde, 1995; Ramaswamy et al., 1994; Reger et al., 1992; Smith and Grimm, 1987; Teece, 1986) directly affect and concern several major industries such as automotive, transportations, farming, chemicals, banking, pharmaceutical and defence—among others—and have been extensively leveraged to preserve the environment (Jaffe and Palmer, 1997). Recent studies show that firms competing in regulated and technology-driven settings maximize their performance by engaging with moderate levels of exploration as regulatory changes turn radical (Marino et al., 2015). In these studies, however, regulatory changes are considered only by their change in magnitude, and not by the potential differences in the direction (i.e., the actual content) of the rule change (Mahon and Murray, 1981; Reger et al., 1992). In fact, from the regulators' perspective—which we adopt in our study—regulatory changes can have at least two main objectives, namely they could be more *restrictive* (i.e., by reducing and binding the agents' allowances and actions) or *permissive* (i.e., by increasing the agents' freedom, or in simple terms by 'deregulating' a specific domain of activity).

Research seems to agree that regulations—both whether permissive or restrictive—stimulate innovation at the firm level (Aggarwal, 2000; Blind et al., 2017; Hart and Ahuja, 1996), as organizations exploratory responses usually manage to find ways to work both 'within' or 'around' regulatory frameworks (Jenkins, 2014a; Porter and Van der Linde, 1995). It is however unclear whether restrictive regulatory enforcement in a specific domain (e.g., road cars gas emissions) might hold contrasting effects on competition compared to shift towards deregulation. For example, one could wonder whether such changes would favour firms that respond by deploying radical (e.g., electrical and hybrid vehicles) rather than incremental innovations (e.g., traditional combustion engine optimizations). In such contexts, the system complexity of the product architecture also plays an important role, (Banbury and Mitchell, 1995; Henderson and Clark, 1990; Simon, 1962; Zirpoli and Camuffo, 2009), but it is not clear whether firms might obtain an advantage in engaging with core (e.g., car engine) rather than peripheral subsystems (e.g., gearbox, hybrid systems) within the overall product architecture (Murmann and Frenken, 2006).

We claim that firms' compliance with increasing or decreasing limitations might differently affect organizational responses as well as the optimal type of innovation that maximizes performance. However, research still lacks an understanding of such phenomenon, particularly in a longitudinal perspective (Blind, 2012, p. 391). In this study, we thus investigate the following research question: *What are the firms' superior responses in terms of technological innovation when regulatory changes are characterized by different directions (i.e., restrictive vs. permissive)?*

If previous literature mentions the importance of studying the magnitude of environmental change —i.e., 'how large' the shock is— (Abernathy and Clark, 1985; Dosi, 1982; Tushman and Anderson, 1986) as well as the frequency—i.e., 'how often' new shifts happen—(Nadkarni and Narayanan, 2007; Posen and

Levinthal, 2012), the direction of change—i.e., 'what kind' of variation—is rarely studied. More importantly, prior studies have already warned scholars about the importance of refraining from "lumping together" multiple dimensions of change (McCarthy et al., 2010, p. 610), but rather paying careful attention to the individual dynamics that each of them entails. In these regards, our investigation aims to provide a valuable contribution in understanding the fine-grained mechanisms involving regulations and firm exploratory innovation, as regulatory change is one of the key dimensions of environmental change both for theory (Bourgeois and Eisenhardt, 1988; 2014a; McCarthy et al., 2010; Ramaswamy et al., 1994) and practice (Jenkins, 2014a; Stewart, 1993) across multiple disciplines and industries. Further, providing a response to our research question is not trivial, as—beyond the specific firm's innovation responses—several factors might influence the final outcome for organizations. Above other aspects, scholars warn to consider that the value of prior experience and knowledge (see among others Balconi, 2002; Cohen and Levinthal, 1990; Grant, 1996; King and Tucci, 2002; Zahra and George, 2002) as well as to its position within a particular technological trajectory (Dosi, 1982; Jenkins and Floyd, 2001), whose pace might be accelerated in hypercompetitive settings (D'Aveni, 1994; Hoisl et al., 2017; Volberda, 1996).

In this paper we classify firm's exploration strategies in terms of radical vs. incremental innovations that might be related to changes in a specific technological product (Henderson and Clark, 1990). To reach a more nuanced understanding we also identify whether the change affects a subsystem that is *core* or *peripheral* to the overall product architecture (Murmann and Frenken, 2006, p. 940). Such innovations will be analysed in a setting where regulatory releases vary in terms of magnitude (i.e., *radical* vs. *incremental*), but also direction (i.e*., permissive vs. restrictive*), while frequency of regulation release is kept constant (i.e., once a year), and predictability is equal for all rivals (i.e., all firms learn about the new rule change around two years before their enforcement). In doing so, we want to specifically isolate the role played by the direction of change, due to its relevance for firms operating in settings where regulations may influence the nature of competitive dynamics (Blind et al., 2017; Ramaswamy et al., 1994; Stewart, 2010). Finally, given the hypercompetitive nature of our setting (D'Aveni, 1994; Hoisl et al., 2017), we take into account the role of firms' prior technological knowledge, and thus control for the influence prior experience (King and Tucci, 2002), which we specifically classify as *general knowledge* or *specialised knowledge* (Balconi, 2002; Grant, 1996; Hamel, 1991)—depending on its proximity to the actual field of application. Embracing a longitudinal view in regulatory settings (as recommended by Blind, 2012) also allows us to carefully reflect on the value of prior technological assets (Dierickx and Cool, 1989) within specific technological trajectories (Dosi, 1982; Jenkins and Floyd, 2001).

By following rigorous protocols of qualitative analysis, we develop a comparative, multiple case study (Eisenhardt, 1989a; Yin, 2008) on the technological innovation strategies adopted by car constructors participating the Le Mans Prototype 1 (LMP1) racing series—which is part of the FIA World Endurance Championship (WEC) —in response to regulatory changes throughout the period 2012-15. Since 1923 and the first race of the iconic '24 hours of Le Mans', endurance racing has become one of the leading and most technologically advanced motorsport events, and we identify and discuss several reasons that make LMP1 an ideal setting to respond to our research question. Among others, in year 2012 the FIA-ACO governing body introduced hybrid power units[1] for the first time in WEC history. A careful investigation of car blueprints, technical commentaries and official regulation bulletins, together with in-depth interviews with experts, revealed that in the following four years all four possible combination of *incremental vs. radical* and *restrictive vs. permissive* changes were introduced—a unique occurrence, which makes this setting almost an ideal natural experiment for our study, and gives us the opportunity to pioneer the very first management study based on data from the iconic Le Mans Prototype racing. We track a precise and nuanced account of the firms' competing technologies and race result; we identify not only the specific configurations associated with superior performance vis-à-vis different regulatory conditions, but also explanations of the conditions and mechanisms underpinning such outcomes.

After reviewing the theory that informed our study, we will present our empirical setting, our research methods, and findings. Finally, we will identify and discuss a set of propositions representing the contributions for present and future research, and depict two overarching models. Limitations of the study and implications for theory and practice will be also addressed in the concluding section.

2. THEORETICAL BACKGROUND

2.1. Technological innovation as firm response to environmental change

Organizational adaptation to changing environments and the firm's responses—for example via exploration and exploitation (March, 1991)—are traditional topics in studies investigating the role of

[1] Hybrid systems allow an energy saving by powering a car with two different sources of energy: fuel and electricity. In the FIA-WEC, the electricity can be produced via the recovery of the kinetic energy created by braking or the heat produced by exhaust gases. See our "Appendix" for an illustration of the Hybrid System used by Porsche in 2014.

innovation (Benner and Tushman, 2002, 2003; He and Wong, 2004; Jansen et al., 2006). According to Benner and Tushman (2002, p. 679) "exploitative innovations involve improvements in existing components and build on the existing technological trajectory, whereas exploratory innovation involves a shift to a different technological trajectory." [2] In this paper, we will focus on the value of exploratory innovation in a technology-driven, hypercompetitive setting (Hoisl et al., 2017). While venturing into different technological trajectories (Dierickx and Cool, 1989; Dosi, 1982), innovation efforts can be radical or incremental, depending on the magnitude of technological advance compared to the current technological standard in the industry (Banbury and Mitchell, 1995; Henderson and Clark, 1990). Recently scholars affirmed that exploratory innovation brings curvilinear returns to performance, and that beyond a specific optimum such returns might actually become negative (Gupta et al., 2006).

Striking such optimum is particularly complex during environmental shifts, which makes the performance-maximizing point a "moving target" (Posen and Levinthal, 2012). While some studies highlight the positive outcomes of increasing exploration when environmental change occurs (Geroski, 1995; Jansen et al., 2006) others rather focus on the pitfalls, and warn that, beyond a certain point, environmental change might erode the rewards of exploratory efforts, thus rapidly turning performance returns flat or even negative (Marino et al., 2015; Posen and Levinthal, 2012; Zhou and Wu, 2010). If fostering exploration can help adapt to environmental changes (Blundell et al., 1999; Levinthal, 1997; Teece et al., 1997), it may also increase costs and risks, thus significantly reducing the likelihood of enjoying its potential benefits. Research has only recently started inquiring on the reason of such diverging positions, and there is common agreement that advancing a consistent and nuanced understanding of such complex phenomenon is a challenging task, which requires a careful dissection of its main intervening factors. Particularly in technological setting, scholars have advised to critically consider the firm's prior investments, activities, and learning experiences, whose general and specialised knowledge can be more or less complementary to the current firm's innovation task (Cohen and Levinthal, 1990; Grant, 1996; King and Tucci, 2002; Tallman et al., 2004).

Further, the value of innovation might depend on its fit within the technological trajectory the firm is pursuing (Dosi, 1982; Jenkins and Floyd, 2001). Technological trajectories are defined as a series of path

[2] By joining studies envisioning exploration and exploitation as orthogonal, independent forces (Gupta et al., 2006: 697) this paper follows recent studies (Marino et al., 2015) in assessing the net value of exploration on performance by specifically investigating an empirical setting where exploitation plays a negligible role on performance.

dependent experiences that track the evolution of a technology (Dierickx and Cool, 1989). Reasoning on technological trajectories thus requires mentioning an important caveat: environments where the competition is fiercer will usually display higher rates of firm innovation, which will reduce the average life-span of each solution, and thus create further incentives for firms to shift towards more promising technological trajectories. Simply put, the obsolescence rate of technologies is often exacerbated by competition, and this might reduce the incumbents' advantage and their product life-cycle (Suarez and Lanzolla, 2005, 2007). This also explains why scholars have traditionally favoured so-called "hypercompetitive settings" to investigate the dynamics connecting environmental change to firm innovation and performance (D'Aveni, 1994; Hoisl et al., 2017; Volberda, 1996). In fast-paced competition, in fact, the interplay between firm innovation and the environment is usually tighter, more visible, and it develops in shorter time-spans. Yet, even in hypercompetitive settings, environmental change remains per se a complex construct to investigate (Bourgeois and Eisenhardt, 1988; Eisenhardt, 1989b; McCarthy et al., 2010), which calls for a meticulous and fine-grained approach.

2.2 Understanding regulations and their dimensions within environmental change

To fully understand the reason of different and sometimes diverging results on the relation between exploratory innovation and performance under shifting contingencies, scholars have been advised to carefully consider the faceted nature of environmental change (McCarthy et al., 2010). Along these lines, in 1988 Bourgeois and Eisenhardt introduced the pivotal concept of environmental velocity. A high velocity environment is described as a setting with "rapid and discontinuous change in demand, competitors, technology and/or regulation" (Bourgeois and Eisenhardt, 1988, p. 816). Building on Bourgeois and Eisenhardt (1988), more recent studies conceptualized environmental change as "multidimensional" (McCarthy et al., 2010, p. 604) and argued that velocity holds paramount implications for a firm's strategy and performance. To understand such relation scholars must appreciate the different nature and dimensions of environmental change.

Indeed, literature shows that sources of environmental change can have different origins. These environmental dimensions are linked in non-trivial ways, and their mutual interdependence is—more often than not—difficult to assess (Garud et al., 2013). For example, in recent years the availability of greener technologies for the car industry allowed policy makers to release and enforce regulations that further pushed firms' research and development efforts for engine efficiency and low emission. This nurtured mixed effects on competition. In fact, on the one hand regulatory changes created market opportunities for newcomers such as Tesla, but on the other they also motivated incumbents to pioneer innovative solutions such as hybrid and electrical engines (see for example the BMW i3 and i8 series in the high-end market or Nissan Leaf in the low-end). Rising pressure to cope with increasingly environmentally-conscious markets (i.e., consumers and regulations) also were one of the factors inducing the adoption of illegal technological solutions at Volkswagen, which were unveiled in the recent emission scandal and ultimately motivated the regulators to further exacerbate controls and constraints in the industry (Spicer, 2015).

In technology-driven competition, regulations represent one of the major sources of environmental change and they directly influence firms' strategic orientation and innovation (Mahon and Murray, 1981; Ramaswamy et al., 1994; Reger et al., 1992). Yet, scholars lament that "regulation, innovation and competitiveness in global markets have been discussed for several decades. However, little progress has been made to understand the effect of regulation on the ability of industries to innovate" (Blind, 2012, p. 391). Regulations are a velocity dimension that measure "the nature and the scope of the control provided by new laws and regulation in a given period" (McCarthy et al., 2010, p. 609). Regulatory changes—similarly to other types of environmental change—may also vary across multiple dimensions, thus making shifting scenarios harder to interpret unless one adopts a precise classification of change.

As pointed out by recent contributions (Marino et al., 2015; McCarthy et al., 2010) scholars traditionally distinguish between two main dimensions of environmental change: the *frequency* (e.g., Child, 1972; Wholey and Brittain, 1989) and the *magnitude* of the change (e.g., Abernathy and Clark, 1985; Tushman and Anderson, 1986). The former corresponds to the amount of time between subsequent changes, while the latter defines the degree of difference between states at subsequent points in time. The magnitude of change is traditionally codified either as incremental or radical (Henderson and Clark, 1990; Tushman and Anderson, 1986). Incremental changes are "competence-enhancing", meaning that they aim to improve and advance the firms' existing set of knowledge, competences, and technologies. Radical changes instead are "competence destroying", meaning that they establish a new set of knowledge, competences, and technologies which substitute the existing firms' assets and capabilities (Tushman and Anderson, 1986, p. 442). For this reason, radical shifts can trigger disruptive changes (Ansari and Krop, 2012; Christensen, 1997) and lead to new technological standards and industry paradigms (Romanelli and Tushman, 1994; Spender, 1989), which in certain cases might destabilize the market's status quo and favour new entrants

(Abernathy and Clark, 1985; Abernathy and Utterback, 1978; Porter, 1980; Suarez and Lanzolla, 2007). An industry could for example have a high or low rate of new regulations—e.g., depending on how often new rules are released or replaced; see Reger et al. (1992), and can involve either incremental or radical regulations—e.g., depending on whether they aim at refining the application of an existing technology or to completely substitute it with a new one; see Marino et al. (2015). Further, such changes can be more or less predictable—which affects the firm's ability to absorb increasing magnitudes and frequencies; see Ungson et al. (1985). Frequency, magnitude and predictability are important dimensions to understand environmental change (see Table 1 for an essential literature review), but—particularly in the case of regulations—they fail to capture another critical aspect, which is what we term here as the *direction* of regulation change, or in simple words, whether the rules become more *restrictive* or *permissive* (see discussion in Reger et al., 1992, p. 191). From the regulators' perspective, regulations are in most cases restrictive in nature, as they usually aim to control and reduce the competitors' degrees of freedom within a specific arena—supposedly with the intent to promote free competition and public welfare (Blind, 2012). This usually correspond to banning specific technologies or solutions, or limiting their adoption (Mahon and Murray, 1981; Reger et al., 1992). Yet, in cases where regulations move in the opposite direction, scholars and practitioners use the term "deregulation" (Reger et al., 1992) to identify, for example, more permissive "policies measures such as a relaxation in sectoral restrictions on technology imports, substantial tax cuts on royalties and technical fees, simplification of tax structure" (Aggarwal, 2000, p. 1082). Accordingly, to theoretically and empirically distinguish the two domains, we adopt the dichotomy *restrictive regulations vs. permissive regulations* to identify changes in the regulation body aimed at reducing rather than increasing the degrees of freedom in firms' technological exploration (for a review on different regulatory classifications see Blind, 2012).[3]

[Insert Table 1 about here]

Understanding the nature of regulations also requires a reflection on their objectives and outcomes. In line with prior contributions (Blind, 2012; Blind et al., 2017; Reger et al., 1992) we observe that the initial

[3] We prefer to use the term 'permissive regulation' instead of simply 'deregulation' as the latter usually implies the presence of prior regulatory constraints (Reger et al., 1992). Our setting, however, presents a slightly different connotation, as the regulatory action initially operated in a *vacatio legis* (i.e., absence of rules on a specific matter), where the regulator decided to provide some general indications to create a new market for a novel product category (i.e., a new technological standard for a new racing series). Yet, such indications were originally designed to create a deregulated competitive space (Mahon and Murray, 1981)—a condition which is traditionally aimed to attract new entrants and foster incumbents' innovation (Blind et al., 2017; Porter, 1980).

intention of the regulator might effectively trigger diverging behaviours among the rule recipients—might these be individuals, organizations or countries. Despite several scholarly attempts, Blind (2012, p. 395) highlights that “especially the quantitative studies are not able to distinguish between the influence of changes in the legislation and their enforcement or the compliance of companies on innovation activities”. This reflection leads to at least two important implications for our research endeavour. First, we acknowledge that a qualitative, population-level perspective is perhaps more suitable to capture the nuances of firm behaviours. Second, and perhaps more importantly, we purposefully adopt the regulators’ perspective and classify regulations in line with the initial objectives that the regulator envisioned, independently from the effects they trigger at the firm level. This means that, for example, we define as “restrictive” a set of rules that the regulator defined as aimed at reducing the competitors’ technological options; and “permissive” those originally promoting free experimentation with multiple solutions (Reger et al., 1992). By doing so, we do not exclude the possibility that even restrictive frameworks might nonetheless offer firms the opportunity to ‘work around the rules’, thus fostering innovations that somehow cannot be openly banned by the governing body.

2.3. The relation between regulations and firm outcomes

With few exceptions, literature connecting regulatory changes to firm-level outcomes is still scarce (Blind, 2012, p. 395), and mostly skewed towards studies exploring the effect of regulation as a policy to foster firm innovation—mostly for negative externality reduction or environmental preservation (e.g., Jaffe and Palmer, 1997; Palmer et al., 1995; Porter and Van der Linde, 1995). In addition, the literature presents “great controversy” as the scholar’s positions cluster across two diverging points of view (Blind et al., 2017, p. 249). On the one side, scholars highlight how regulations “restrict firms in their innovation activities” as regulation compliance expenditure are directly correlated to research and development expenses (Jaffe and Palmer, 1997). Also, regulations primarily affect the product development and are ‘technology-forcing’, in a sense that by using different types of restrictions, regulations can channel the industry players to abandon some technologies in favour of others (Ashford et al., 1985; La Pierre, 1976). Within this perspective, scholars thus advocate that deregulation can promote “complementarity between technology imports and R&D efforts significantly” as well as “product differentiation, demand conditions and technology-related factors” (Aggarwal, 2000, p. 1081).

Yet, several scholars embrace the opposite point of view and agree that regulations—if properly designed—can stimulate firms to increase their innovation efforts (Porter and Van der Linde, 1995) and observe that even when regulations make compliance costs surge, the patenting of new technologies also raises within a short time (Lanjouw and Mody, 1996). Regulations, as all other dimensions of environmental change, trigger adaptive responses at the firm level (Mahon and Murray, 1981), and therefore scholars affirm that regulations—might they be permissive or restrictive—do not necessarily straitjacket innovation (Jaffe and Palmer, 1997; Marino et al., 2015; Porter and Van der Linde, 1995; Smith and Grimm, 1987; Young, 2002). For this reason, expert scholars have recently declared that, particularly in technological settings, "regulations are challenges which provide opportunities to be more creative" (Jenkins, 2014a).[4]

What is less clear—and largely underexplored—is how different regulatory *directions* affect the relation between firm innovation and performance (for an exception see Smith and Grimm, 1987). In other words, one could imagine that different types of firm responses (e.g., radical vs. incremental innovation; related to core vs. peripheral subsystems) might better fit regulation changes that are either restrictive or permissive in nature, and thus lead to superior performance outcomes. A recent study examined the relationship between firm exploration efforts and performance under regulatory changes of different *magnitude*, and suggested that when the regulations undergo radical changes, firms' incremental explorations such as "imitation and reverse engineering of technologies, may be the best approaches" (Marino et al., 2015, p. 1095). On the contrary, when regulation change moderately, or do not change at all, firms that pursue radical explorations will maximize their performance. However, this case does not inform us about the different directions of change, and particularly it is agnostic on the moderating effect of deregulations or permissive regulations, thus leaving our understanding incomplete. Smith and Grimm (1987, p. 373), for example, show that when a major deregulation is established, a strategic change from an "unfocused follower strategy to an innovation strategy" seems to be the most profitable option. This suggests that the direction of change (e.g., from restrictive to permissive) might revert the expected prediction a mere account of a change in magnitude would entail. And yet, there is almost no research inquiring on what kind of firm innovation maximizes performance under regulation changes that vary between permissive or restrictive. Scholars have only started to scratch the surface of an issue that, given the increasing regulatory actions in most industries, holds

[4] Notably, Jenkins (2014a) specifically identifies similar dynamics both in motorsport settings (i.e., Formula 1) and more traditional industries.

promises to provide important contributions for theory and practice (Blind et al., 2004). To respond to this timely issue, we selected a setting whose characteristics uniquely allows us to dig deep into the nuanced interplay between regulatory change, firm technological innovation and performance: The Le Mans Prototype 1 category (LMP1) within the World Endurance Racing (WEC) series, better known for the iconic race called 'The 24 Hours of Le Mans'.

3. METHOD

Our qualitative investigation is based on a longitudinal (2012-2015) comparative case study (Eisenhardt, 1989a; Yin, 2008) of the exploratory innovations adopted by the three car manufacturers (i.e., Audi, Toyota and Porsche) participating to the FIA WEC championship (racing class Le Mans Prototype 1, often shortened as LMP1) in response to environmental change of varying magnitude and direction (but constant temporal frequency and predictability). The study analyses a total of ten firm-year cases. We identified a setting that is small enough to observe the entire population of firms in great detail. By leveraging the rich and nuanced data from our setting, and by building several comparative tables (as recommended by Eisenhardt, 1989a) where variables and measures are coded through categories that are common in the field (Gioia et al., 2012), we qualitatively identified meaningful association between firm's technological strategies and their performance under different regulatory contingencies, and ultimately tried to suggest dynamic patterns that explain the underlying mechanisms of such associations.

3.1 Research setting

Recently, scholars have increasingly leveraged empirical settings from different racing series to advance management research such as NASCAR (Bothner et al., 2007; Bothner et al., 2012) and Formula 1 (Aversa et al., 2018; Aversa et al., 2015; Castellucci and Ertug, 2010; Castellucci and Podolny, 2017; Hoisl et al., 2016; Jenkins, 2010; Marino et al., 2015; Piezunka et al., 2018). In this work, we decided to explore dynamics in another high-tech racing setting called the FIA World Endurance Championship (WEC). With the prestigious 24 hours of Le Mans as flagship (established in 1923) this series—which is run by the Fédération Internationale de l'Automobile (FIA) and by the Automobile Club de l'Ouest (ACO)—currently includes four different categories of competition and is composed of nine races that take place around the world. In this study, we focus on the most recent and technology-advanced category called Le Mans Prototype 1 (LMP1). This competition is open only to major car manufacturers, which must race with their own prototype cars. This allows us to observe the efforts of major car makers engaging with the perils of developing a futuristic vehicle that pioneers some of the latest discoveries in automotive—a motorsport phenomenon that mimics the broader introduction of hybrid and electric vehicles in the main automobile market (Sierzchula et al., 2012). When LMP1 cars are powered by a combination of traditional combustion engine and electrical energy recovery systems (ERS), the sub-series is also called 'LMP1 Hybrid or LMP1-H'. Also, we bracketed our analysis on the period between 2012 and 2015, which displayed unique conditions to support our research endeavour. Indeed, two radical changes of regulations occurred during this period (i.e., in 2012 and in 2014) and three constructor teams (i.e., Audi, Toyota and Porsche) competed against each other by using three different hybrid systems and three different innovation strategies.[5] Also, in these racing seasons we can interestingly observe the dynamics connected to two new entrants: Toyota and Porsche. This situation makes the competition an ideally simplified setting with enough variance to respond to our research questions, but small enough to qualitative unveil the granularity of the underlying mechanisms connecting regulatory changes to firm technological innovation and performance.

As other racing series, the LMP1 championship presents different qualities that makes it a "perfect laboratory for research" (Gino and Pisano, 2011, p. 70). We describe here the advantages of our setting, while limitations will be carefully addressed in the concluding paragraph. First, by not only being a technology-based, but also a highly regulated setting, it presents similar traits to more common industries such as automotive (Lee et al., 2011; Narayanan, 1998), chemicals (Hartnell, 1996), pharmaceuticals (Morris, 2000) and railways (Smith and Grimm, 1987). Therefore, it allows—to some degree and within some boundary conditions—to generalize our findings and strengthen the external validity of our study. Second, firms competing in the LMP1 are not only comparable in size (i.e., all racing teams are owned by major car manufacturers), organizational structure, team roles and objectives, but also similar in the type of products they develop: as they all are completely and exclusively focused on the yearly production of a high-tech car prototype, they can be effectively considered single-product organizations. This means that spurious effects related to product and technology diversification are less of a concern in this setting. Also, in all LMP1 teams learning curves for process innovations, economies of scale, and efficiency-based objectives do not significantly influence the performance outcome, thus reducing concerns for an array of common

[5] During the 2012 season, Audi also run two cars without hybrid systems called Audi R18 Ultra. For this reason, we have excluded those cars from our observed sample.

confounding effects that could hardly be controlled in a qualitative study. Third, giving the duration of endurance races (up to 24h), the WEC is a discipline where reliability and consistency matter more than mere top speed, thus representing an ideal ground testing for product performance under extreme circumstances. Fourth, all firms race simultaneously and in the same location so they have to adapt to the same exogenous conditions such as weather and racetrack characteristics—as well as regulations, of course. Fifth, the popularity of such competition allowed us to access a wide and fine-grained amount of public, high quality, official data covering several aspects of the regulations, the car technology and the results. Such archival data also include several interviews with experts and top professionals that were collected directly at the races or immediately after; this reduces concerns for retrospective call biases in comparison to traditional ex-post interviews. Last but not least, racing naturally offers precise metrics on regulations and product performance (Aversa and Berinato, 2017; Hoisl et al., 2017; Jenkins et al., 2016; Marino et al., 2015).

3.2 Data

Our research is based on a collection of official archival and primary data (i.e., interviews). In line with former qualitative research in motorsport (e.g., see among others Aversa et al., 2015; Jenkins, 2014b) the archival document collection was developed through a broad range of different sources such as books, official FIA and ACO releases, official documents from the manufacturers, generalist and specialised press and technical blogs (see Table 2 for a precise account of the data sources). Altogether, we collected more than 1,100 pages of archival data.

The use of multi-source, public, official data allowed us to extensively triangulate individual informants' cognitive biases and retrospective sense-making. We firstly inspected all official FIA-ACO regulations bulletins between 2012 and 2015 with the intent to track every regulation change. We also studied prior documents that prepared to the introduction of such changes (e.g., meeting reports where the change was discussed, interviews with key decision makers, official proposals, etc.). Then, we looked at the specialised press and blogs to gain insights into each car's development before and during each season of our observation period. We mostly focused on the firms' innovation regarding the different components of each LMP1 car, the yearly regulatory changes and the teams' performance. Our initial body of documents was skimmed based on relevance, reliability of the information and the source, repetition (several websites tend to re-post the same information), which ultimately led to a compound, refined selection of 110 documents for a total of 221 single-space pages of relevant text.

[Insert Table 2 about here]

Despite this study is mostly based on secondary archival data (which often report extensive interviews to the most important executives and experts in the field), we also directly ran several interviews with industry informants and professionals to gain specific understanding of the relation between the variables, and ultimately to verify our interpretations. The experts were selected based on their acclaimed experience in the field, and all of them extensively worked in LMP1, WEC or motorsport. The interviewees included team executives, journalists, opinion leaders, engineers and members of the governing body—see Table 3 for details on our informants and interviews from primary data. However, thanks to secondary archival data, we additionally reviewed 63 useful interviews whose topic was significantly related to our inquiry. The interviews conducted in French were translated by scholars who are bilingual and cross-checked with external data. Controversial interpretations about the translation have been jointly discussed until reaching agreement, or discarded when this was not achieved.

[Insert Table 3 about here]

3.3 Coding and analysis

We conducted a structured coding process to classify qualitative evidence as discrete variables both at the firm (i.e., innovations) and the environment (i.e., regulation) level (Strauss and Corbin, 1990). Then, by associating our codes to racing performance measures, we identified a series of theory-informing patterns that link firm exploratory innovation to performance within different regulatory contingencies. Knowledgeable experts' opinions were incredibly useful in identifying the underlying processes and mechanisms in this interplay, and some of their most significant quotes are reported in our analyses. Finally, in line with common protocols for qualitative analysis, one of the scholars played the "devil's advocate" (Gioia et al., 2012, p. 19) and challenged the weaker interpretations, discarding those that were not sufficiently supported by evidence or shared understanding.

3.3.1 Environmental level variables

At the environmental level, we followed the method used by previous research that were also studying regulation change in motorsport such as Marino et al. (2015). Given the impossibility to fully distinguish the aim of the regulator from the specific firm's interpretation and compliance (see discussion in Blind, 2012, p. 395) we aligned to traditional procedures and classified the rules based on the regulators' original aim. We chose the *magnitude of the regulation changes* by coding the variations in the FIA-ACO technical regulations. We noted competence-destroying changes in the regulations as *radical*, and competence-enhancing changes in the regulations as *incremental*. Furthermore, we coded regulation dynamism based on the direction of change (Reger et al., 1992), either *permissive* when regulators aimed to give more freedom to the teams in terms of technological development and when effectively deregulating a specific domain; or *restrictive* when regulators released frameworks that were aimed to reduce the teams' freedom or increase controls and ceilings on the technological development. Table 4 offers a precise account of our rule coding.

[Insert Table 4 about here]

3.3.2 Firm level variables

At the firm level, we examined and associated performance outcomes to technical articles and official blueprints[6] concerning the design and engineering of the entire population of cars competing in the LMP1 between 2012 and 2015 (10 cars in total, 2 vehicles in 2012-2013 and 3 competing in 2014-15 respectively) and we used four different groups of variables in order to give us insights into: (1) The racing teams' performance (final championship tally related total number of points as per Jenkins, 2010, 2014b); (2) The type of subsystem involved (core subsystem vs. peripheral subsystem; as per Murmann and Frenken, 2006); (3) The magnitude of the change (incremental vs. radical; as per Henderson and Clark, 1990) (4) The firms' prior technical knowledge in the form of *general* vs. *specific knowledge* (Grant, 1996; Tallman et al., 2004), and whether this related to core or peripheral subsystems. Simply put, we coded 'how well' the team did in the racing, 'what' technology was changing, 'how radical' the innovation was, plus 'what prior knowledge' informed the process.

Firm performance. To measure each firm performance record and in line with previous research related to Formula 1 (see Aversa et al., 2015; Jenkins, 2010; 2014b among others), we used the official FIA-ACO rankings from the yearly Constructor Championship.

Subsystems involved. In line with former studies about complexity of system architecture (Baldwin and Clark, 2000; Brusoni et al., 2001; Henderson and Clark, 1990; Murmann and Frenken, 2006; Simon, 1962;

[6] Differently from other technology-intensive series, prototype racing almost never relies on patenting, but rather on industrial secrets. In fact, patents would reveal important information to rivals, thus favouring imitation and putting a firm's competitive advantage at risk. Further, the intense pace of the yearly tournament does not leave enough time to undergo patenting protocols. For these reasons, all works based on similar settings to LMP1 (e.g., Formula 1) have never relied on patent analysis, but on codification of technical blueprints, which often become publicly available when the championship ends.

Simon, 2002), we conceptualized cars as a complex systems "that evolve in a form of a nested hierarchy of technology cycles" (Murmann and Frenken, 2006, p. 931) thus allowing a longitudinal analysis across multiple hierarchical subsystems of a product architecture. By understanding the hierarchical structure of a car (for similar applications see Cabigiosu et al., 2012; Marino et al., 2015), we identified that a racing car was made by integrating different 'core' subsystems such as chassis, powertrain and aerodynamics, and 'peripheral' subsystems such as ERS, brakes and wheels. This classification was based on the Murmann and Frenken's concept of "pleiotropy" (2006, p. 925) and it is aimed at identifying at which hierarchical level innovation was taking place, and it is based on principles related to the system's centrality in the overall product design, its importance for performance upgrades, and the complexity, costs and risks in replacement or retrofit (Baldwin and Clark, 2000; Murmann and Frenken, 2006; Soda and Furlotti, 2014). Core subsystems (i.e., technological components) connect multiple others and embed more knowledge, so they are more impactful on the performance of the broad system, though they are complex, more tightly integrated in the product architecture, and demand major development and substitution costs. In turn, peripheral parts are less complex, less tightly integrated in the product architecture, and impactful on performance, but need notably less effort to build or substitute (i.e., low risk/low gain; Tushman and Murmann, 1998).[7]

Magnitude of change. To track the *magnitude* of change we used a very common dichotomy by Henderson and Clark (1990) distinguishing between *radical* vs. *incremental* innovations and we applied in relation to whether the innovation was new to LMP1 or not—for a similar operationalization in motorsport see Marino et al. (2015). Specifically, we coded changes at the firm level as radical when it was the first time a technological solution was used in LMP1 (i.e., new to the field, coming from F1 or more broadly from automotive) and thus required the organization to undergo a significant resource or capability upgrade; these technologies were often disruptive in relation to prior technological standards. In contrast, we coded changes as incremental when the technological solution was only a progressive enhancement of a system previously in use in endurance motorsport racing.[8]

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[7] In line with Murmann and Frenken (2006, p. 941) "we call high-pleiotropy components core components and low-pleiotropy components peripheral components, because changes in high-pleiotropy components have greater repercussions for the functioning of the system as a whole than do changes in peripheral components. The most important insight, which also is true for the structure of biological evolution, is that once a design has settled on particular variants of core components, further advances are concentrated in peripheral components only".

[8] LMP1 (similarly to Formula 1) is a hypercompetitive setting (Hoisl et al., 2017) as cars are not only among the fastest ever built, but they have to race without stopping up to 24 hours. Technology in LMP1 is at the very ultimate forefront

General vs. specialised knowledge. We collected each firm's prior knowledge and experiences, as this might affect the firm's capability to value, assimilate, and apply new knowledge, for example as an innovation response to a regulatory shift. Specifically, we follow prior contributions (Balconi, 2002; Grant, 1996) in classifying *general knowledge* as the firm's set of knowledge and technological experiences related to more distant fields of application that can nonetheless broadly inform the innovation process in the focal domain. We classify instead as *specialised knowledge* the part of knowledge and experiences that derive from the direct and specific application to the focal domain. Take as an example major automotive manufacturers such as Toyota, Audi and Porsche. Their engagement with hybrid technologies for standard road-cars (e.g., lithium-ion batteries or flywheels) provides a general basis for a broad understanding of the main challenges that an application to LMP1 entails—and thus is coded as *general knowledge*. Yet, given the hyper-advanced nature of LMP1 technology, only a specific and recent application of such devices to LMP1 might provide sufficient understanding to fully engage with contingent technological innovation—which we code as *specialised knowledge*. By going back to the roots of each firm's technological know-how, we can also track the different *technological trajectories* (Dierickx and Cool, 1989; Dosi, 1982; Jenkins and Floyd, 2001) each firm is pursuing (i.e., flywheel vs. supercapacitor vs. lithium-ion battery), and take into account firms' shifts towards new solutions, as well as their constraints and core-rigidities (Leonard-Barton, 1992).

Table 5 offers a tabulation associating the codification of firm level changes to environmental changes. Each car's individual blueprints codification is available in the supplemental materials for review, as well as a precise tabulation on the origins of each firms' prior knowledge.

[Insert Table 5 about here]

3.4 Additional materials for review

To provide a transparent and more informed account of our analyses, we prepared a complete set of additional materials (i.e., qualitative insights and descriptive statistics), which complement the essential exhibits in this manuscript and offer additional nuance to readers who might not be familiar with LMP1 or

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of the automotive sector. For this reason, prior knowledge in road-car, minor racing categories, or even F1 (when dated more than two or three years), might have little or no application and value in current LMP1. Several cases of failure offer face-validity to such statement: among others, Honda disastrous comeback to F1 as McLaren engine supplier (2015-2017) proved the company unable to reach the necessary technological edge despite being the biggest engine producer in the world, a major manufacturer of hybrid technologies, and having successfully competed in F1 until 2009, both as engine manufacturer and constructor (Noble, 2017). Similarly, the underperforming cases of Toyota, Jaguar and BMW in Formula 1 further corroborate this argument—see also our discussion point in the conclusion.

motorsport in general. Appendix A includes a glossary of technical terms used in the paper (Table A1); a tabulation comparing the detailed qualitative codification of all technological innovation at the firm level between 2012 and 2015 (Table A2); a detailed account of each team's general knowledge (from other series and road cars) and specialised knowledge (from LMP1), divided across four subsystems—two core and two peripheral (Tables A3a, A3b, A3c); tables with race results between 2012 and 2015 (Table A4); a comparison of main races' features (Table A5); a detailed account of the yearly firms' final ranking in LMP1 championship (Table A6); a visual comparison of competing technologies developed by the firms (Table A7). Appendix B presents three mini case studies on Audi, Toyota and Porsche, which inform about their past experience in motorsport and endurance racing.

4. LMP1 FIRM TECHNOLOGICAL RESPONSES UNDER REGULATORY SHIFTS (2012-2015)

[Insert Table 4 and 5 about here]

LMP1 racing seasons between 2012 and 2015 represent a unique and ideal setting for our research due to the type and sequence of regulation changes, as well as their effect on the competition. During these four years, a new, disruptive technology was introduced in the field: an energy recovery system (ERS) that transformed traditional combustion engines into hybrid power units. During this period, two different cycles of environmental changes took place: first, a cycle characterized by permissive regulations (2012-2013), started in a radical magnitude (2012) and followed by a more incremental magnitude (2013). FIA-ACO's regulations in these two years were aimed at opening avenues for new technological experimentation, and for this reason they were purposefully *permissive*. In contrast, the second cycle (2014-15) was aimed at controlling and harnessing such experimentation toward few, consistent and useful solutions, thus making the regulations more *restrictive*, first in a radical magnitude (2014) and later in an incremental magnitude (2015). For each of the cycle we will analyse the empirical evidence and consequently advance two propositions (and related corollaries under polar regulatory conditions)—i.e., p1 and p2 for permissive regulations; corollary to p1 and p2 for restrictive regulations.

4.1.1 2012-13: Permissive regulations for a new technological paradigm

After years of hesitation and negotiations, in 2012 the FIA and the ACO decided to jointly establish a new championship for endurance car racing (i.e., WEC). The idea behind this new series was to attract the major road car manufacturers to endurance racing. This in turn would have enhanced the sport visibility and fostered public utility by pioneering solutions that could be later adopted in standard road cars (Goodwin, 2012). The new WEC series revolved around the introduction of a new hybrid systems, as the former ACO's Technical Director confirmed during an interview:

> *"We aimed to create room for them (i.e., the car manufacturers) to develop new technologies that could be commercialized on their road cars later on. The issue was to figure out a way to regulate this new technology while keeping it a competitive championship." [Daniel Perdrix, Former ACO's Technical Director; Source: Interview].*

The new 2012 WEC regulations added for the first time a technical framework to 'upgrade' the prototype category (i.e., LMP1) to the use of hybrid systems (i.e., LMP1-H). The new regulations radically changed the existing ones and started by giving freedom to the constructors regarding the technological development (i.e., flywheel; capacitors; different type of batteries).

> *"We had established a quite high minimum weight for the prototypes (900kg) giving to the constructors room to develop a hybrid system following their own technical choices. (…) We did not want to close doors for innovative solutions as we wanted to promote research on new hybrid systems for road cars during a period where 'the gallon' was incredibly expensive and the automobile industry seen as a danger for the earth's future." [Daniel Perdrix, Former ACO Technical Director, 2016; Source: Interview].*

As shown in Table 4, the new rules not only defined a hybrid car in general, permissive terms—which left room for different interpretations—but also explicitly opened the category to different technical solutions regarding the 'energy recovery system' (ERS) (art. 1.13 and 1.14 FIA-ACO 2012 technical regulations, 2012), which is fundamentally based on a technology that collects excess energy (i.e., heat) in the car—from the brakes, exhaust pipes and engine—transforms it into electrical energy and makes it available for additional acceleration (similar to what happens in Formula 1—see the KERS case in Marino et al., 2015, p. 1090). Although the ERS was initially limited to releasing a total energy of 0.5 MJ[9] (art. 1.13, 2012 FIA-ACO technical regulations, 2012), it was fundamentally independent from the traditional engine, which allowed manufacturers to experiment the new system without affecting the traditional powertrain in the case of malfunctioning, failure or accident.[10] Also, the regulations left the teams free to choose their own fuel tank and fuel flow design. Often described as a transition phase between two years of radical change, the 2013 WEC season presented only minor changes both at the regulatory and firm innovation level (Source:

[9] The megajoule (MJ) is equal to one million (10^6) joules, or approximately the kinetic energy of a one megagram (tonne) vehicle moving at 160 km/h.
[10] For example in 2012, Audi's winning car at Le Mans race damaged its hybrid system few hours before the end of the competition without consequences on its diesel powertrain's performance (Codling, 2012; Codling, 2013).

Endurance-Info.com, 2013). In line with 2012 changes, the technical regulations indeed remained permissive in terms of technological freedom and added only few incremental changes concerning the car safety (see table 3). Also, they advanced some specifications concerning rear extractors and diffusers dimensions (see table 3, art. 3.4.5 and 3.5.2, 2013 of technical regulations).

4.1.2 Firm responses to radical, permissive regulatory changes (2012)

Given the engineering freedom allowed by the rules, the two LMP1 competitors (i.e., newcomer Toyota and incumbent Audi) in 2012 chose two new but different solutions for their ERS. Table 5 codifies firm responses to the regulation change both for the peripheral subsystems (e.g., ERS, gearbox, brakes, etc.) and core subsystems (e.g., engine, chassis, aerodynamics, etc.).[11]

In 2012 Audi equipped its R18 e-tron car model with a hybrid power unit combining an ERS to a TDI engine. It was the first time that a WEC racing car was using such a configuration with a flywheel system[12] instead of batteries as energy storage.[13] The flywheel system had an advantage not only in offering simplicity and superior reliability (Collins, 2013a), but also in releasing the kinetic energy on the front axle making the car effectively a four-wheel drive—a ground-breaking innovation as racing cars usually release the traditional engine's energy on rear wheels (Rügheimer, 2013).[14] Audi uniquely coupled this ERS with the same TDI engine used in the 2011 season (Pruett, 2012) and embraced a F1-inspired light-weight, carbon-fibre gearbox housing aimed to significantly reduce weight (Collins, 2013a). Audi's 2012 chassis and aerodynamics featured solid but nonetheless incremental solutions to its product (Congrega, 2011). However, it is important to notice that in prior years (particularly in 2006 and 2011) Audi had embraced a progressive trajectory of radical architectural change, so that by the beginning of 2012 season its car design had reached good balance and reliability. Audi could thus match an innovative chassis (i.e., core subsystem)—whose technological glitches had already been solved (Collins, 2013a)—to a radically new hybrid power unit and 4-wheel transmission system (i.e., peripheral subsystem) developed specifically for

[11] The detailed codification of the firms' technologies is available in the Appendix, Table A2.
[12] A flywheel system stores the energy mechanically, as rotation energy, by the use of a rotor spinning at a very high speed (Source: Porsche, 2010)
[13] Audi 'borrowed' and adapted this technology from its sister company, Porsche (Meiners, 2012), that had used it for one of its hybrid racing cars in a less technologically advanced racing series (i.e., 911 GT3-R Hybrid in 2010). Porsche, in turn, had originally purchased this system from Williams Formula 1 team (English, 2010).
[14] Such solution was absolutely new in the racing world (Rügheimer, 2013); a similar architecture had been tested for standard road cars in 2011 by Peugeot with its "Hybrid 4 technology" (Hammond, 2012).

the 2012 season. Accordingly, we coded Audi's car in 2012 as incremental at the core subsystems level and radical at the peripheral subsystems level.

Unlike Audi—which had a more recent and successful experience in endurance racing[15]—the newcomer Toyota debuted in 2012 with a LMP1 project elaborated almost from scratch, and despite not massively innovative, it represented a major technological effort for the Japanese contender. Toyota could in part benefit from its Formula 1 experience (Kim, 2012) that was discontinued in 2009.[16] The new Toyota LMP1 car named TS030 combined a traditional design such as a normally aspirated V8 petrol engine—heavily re-worked version of their Toyota Super GT 3.4-litre V-8 used in Japanese racing series (Kim, 2012)—with a hybrid ERS developed via a novel in-house concept of 'supercapacitor', a high-performing storage system based on electrostatics rather than chemical principles of batteries—the only major innovation for Toyota, and a promising solution for energy storage. Toyota had purposefully decided to forego batteries due to their capacity limitations. This was confirmed by interviews with Toyota executives:

> *"(…) Compared to the battery technology of the time, the supercapacitor was able to store a much greater amount of recovered energy within a very short time (braking times of 1-3 seconds). This was the key factor in choosing super capacitor technology (…)" [Marketing manager, Toyota; Source: Interview].*

Despite, releasing more energy than Audi's (Emme, 2012), Toyota's ERC released energy only on the rear axle and only below 120 km/h as per the 2012 regulations (see table 3 art. 1.13, 2012 of technical regulations). If the supercapacitor was almost a new-to-the-world solution,[17] the other elements of the TS030 were largely established. The aerodynamics imitated and improved the Peugeot LMP1 cars (Wittemeier, 2012), while bodywork and exhaust system were inspired by the recent Toyota's experience in F1 (Racecar-Engineering, 2012). The remaining parts were evolutions of solutions used by Toyota in other series (Kim, 2012). Toyota thus released an incremental chassis, engine and aerodynamics (i.e., core subsystems) with a radical supercapacitor-based ERS (i.e., peripheral subsystem).

4.1.3 Firm responses to incremental, permissive regulatory changes (2013)

In 2013 both Audi and Toyota tried to refine and improve the reliability of their 2012 cars. Audi followed the 2012 trajectory by introducing two versions of the R18 e-tron model that were extremely

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[15] The last endurance program from Toyota had ended in 1999.
[16] Toyota participated in the F1 championship from 2002 to 2009 as a constructor team—see Appendix for more details.
[17] The super capacitor system was developed by Toyota since 2006 and experimented in minor competitions on a Toyota Supra in 2007 in Japan (Toyota-Global.com, 2016).

similar to the 2012 model, both in terms of engine, 4-wheel drive and aerodynamics (Collins, 2013a). Indeed, only few incremental changes in the peripheral subsystems could be observed in the Audi 2013 car, such as a new radiator allowing a reduction of the airflow pressure, and a new rear wing extensions in order to reduce drag (Collins, 2013a). The ERS system was the same of 2012 but with slightly increased capacity (Vijayenthiran, 2013). Toyota as well underwent incremental updates for its TS030 car by consistently following the technological trajectory of their promising but still not victorious first season in LMP1 (Collins, 2013b; Mercier, 2013). The company tried to solve the reliability problems that had troubled the first car version. Toyota executives specifically talked about "incremental improvements":

> *"For this year we have achieved some incremental improvements while including some pre-testing of 2014 technologies. We have polished up things like power and efficiency whilst also fine-tuning the powertrain to enhance reliability. Overall we are confident we again have a very competitive and reliable powertrain." [Source: Hisatake Murata, Toyota Hybrid Project Leader (Collins, 2013b)].*

The Toyota TS030 featured an improved chassis and monocoque package that tweaked the overall shape of the car while upgrading its performance (Toyota, 2013). Similarly, the engine also underwent minor updates from 2012 (Collins, 2013b). More discreet changes could also be observed with the component usage optimization that was pursued by removing the deactivated MGU in front of the car (Collins, 2013b). In 2012, Toyota had in fact tested two different options for the MGU's position: one on the front axle and the other one on the rear. The latter being chosen, the team did not have time to change the car's overall design and kept a non-activated MGU on the front axle. By removing such MGU, in 2013 Toyota saved weight and rearranged the chassis space by receding the driver position, which improved the overall weight distribution. Finally, the supercapacitor system was enhanced to 300ps (Source: Toyota, 2014). Yet, as Toyota's technical director Pascal Vasselon explained, the TS030 model 2013 was just an optimization of the 2012 model, but displayed no major upgrades.

> *"…This year's car has to be an evolution of our initial concept. The obvious target is to fix all the little issues we have found during the last season. The very first one is the 2012 car, that being a laboratory car, was able to accept front and rear hybrid systems, so we have redesigned the monocoque to optimize it without the front motor (…) there has been no concept change, just refinement and optimization of the 2012 car." [Pascal Vasselon, Toyota Racing Group Technical Director in Miller (2013)].*

4.1.4 Effects on performance 2012-13 and propositions

In 2012 Audi dominated the championship by winning 5 races out of 8, and by finishing almost every race on the podium. The car overall managed to offer a very high-performing 'technological package', which—thanks also to prior developments—provided a solid and innovative platform to reliably nest the radical hybrid module.[18] Toyota also tried to embrace a different but still radical modular change within a traditional car architecture. Yet, despite three victories the team suffered several reliability issues, which undermined its chances for the championship.

As permissive regulations offered little or no limitations to experimentation, it became harder for racing firms to identify the 'performance ceilings' and structural boundaries that each technology entailed. In other words, causal ambiguity (Powell et al., 2006; Reed and DeFillippi, 1990) increased between different technological options and performance outcomes as team were uncertain on which specific solution (i.e., flywheel, supercapacitor, battery, etc.) was systematically superior. This ultimately reduced the firms' incentives for shifts towards new technological trajectories, and by focusing on progressive optimizations, both Audi and Toyota continued their trajectories in 2012 and 2013, but in the second year the performance gap between the two rivals further diverged: Audi obtained the constructor championship by winning 6 races over 8, while Toyota won only the remaining 2. Accordingly, we suggest:

> ***Proposition 1.*** *Permissive regulations increase technological uncertainty in the form of causal ambiguity between technological solutions and performance outcomes.*
>
> ***Proposition 1a.*** *Technological uncertainty reduces firms' tendency to shift their technological trajectory.*

Field evidence helped us interpret the reasons behind the teams' performance in these first two years. At the environmental level, permissive regulatory changes initially provided the conditions to explore diverse technological options. Field quotes strongly confirm this was the regulators' original intention:

> *"Every element of the regulations is permissive (...) they can do what they want regarding the technological development of their car from the hybrid system to the engine. (...) We wanted from the constructors to present us different technological possibilities." [Vincent Beaumesnil, ACO Technical Director, 2017. Source: Interview].*

Such conditions increased technological differentiation between competitors—in our case while Audi focused on the flywheel, Toyota relied on a supercapacitor, two very different technologies with different functioning and performance returns. The radical nature of the regulatory change is expected to favour firms

[18] Audi also run two "R18 ultra" without hybrid system. Since we focus on the adoption of a new technology (i.e., the hybrid system), we have not considered in the analysis competitors and vehicles displaying only the traditional engine.

with longer and broad technological experience (Eggers, 2012a; Eggers, 2012b)—as prior learning should in general support firm adaptation in changing environments (Cohen and Levinthal, 1994; Levinthal and March, 1981). In these regards, both Toyota and Audi could leverage an extensive and successful technological background—thus allowing us to claim high levels of prior general knowledge for both organizations (developed in standard automotive and other racing series). Yet, it is noticeable that the two contenders were different in terms of general vs. specialised knowledge across their core and peripheral subsystems. Toyota could enjoy general knowledge both at the core and peripheral subsystem level, while Audi was mainly focused only on peripheral subsystems (see Table 3). However, Audi strong experience in LMP1 offered higher levels of specialised knowledge, particularly for the core components.

> *"I agree to say the experience is very important in endurance. In 2012, Audi had more than a decade of experience and developed the diesel technology in 2014" [Vincent Beaumesnil, ACO Technical Director, 2017. Source: Interview].*

The Audi specialised knowledge and extensive experience in LMP1 shed light on superior technological trajectories among the broad gamut that the permissive regulations allowed. Specifically, Audi soon realized the importance of coupling their new hybrid powertrain within an equally innovative TDI engine. The applied advantage (derived from Audi's specialised knowledge) offset the Toyota's broader general knowledge (mainly based on general automotive knowledge, particularly in hybrid systems—e.g., Toyota Prius and many other standard models) in identifying solution in a time where rule changes were providing loose indications on superior technological trajectories. Research carefully warns that, despite useful, general knowledge does not always grant an effective and high-performing application (Zahra and George, 2002).

The broader availability of technological options raised the complexity of effectively integrating core and peripheral subsystems in functioning product architectures. Simply put, when upgrading a tightly-coupled component in an architecture, the increasing availability of potentially suitable options escalates the number of possible combinations, thus exacerbating the risks of 'misfit' (Brusoni et al., 2007). Further, the fast-paced nature of hypercompetitive settings (Hoisl et al., 2017) reduces time and opportunities for firms to trial the various options. In such conditions, organizations face time-based cognitive limitations (Marino et al., 2015) which in turn affect the ability to achieve a high-performing integration across subsystems and/or components. Yet, firms with a relevant base of specialised knowledge can sequentially develop a technological core first, around which upgrading the peripheral sub-systems in a later phase. This is in line with pleiotropy principles (Murmann and Frenken, 2006), where the nested nature of complex systems traditionally allows to leverage more complex knowledge at the core first, to upgrade less complex knowledge at the periphery (Baldwin and Clark, 2000; Soda and Furlotti, 2017). This in turn allows to foster products whose overall design presents radical innovation, while reducing reliability threats that typically affect major design overhauls (Marino et al., 2015).

In our case, Audi had undertaken innovations for the core subsystems (i.e., car chassis, engine, aerodynamics, etc.) during prior years (particularly in 2006 and 2011), while radical changes for the peripheral subsystems were restricted only to 2012 (which we identified as specialised knowledge at the core). When we asked to explain the difference of performance between the Audi R18 e-tron and the Toyota TS030, an Audi team member firstly mentioned the "*aerodynamic efficiency that we gained from our experience of 13 years in endurance racing"* [Audi team member, 2016; Source: Interview]. By experimenting core upgrades in prior years, Audi could better orchestrate the progressive adoption of radical changes at the periphery, and ultimately combining a sufficiently innovative package. Foregoing the simultaneous development of radical changes both at the core and peripheral subsystems reduced the technological complexity—which could have likely resulted in reliability issues and underperformance. Quotes supported this interpretation:

> *"Whereas Toyota started almost from scratch, Audi worked on its diesel technology since 2006. They had a real advantage from this experience (...) By using the 2011 car's aerodynamic body, Audi had enough time to develop and work on the reliably of the flywheel system." [Laurent Mercier, Endurance Racing journalist and expert, 2016; Source: Interview].*

Toyota's alternative strategy resulted in a suboptimal outcome. Despite its extensive general knowledge in several related settings, Toyota's entry strategy exclusively focused on radically innovating the peripheral subsystems on by nesting them on an out-dated core technology did not suffice to offer a competitive advantage against Audi. The car's overall architecture was traditional in nature, merely incremental from industry technological baseline, and thus not suitable to proficiently host the new hybrid subsystem nor to unleash its energy potential. Ultimately, the car emerged as unreliable due to misfit issues between core and peripheral parts—thus hinting at a suboptimal integration. Accordingly, we suggest:

> ***Proposition 2****. Under conditions of permissive regulations, sequentially innovating core and peripheral subsystems will lead to superior performance.*

4.2.1 2014-15: Restrictive regulations for shifting competitive dynamics

Described as “a revolution” by the ACO’s sport director (Miller, 2014), the regulations introduced in 2014 had a restricting, fundamental objective: limiting fuel consumption so that no competitor could gain a performance advantage by consuming more fuel than the others (Carter, 2015). The FIA-ACO highlighted in multiple occasions their clear intent to keep the regulatory process transparent, inclusive, while avoiding any systematic favour to any team. As a matter of fact, this was necessary to demonstrate fairness in the competition and attract new car manufacturers to LMP1. Thus, the radical regulation restrictions tightly capped fuel consumption and pushed teams into fully exploiting their ERS (Mercier, 2014b). The regulator established four different hybrid power categories, each of which was capped at a specific number of Mega-Joules (i.e., 2MJ; 4MJ; 6MJ; 8MJ), (art.5.2.3, 2014 of technical regulations). All LMP1 hybrid cars had to install a fuel flow meter to be checked during the race (art. 5.1, 2014 of technical regulations), and fuel ratio was based on the hybrid power category, so that the more energy the ERS released, the less fuel the car was allowed to consume—thus creating a constraining trade-off. Competitors could deploy up to two motor generator units (MGUs) per car (art. 5.2.1, 2014 of technical regulations). By making boundaries more specific, however, the new restrictive rules helped the best technological trajectories emerge.

> *“Due to the amount of fuel we allow them to use, the naturally aspired engine was not the optimal solution.” [Vincent Beaumesnil, ACO Technical Director, 2017. Source: Interview].*

Like in prior seasons, Audi and Toyota presented diverging technologies for their ERS, but Porsche, the new entrant, introduced the most radically innovative solution. Following the 2012-13 regulatory pattern, after a year of radical rule change (2014) a more incremental one followed, and in 2015 only few minor restrictions were introduced in the regulations, which mostly related to the aerodynamics in the car rear sections (art. 3.4, 2015 of technical regulations).

4.2.2 Firm responses to radical, restrictive regulatory changes (2014)

After 16 years away from the LMP category, in 2014 Porsche returned to endurance racing with the new 919 Hybrid model. This was acclaimed as one of the most radical racing cars ever built (Stoklosa, 2014), which pioneered ground-breaking solutions both in terms of core and peripheral subsystems. The car was powered by a unique turbocharged 2-litre V4 engine—a very unusual engine architecture that had almost never been applied in any major car racing series before.[19] Unlike Audi (with the flywheel) and Toyota (with the supercapacitor), Porsche chose a system of lithium-ion batteries as ERS storage device, which was connected to two different MGUs (Source: Porsche.com, 2014).[20] The first MGU was placed on the front axle and was similar to the MGU used by Audi and Toyota (Collins, 2014). The second one, representing a radical innovation as a peripheral subsystem, collected waste heat in the exhaust pipes and transformed it into electrical energy for additional boosts throughout the entire race—this differed from competitors that could collect waste energy only during braking [21] (Choy, 2014). This solution took in part inspiration from Formula 1 ERS, but was uniquely engineered for LPM1 (Fagnan, 2016). For many expert observers, Porsche's extreme car had potential for superior performance (Collins, 2015), but represented a hazard for reliability, especially considering the major 'mechanical stress' on components in endurance racing.

> *"The car as a whole was a redefinition of an endurance car with an extremely innovative architecture, the V4 architecture and the two different MGUs connected to lithium-ion batteries were two complementary innovations. (…) The V4 architecture was a really ambitious and risky choice with a lot of concerns regarding the reliability for long races such as those in endurance" [Alexandre Stricher, Endurance Racing Professional, 2016; Source: Interview].*

Toyota and Audi had formerly disregarded battery systems, as they wanted to avoid the weight increase it brought compared to the flywheel and the supercapacitor. Yet, in 2014 it became evident that the battery itself had potential for superior powertrain. Coming from two consecutive seasons of domination, in 2014 Audi chose to continue with its prior technological trajectory and only made incremental changes to the core and peripheral subsystems. Talking about Audi's 2014 model, expert affirmed:

> *"The basic elements of the Audi R18 e-tron Quattro's new configuration were defined back in 2012 and the design of all the single components started at the end of 2012." [WEC Journalist's quotes (Joest Racing, 2014)].*

[19] Such solutions was systematically foregone in car design due to an unbalanced overall structure that often generates strong vibrations (Choy, 2014)—the V4 design is in fact common rather for motorbikes, rather than cars (Bennetts, 2015). One exception is the classic Lancia Fulvia that won the world rally championship in 1972 with this engine's architecture (Wan, 2010).

[20] The batteries used by Porsche are lithium-ion, made by A123 Systems. This technology offers a higher energy density and was used for the first time on a production vehicle 2010 by Mercedes-Benz with its S400 Hybrid model, where however the energy stored and released was significantly more modest than for Porsche 919. Other hybrid car manufacturers usually use nickel-metal hybrid batteries (e.g., Toyota Prius): an older and less advanced technology that cannot be compared to lithium-ion batteries used in the Porsche 919 Hybrid (Miller, 2015)

[21] This system is different from the one used in F1 called MGU-H (Source: Formula1.com, 2016). Indeed, the Porsche system used two turbines linked to a turbo-charger layout and to an electric generator, while F1's layout is linked to a turbo acting as ERS and as anti-lag (Collins, 2015).

The 2014 Audi R18 e-tron used the same single ERS system and the same flywheel system of the 2012 model. Audi was classified as a lower energy category (i.e., 4MJ) compared to Porsche and Toyota (i.e., both in the 6MJ category) and therefore could use more fuel—thus creating incentives for a bigger engine, whose capacity was increased up to 4.0 litres. Even though still turbo diesel-powered (V6 TDI), the engine underwent a redesign that made it lighter than in 2012 (Mercier, 2014a). Finally, the 2014 Audi R18 also featured a chassis made of composite materials to reduce the weight—the overall design was however in line with the former one.[22]

Using a different strategy than its competitors, Toyota developed for 2014 a new TS040 Hybrid vehicle presenting a radical evolution to the previous TS030 (Collins, 2014).

> *"As a team, we learnt a lot in our first two seasons in WEC and all this know-how has gone into our new TS040 Hybrid, which is the most technologically-advanced Toyota ever to compete on the track." [Yoshiaki Kinoshita, Toyota team president in Lavrinc (2014)].*

The Japanese constructor underwent several radical changes, thus finally matching an innovative peripheral subsystem to what had been so far a quite out-dated core subsystem within a traditional vehicle architecture. Indeed, if the naturally-aspirated V8 was still supported by a kinetic ERS, the brand-new engine with increased capacity (from 3.4 to 3.7 litres) displayed an improved combustion system and was coupled to an additional MGU transforming the car to a four-wheel drive with 998 hp (Prince, 2014). The TS040 was the first car in endurance racing whose ERS could recover energy from the four wheels (Hanlon, 2014) and it now massively benefitted from Toyota's prior experience in LMP1. The development of this double ERS system was coupled with a redesign of each MGU to obtain overall more power (Collins, 2014). The chassis as well underwent a radical redesign with unique aerodynamic solutions (Collins, 2014). The main objective of this effort was clearly explained by Toyota's executives:

> *"New regulations always create a challenge and the obvious challenges for 2014 have been to change so many things at the same time, with significant regulation changes in terms of chassis and powertrain. The main challenge has been to create a more complex car with more hybrid hardware to achieve higher hybrid power and at the same time reduce significantly the weight due to a 45kg reduction in minimum weight." [Pascal Vasselon, Toyota Racing Group Technical Director in Collins (2014)].*

[22] Interestingly, Audi's original plan also included an additional ERS (as for Porsche) aimed at recovering waste heat from exhaust pipes but the idea was ultimately abandoned few weeks before the season started and never featured in 2014 (Joest Racing, 2014).

4.2.3 Firm responses to incremental, restrictive regulatory changes (2015)

In 2015 all three competing teams deployed and improved version of their 2014 car models, thus fundamentally pursuing the same technological trajectory they had started the year before.[23] Porsche presented an evolution of its 919 Hybrid model that was aimed at tuning the peripheral subsystem in its hybrid components to reach the top energy category (8MJ).

> *"The team's 2015 World Endurance Championship challenger is a ground-up design based on the same concept as the original 919." (Watkins, 2015)*

At the architectural level Porsche developed a similar chassis designed as a single unit rather than in two parts as in 2014, which increased rigidity while reducing weight. Also, it developed three aerodynamic packages to better adapt to the different tracks, which included a new nose and splitter (Collins, 2017). Finally it advanced a new twin exhaust system aimed at making the engine lighter (Tutu, 2015). Those changes can be defined as incremental since they are only progressive evolutions of previous technologies, which, however, did not change the basic design and engineering principles.

Toyota presented a very similar car to its 2014 winning model (Noah, 2015).

> *"The regulations have been essentially stable so there was no reason to review completely our concept, considering our performance throughout 2014. So, the updated car is no revolution but it's an evolution almost everywhere." [Pascal Vasselon, Toyota Racing Group Technical Director, in Noah (2015)].*

At the core subsystems, Toyota tweaked the 2014 chassis design and fostered an improved aerodynamic package (Collins, 2015). Also, the suspensions (peripheral subsystems) were redesigned to reduce tire wear (Noah, 2015).

Finally, Audi changed its car to offset the disappointing performance drop in 2014. Engineers incrementally worked on the peripheral subsystems by increasing the storage capacity of the flywheel, thus allowing Audi to be classified in the 4MJ power category (Audi, 2015) while reaching a 40% energy increase to the electric motor (Florea, 2015). The 4.0 litre engine was also upgraded to release more energy (Florea, 2015) while the aerodynamic package presented new front wings and sidepods.

[23] in 2015 Nissan entered LMP1 hybrid with a new model. However, it competed for only one race, and thus we did not include it in our analyses.

4.2.4 Effects on performance 2014-15 and propositions

The 2014 LMP1 season presented significantly different results compared to previous years. After solving its reliability issue and maturing an overall innovative car both in terms of core and peripheral subsystems, Toyota obtained the manufacturer championship by winning 5 times with at least one car on the podium at each race (see Table A4 in the Appendix). On the contrary, former champion Audi dropped to second place. Once again, Audi's challenger proved to be a solid, reliable car—which was confirmed by Audi's victory at the 24h of Le Mans in 2015. Yet, it also soon appeared increasingly clearer that Audi and Toyota had tapped their technologies' performance potential, and without major innovation breakthrough they would have been hopelessly outclassed.

> *"I think the TDI technology was at its maximum of capacity, they could not extract more performance from it. Same situation for the hybrid system, we all know that a flywheel cannot generate enough energy to be successful under the 2014 regulations. They needed to change but for that you need to invest a huge amount of money and to think outside the box. (...) You cannot offer a high level of competitiveness when your car is in the lowest energy category." [Laurent Mercier, Endurance Racing journalist and expert; Source: Interview 2016].*

Instead, in its first year in LMP1 Porsche paid a high price for its bold approach to radical innovation and faced severe reliability issues during the first part of the season (Lamarche, 2014). Porsche finished last, but it obtained a victory in the final race of 2014. Such progression hinted at the Porsche's potential, which matured in 2015 when it leapfrogged all the competitors throughout the entire racing season, and left only 2 victories to Audi—which, however, failed to win the 24h of Le Mans for the first time in 6 years (see the Appendix for detailed race results).

In 2014 and 2015 regulatory restrictions clarified the performance ceilings of each competing technology. For example, the flywheel system—which was originally considered offering the highest potential—under tighter restrictions emerged as worryingly underperforming. Clearer regulatory guidelines reduced causal ambiguity between available technologies and performance outcomes, and overall firms faced less technological uncertainty. New rule specifications also capped the performance of the flywheel and the supercapacitor, thus creating strong incentives for firms to move towards other technological options such as the lithium-ion batteries—which had previously dismissed. For example, Audi realized that its former choice of running a diesel engine with a double ERS clashed with weight limitations, and thus decided to move to the battery system (in 2016). Evidence from our expert informants corroborates this interpretation.

> *"In 2013, we tested a car equipped with a double ERS system to use the room given by the 2014 regulation. Unfortunately, this double ERS system was not deployable with the weight limit established by the regulation for the diesel engines (...) it was too late for us to try another storage system." [Engineer at Audi Sport; Source: Interview 2016].*

It is reasonable to notice how, already in 2013, the flywheel and supercapacitor were giving signals of their limited performance potential. Yet, in line with former literature (Suarez and Lanzolla, 2005, 2007), we notice that the abrupt and restrictive regulatory shift in 2015 further exacerbated the already rapid S-curve of older technologies' life-cycle—given the hypercompetitive nature or LMP1—thus increasing the firms' incentives towards other technological trajectories. Given the above, we claim:

> ***Corollary to Proposition 1.*** *Restrictive regulations reduce technological uncertainty in the form of causal ambiguity between technological solutions and performance outcomes.*

> ***Corollary to Proposition 1a.*** *Reduced technological uncertainty increases firms' tendency to shift their technological trajectory.*

Similarly to other similar settings, regulations (despite restrictive) did not harness firm efforts for innovation (Jenkins, 2014a); on the contrary, the racing teams explored different innovation strategies by adapting to both permissive and restrictive rule changes. Despite not straitjacketed, evidence suggest that restrictive rules clustered the competitors' innovations across a limited and more adjacent set of technological trajectories.

> *"After 3 or 4 years of competition I am not surprised to see competitors converging to the same technological solution. By pushing their engineers, all competitors fund a glass ceiling to their own technology." [Vincent Beaumesnil, ACO Technical Director, 2017. Source: Interview].*

Accordingly, by diminishing technological heterogeneity, relative performance differences across competitors reduced. Particularly Toyota and Audi's performance gap got significantly smaller (e.g., Audi and Toyota moved from a gap of 74 points in 2012, to 64.5 points in 2013 and a gap of 45 points in 2014). Contenders that tried to further refine older technologies tapped their performance potential and lost ground in the competition:

> *"(...) The original calculations by Toyota's powertrain department suggested that a large-capacity naturally aspirated engine would be the most efficient solution and this was in principle correct. But that was only true within a specific operating window. (...) The biggest issue we faced in 2015 was powertrain performance; our rival (i.e., Porsche) made significant gains in this area but our powertrain was mature, with very little extra performance to find. It became clear very quickly that we needed a new powertrain (...)." [Marketing manager Toyota Motorsport; Source: Interview 2016].*

In fact, while in 2012 and 2013 Audi's long experience in this racing category helped identifying superior technological trajectories, thus quickly obtaining and maintaining an advantage for two seasons in a row, in 2014 Porsche's minor levels of specialised knowledge (both at the periphery and the core subsystems—see Table 5) allowed the newcomer to innovate with a 'blue-sky approach' and free from inertial constraints towards any prior technological investment. Porsche thus decided to challenge incumbents with a radically new car that better interpreted and exploited the (now more certain) technological boundaries defined by the restrictive rules; the German team invested on a successful medium-to-long term strategy, which led to obtaining the championship in 2015 (and later in 2016 and 2017). It is noteworthy that—differently from permissive regulations—when restrictive regulatory changes are enforced, new constraints seem to pose more challenges to incumbents with longer technological experience and established specialised knowledge, than to newcomers. In fact, the former might have found themselves investing in technological trajectories that the new regulatory restrictions later harnessed. Retrospectively, ACO's technical director in fact affirmed:

> *"I would rather say they [i.e., the new entrants] are less disadvantaged than their competitors already present in the championship. This is why there is an interest for a new entrant to come in the championship the year of a radical change in the regulation than at another time." [Vincent Beaumesnil, ACO Technical Director, 2017. Source: Interview].*

In general terms, while prior knowledge and capabilities might represent an asset to further pursue technological innovation in relatively deregulated environments, in restrictive environments they become a core rigidity that can backfire in case the former solutions—and their related knowledge and routines—do not fit the incoming restrictions (Leonard-Barton, 1992). The fact that Audi and Toyota did not change their technological trajectory—despite enjoying major budgets and openly acknowledging that their technological solutions had tapped a performance ceiling—further corroborates this intuition.

Another interesting insight emerges from observing the firms' innovation strategies across core and peripheral subsystems. Ditto, restrictive regulations clearly identified superior technological trajectories both at the core and peripheral subsystems. In such conditions, innovating core and peripheral subsystems in two sequential phases did not emerge as the most effective long-term strategy. Table 5 shows that Toyota and Audi opted for a two-phased innovation strategy, while Porsche decided to simultaneously upgrade core and peripheral subsystems—both Porsche's subsystems underwent radical innovations in 2014 and incremental in 2015. Such strategy allowed Porsche to early identify complementarities across component technologies (Lee et al., 2010), thus pursuing a well-integrated development across the entire product architecture.

Experts' quotes hints at Porsche ability to early on combine complementary technologies and jointly develop them.

"(Porsche's) V4 architecture and the two different MGUs connected to lithium-ion batteries were two complementary innovations. If you choose batteries as storage, you need a smaller engine due to the weight restrictions imposed by the technical regulations and the space taken by the batteries. Their MGU-H was composed by two turbines incorporated in the exhaust system and was designed for a V4 mono turbo engine. Their choice regarding the powertrain forced them to find a solution for their heating recovery system." [Alexandre Stricher, 2016—endurance racing media expert; Source: Interview 2016].

In multiple occasions, the experts underlined how Porsche's strategy ideally fit the rule restrictions:

"Porsche was smart enough to use a grey zone in the regulation with their ERS-H. They got energy 'for free' as the system didn't deteriorate the specific consumption. The only way to match their pace was to jump to higher ERS classes" [Engineer at Audi Sport, 2016; Source: Interview].

To summarize, it emerges how restrictive regulations reduce the options for subsystem integration, thus making the product architecture more rigid, and subsystems more tightly-coupled. This in turn limits the opportunities for explorations of different combinations between core and peripheral technologies, and favours instead a joint development of both subsystems. Sequential subsystem innovation prolongs technological imbalances due to an uneven rate of technological change, as well as complex integration challenges between core and peripheral parts. A joint development of core and peripheral subsystems, however, implies a major increase in design complexity, which scholars identify as a challenge that traditionally arises when entire product architectures undergo design overhauls—particularly under radical regulatory shifts (Marino et al., 2015). This explains while such trajectory might take longer to provide superior returns. In fact, in season 2014 Porsche's reliability problems left space for Toyota's success. Still, Toyota's dominance soon appeared as short-lived: starting with 2015 (and continuing in 2016 and 2017) Porsche solved the aforementioned reliability issues and dominated LMP1 thanks to a vehicle that was equally innovative and balanced. We thus conjecture:

Corollary to Proposition 2*. Under conditions of restrictive regulations, simultaneously innovating core and peripheral subsystems will lead to superior performance in the long term.*

The diagrams in Figure 1 depict the models underlying the propositions and their corollaries.

[Insert Figure 1 about here]

5. DISCUSSION AND CONCLUSION

The impact of regulation on markets and competition is not only a central topic in financial markets, economics, political economy and management (see for example Rochet and Tirole, 2005), but it also fuels timely and compelling debates across multiple settings of international policy—from gas emission control (European Commission, 2016) to international trading regulation (Timiraos et al., 2016). Regulations create incentives for innovation and disrupt markets by sometimes inhibiting, sometimes promoting new technologies and business models (Blind, 2012; Blind et al., 2017). For centuries, nations and industries have relied on regulations to steer the direction of economic development and competition (Buysse and Verbeke, 2003; Mahon and Murray, 1981; Porter, 1980; Reger et al., 1992). Yet, scholars lament that the literature on this timely topic is still scarce (Blind, 2012, p. 395) controversial (Blind et al., 2017, p. 249) and more often than not concentrated on explaining the impact of regulation on firm innovation productivity (Jaffe and Palmer, 1997). Yet, and perhaps more importantly, we know very little about which type of firm innovation responses better fit different regulatory shifts, particularly when variations in restrictive vs. permissive regulatory frameworks occur. In response to calls for studies on this pivotal and yet understudied topic (Blind, 2012) our work examines the association between firms' innovation and performance under regulatory changes of different direction—i.e., permissive vs. restrictive—(Bourgeois and Eisenhardt, 1988; McCarthy et al., 2010). To further enrich our understanding, we dedicated specific attention to patterns of innovation across different product subsystems (i.e., core vs. peripheral components as per Henderson and Clark, 1990) and carefully considered prior experience in technological development—in the form of general and specialised knowledge (Grant, 1996). Such analytical framework offers not only implications firm performance (Marino et al., 2015), but thanks to a longitudinal research design it also sheds light on innovation macro-processes across different technological trajectories (Dierickx and Cool, 1989; Dosi, 1982; Jenkins and Floyd, 2001).

Our study—we believe—contributes to a compelling research inquiry and offers insights that are at the same time new and unexpected vis-à-vis what current literature suggests. Given the major gap in the literature, we discuss the novelty of our contribution by mostly focusing on the few works that directly address our specific question (e.g., Marino et al., 2015; Reger et al., 1992; Smith and Grimm, 1987).

Our evidence confirms that both regulations whose aims are permissive or restrictive trigger innovation responses at the firm level (Jenkins, 2014a; Marino et al., 2015; Smith and Grimm, 1987). Yet, by promoting technological heterogeneity, permissive regulations tend to shadow the performance ceiling of different options, increase causal ambiguity between different solutions and performance, and foster overall technological uncertainty (*proposition 1*), thus in turn reducing firm tendency to switch towards other technological trajectories (*proposition 1a*). Such findings point to unexpected outcomes, given bourgeoning evidence that policy makers and organizations often associate deregulation to an antecedent of technological heterogeneity at the firm level.

Further reflections are also worth being considered in relation to optimal firm responses. Former studies highlighted how radical regulatory changes favour firm incremental innovation, and vice-versa incremental regulatory changes favour firm's radical innovation (Marino et al., 2015). We confirm that looking at the mere magnitude of firm innovation at a specific point in time might not be sufficient to reveal the entire set of intervening mechanisms and patterns, unless the analysis carefully includes pivotal aspects such as the direction of change (i.e., permissive vs. restrictive as per Reger et al., 1992) the firm's prior knowledge (Grant, 1996) across both core and peripheral subsystems of the complex product architecture (Murmann and Frenken, 2006). We notice that in hypercompetitive technological settings, firm's radical innovations might in general provide superior returns—sometimes in the short, sometimes in the long run. This is the exact opposite to what Marino et al. (2015) predict in a very similar competitive setting (i.e., F1), but it is important to notice that this study only focused on short-term results and their setting only allowed to observe the magnitude of regulatory change. We thus remark that conditions of permissive vs. restrictive regulations—when present—might determine significantly different outcomes.

Our study also provides nuanced evidence on the mechanisms taking place at the subsystem level and across the overall system architecture (Brusoni et al., 2001; Henderson and Clark, 1990), which also revolve around executives' cognitive limitations (Gavetti and Rivkin, 2007; Marino et al., 2015; Tripsas and Gavetti, 2000) in the form of causal ambiguity (Powell et al., 2006; Reed and DeFillippi, 1990) and technological uncertainty (Fleming, 2001). Permissive rules increase the span of possible technological options, thus making product architectures more flexible. This means that—following a nested hierarchy of subsystems—for a given core component, firms can choose across a broader array of different peripheral integrations. Hence, firms can better face complex design optimization by adopting a sequential (i.e., multi-phased) approach to innovation, by upgrading the core subsystems first, and in a later phase by identifying and integrating the most suitable peripheral subsystem (*proposition 2*). This resonates with the literature on system complexity (Simon, 1962), and the principle of pleiotropy (Murmann and Frenken, 2006), which highlights how a nested hierarchy of subsystems allows an upgrade of the periphery thanks to the superior knowledge acquired in core technology development (Soda and Furlotti, 2014).

Under conditions of radical rule restrictions, former research predicts that incremental firm's innovation responses would reduce the architectural (re)design challenges, and thus lead to superior performance (Marino et al., 2015). We also find that in such years, incremental decision offer superior returns, but we add that the advantages emerge as short-lived. In fact, radical responses that fully embrace the new restrictive regulatory framework seem to provide opportunities for sustained competitive advantage in the long-run.[24] By severely reducing the portfolio of options across alternative technologies, restrictive regulatory shifts decrease opportunities for complementary subsystem integration (simply put, for each core technology an inferior number or peripheral subsystems can be successfully fit in the product architecture). This in turn sheds lights onto the few specific solutions that hold potential for superior performance. In such conditions, uncertainty and causal ambiguity decrease, as the performance ceilings of different solutions emerge more distinctively (*corollary to proposition 1*), therefore increasing the firms' incentive to move towards more promising technological trajectories (*corollary to proposition 1a)*. This promotes technological heterogeneity and different performance across the competitors. More stringent regulations limit the potential for components integration, and thus constrain the overall product design, and the available portfolio of possible solution. In such case, firms enjoy superior returns when they early on explore possible complementarities among the few viable subsystems—that means, simultaneously innovating both core and peripheral subsystems. In line with former predictions under restrictive regulations (Marino et al., 2015), our results point to inferior returns in the short term—mostly due to rising complexity and reliability issues, which are common to major architectural overhauls. However, once the firm resolves such technical holdups, their joint development across core and peripheral subsystems leads to superior performance in the long term (*corollary to proposition 2*).

[24] See the case of Mercedes anticipating engine research to dominate the hybrid era in Formula 1 (Moldrich, 2016).

We believe our findings offer a valuable contribution to management literature, particularly at the intersection of technological innovation, regulations and environmental changes. We respond to recent calls for more precise appreciation of the diverse nature of environmental dynamism (McCarthy et al., 2010, p. 622), and—by singling out the interplay between regulation and firm innovation—we start exploring "the nature and the scope of the control provided by new regulations" (McCarthy et al., 2010, p. 609). If previous studies have already investigated the mechanisms making a firm successful when the environment changes in a radical or incremental way (e.g., Marino et al., 2015), the direction taken by the environmental change (i.e., permissive vs. restrictive) had not previously been considered (for an exception see Smith and Grimm, 1987). Further, we engage with a major stream of technology-related literature (Brusoni and Prencipe, 2001; Brusoni et al., 2001; Cabigiosu and Camuffo, 2012; Henderson and Clark, 1990; Jacobides et al., 2016) and provide a dynamic explanation of how choices in different product subsystems (i.e., core vs. peripheral components) are affected by different environmental shifts (Benner and Tushman, 2002). We aim at specifically responding to recent calls lamenting that scholars "have only recently begun to consider the distinction of core and peripheral technologies" (Murmann and Frenken 2006; p. 933). Our longitudinal research design follows and complements prior studies on technological trajectories (Dosi, 1982), not only by embracing a multi-level approach that includes (regulatory) institutions, firms and technologies (Jenkins and Floyd, 2001), but also by exploring the role of prior knowledge assets (Dierickx and Cool, 1989) in the form of general and specialised knowledge (Balconi, 2002; Grant, 1996). Our evidence counter-intuitively suggests that even in knowledge-intensive settings, prior knowledge investments might lead to different returns vis-à-vis the contingent regulatory framework. While in hypercompetition general knowledge only partially offers a systematic advantage to firms, specialised knowledge holds relevant value in directing innovation decisions during regulatory shifts. Yet, such knowledge assets become a liability once regulations tighten, and related capabilities and routines become a rigidity and a source of inertia (Leonard-Barton, 1992). This suggests valuable insights on boundary conditions that might explain mixed results and inverted-U shape effects between prior technological experience and performance (Gupta et al., 2006; Zhou and Wu, 2010), as well as interesting perspectives to explore the role of new entrants and incumbent's short-lived competitive advantages (D'Aveni et al., 2010). Further, we underline how different approaches to innovation—i.e., sequential vs. simultaneous—might better fit not only different environmental dynamics and product life-cycles (Suarez and Lanzolla, 2007), but also different regulatory contingencies—i.e., permissive vs. restrictive rules—, thus holding promises for sustainable competitive advantage for firms that better interpret critical environmental changes (Brown and Eisenhardt, 1997; D'Aveni et al., 2010).

Our work also aims to offer a valuable and applicable contribution to practice. Executives are often confronted with the challenging task of adapting their innovation to transient environments (Christensen, 1997)—in these regards, regulatory shifts are a very common and thorny contingency to face. In our work a practical contribution stands out: we suggests a framework to better interpret regulatory changes, forecast competitive dynamics, and ultimately optimize innovation efforts—while considering the advantages that incumbents or new entrants might enjoy in permissive or restrictive contingences, respectively (Suarez and Lanzolla, 2005). It is plausible to notice how companies and business leaders tend to prefer deregulated markets and competitive settings, where they can more freely pursue innovation (Timiraos, 2017). Yet, we warn executives not to underestimate the complexity arising from such contingencies. The lack of precise guidelines increases causal ambiguity and uncertainty about superior technological solutions. This might lead to severe cognitive challenges and ultimately result into suboptimal decisions—despite firms' extensive knowledge-base to address such tasks. Similar dynamics might explain the recent failure of major automotive manufacturers in trying to redeploy their extensive expertise in the road-car segment (or even a prior racing experience) into cutting-edge settings that leave competitors relatively free to innovate—see Toyota, Jaguar, BMW and more recent Honda's fiascos in Formula 1. This might also inform similar failures in emerging (and thus deregulated) contexts, such as Virgin trying to develop a commercial spaceflights (i.e., Virgin Galactic) by leveraging its technological and business expertise in commercial airways (Novak, 2014). This is—to a certain degree—consistent with Smith and Grimm (1987), which praise the adoption of more focused (and thus applied) approaches during deregulation. Yet, within the realm of such technology-based competition, our study further specifies the boundary conditions and innovation patterns leading to diverging performance outcomes.[25]

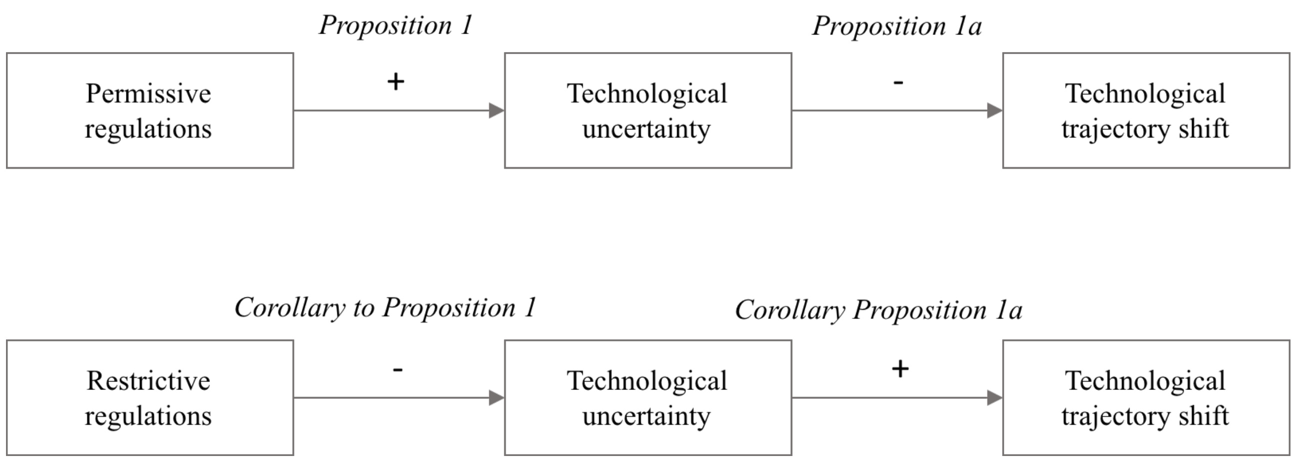
We purposefully chose to conduct our study in a setting whose simplified features support in-depth qualitative cross-case comparisons in a longitudinal fashion—a research design that has been deemed as ideal for regulation-specific studies (Blind, 2012, p. 395). Despite ours is the first work on the iconic Le Mans racing, former works have already leveraged regulatory changes in other motorsports to offer

[25] Smith and Grimm (1987) instead observe the impact of firm broader strategies (such as marketing and sales) in a condition of deregulation the railroad industry.

generalizable insights that naturally apply to other heavily regulated industries (Marino et al., 2015). Clearly, the nature of our study also carries several limitations; and yet, if carefully acknowledged, these can shed light on promising avenues for new research. First, our qualitative approach does not allow to rigorously test causality, but only to observe mere association patterns. This excludes the possibility to control for other intervening factors that could play a role in explaining performance returns (in particular individual-level effects). Among those—and despite evidence suggest that regulators did not systematically favour any competitor in LMP1—we cannot fully rule out the possible intervention of firms' secret lobbying (Gurses and Ozcan, 2015; Ozcan and Gurses, 2017), regulatory capture, and possible information asymmetry (a common and to a certain extent unavoidable aspect, as suggested by Blind et al., 2017; and Stigler, 1971). Second, scholars warn that fierce innovations races, dynamic and competitive reshuffling among rivals, and other peculiar hypercompetitive features of motorsport settings (Hoisl et al., 2017) might not well resemble those of more traditional industries, where environmental shifts are rare, firms' competitive advantages are long-lived, and learning curves for process innovations, economies of scale, and efficiency-based objectives play a major role for firm outcomes. We thus recommend avoiding uncritical extensions of our insights to more traditional, slow-paced industries. Third, firms in our empirical setting exercise great secrecy on their research and development activities. This means that budgets are seldom revealed, and patenting is incredibly rare. This does not allow to adopt established measures to track important intervening factors in technological exploration, such as the firms' absorptive capacity (Cohen and Levinthal, 1990; Zahra and George, 2002)—which might in part explain some of the performance outcomes. However, our tracking of firms' prior knowledge provides an alternative proxy which might help consider important issues in part related to absorptive capacity. One could wonder whether superior knowledge in a specific technology might lead to better learning abilities for future knowledge absorption—perhaps by collaborating with third parties (Lane and Lubatkin, 1998). Our work does not resolve this key point, but offers a guidelines for future studies where traditional measures for tracking absorptive capacity are available. Fourth, our setting keeps the frequency of regulatory change constant as LMP1 rules are released on a yearly basis; also, new releases are communicated to all players in advance—thus making them predictable. Yet, frequency and predictability are fundamental aspects that also deserve further investigation (Reger et al., 1992; Ungson et al., 1985), not only for their individual effects, but also for a broader interplay with the other dimensions or environmental changes. Finally, racing competitions are measured on racing performance, which equals to a measure of product—rather than financial—effectiveness. Despite racing success usually correlates to better financial performance (Mourao, 2017; Sylt and Reid, 2010), we suggest caution when extending interpretations of product performance to other types of organizational outcomes.

All in all, we hope that future endeavours might better tackle the open issues left by our contribution, which nonetheless might provide a valuable starting point to shed light on the complex issues of regulatory shifts in competitive environments.

FIGURE 1
Relation between regulations, firms' technological innovation and performance



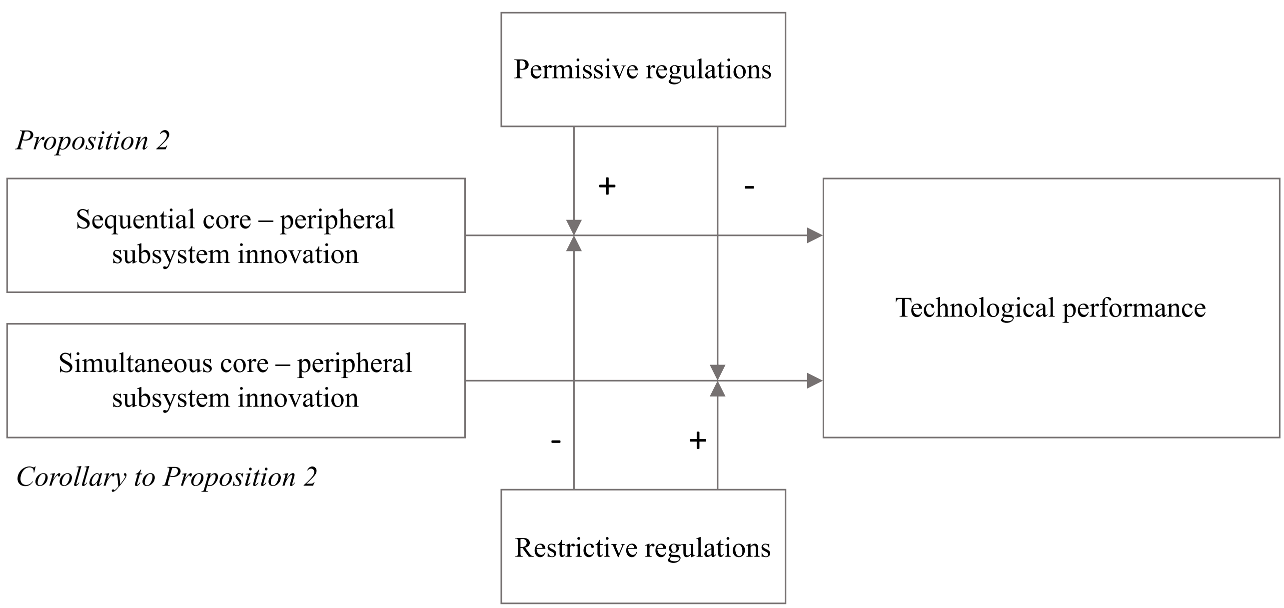


TABLE 1
Review table of the studies exploring the relation between firm innovation and changes in the regulation

			Firm innovation: *Radical*	Firm innovation: *Incremental*
Regulations	**Magnitude of change**	***Radical***	Negative effects*	Positive effects*
		Incremental	Positive effects*	Negative effects*
	Direction of change	***Restrictive***	Negative effects**	
		Permissive	Positive effects**	
	Frequency of change	***High frequency***	Positive if incremental***	
		Low frequency	(Not applicable)	
	Predictability of change	***High predictability***	Positive effects****	
		Low predictability	Negative effects****	

*Marino et al. 2015; *Notes = The focus is on firm innovation. The direction of regulatory change is not considered. Frequency of change is constant (once a year). Predictability of the setting is high.*

**Smith and Grimm, 1987; *Notes = The focus is not on innovation, but on the firm's strategic change. Frequency relates to a single major deregulation event. There is no comparative analysis in cases of restrictive regulations. There is no specification on the magnitude of firm responses (i.e., radical vs. incremental).*

***Reger et al., 1992; *Notes = The focus is on "incrementalism", which stands for the possibility of introducing progressive major regulatory changes. Setting: risk and financial performance in banking. There is no specification on the magnitude of firm responses (i.e., radical vs. incremental).*

****Ungson et al., 1985; *Notes = The focus is on the predictability of change. Firms can absorb the shock of major regulation changes when predictable. Despite the setting is technology-based, there is no reference to the innovation options that might maximize firm performance. Direction and frequency of change are not considered.*

TABLE 2
Data sources

Types of source	Sources	Nr. of docs	Pages
Books	24 heures du Mans 80 éditions de légende (Palmet, 2012)	1	4
	24 heures du Mans 90 ans de passion (Palmet, 2013)	2	3
	Art of Le Mans Race Car: 90 years of speed (Codlin, 2013)	1	8
Technical Press	Racecar Engineering	12	36
	L'Automobile Magazine (France)	3	6
	Motor Sport Magazine	1	6
	Road and Track Magazine	3	6
	EVO Magazine	4	10
General Press	L'Equipe (France)	1	3
	Ouest France (France)	2	4
	Le Maine Libre (France)	3	6
Websites	Endurance-info.com	8	21
	Toyota-global.com	10	16
	Porsche.com	6	11
	Joest-racing.de	3	9
	Caranddriver.com	2	5
	Fiawec.com	8	20
	Lemans.org	4	10
	Williamsf1.com	1	2
	Leblogauto.com	1	4
	Imotortimes.com	1	1
	Greencarcongress.com	2	2
	Driving.co.uk	3	5
	Others	12	23
Videos	Toyota UK Youtube channel	3	n.a.
	Audi Youtube channel	2	n.a.
	Porsche Youtube channel	3	n.a.
	Jpetrolhad Youtube channel	2	n.a.
	Nuvolari Channel	5	n.a.
	Technological vehicles Youtube channel	1	n.a.
		110	221

TABLE 3
Direct interviews with experts

Name	Job/role	Expert's profile	Hours
Vincent Beaumesnil	*ACO's Technical Director*	Director of the Governing body in charge of the WEC regulations	2
Laurent Mercier	*Endurance media expert*	Editor in chief of the leading French language website for endurance racing	1
Bernard Beaumesnil	*Endurance expert*	Former engineer, external consultant on technical regulations for the ACO	2
Alexandre Stricher	*Endurance media expert*	Former in charge of the communication for Alpine LMP2, blogger	2
Alastair Moffitt	*Endurance professional*	Marketing manager Toyota Motorsport GmbH	2
Daniel Perdrix	*Endurance professional*	Former technical director of the Automobile Club de l'Ouest (ACO)	1
Anonymous	*Endurance professional*	Currently working as engineer at Audi Sport	2
			12

TABLE 4
Qualitative codification of change at the environment level (i.e., regulations)

Season	Coding	Empirical evidences
2012	**Radical and permissive regulations**	**New to the field, permissive rules:** - Freedom of choice concerning the Energy Recovering System (ERS) but limited to two wheels only (art. 1.13, 2012 technical regulations). - Different ERS systems proposed explicitly by regulations: flywheel; capacitors; different types of batteries (art. 1.14.1; 1.14.2; 1.14.3, 2012 technical regulations). - Permissive definition of Hybrid: “to be considered as hybrid the car must be able to move along the whole length of the pit lane”, giving rooms for innovation (art. 1.13, 2012 technical regulations). - Modifications through the season authorized under homologation by the ACO (art. 1.2.2, 2012 technical regulations). - If ERS connected to the front wheels, the energy release can happen above 120 km/h (art. 1.13, 2012 technical regulations). - Power released by the ERS only limited at 0.5 MJ between two braking stints. (art. 1.13, 2012 technical regulations). - Overall: hybrid system increases car performances (Laurent Mercier, 2012).
2013	**Incremental and permissive**	**Used in the field, permissive rules:** - Few changes related to the air extractors dimensions and the read diffuser size (art. 3.4.5 and 3.5.2, 2013 technical regulations).
2014	**Radical and restrictive**	**New to the field, restrictive rules:** - Creation of a new category called LMP1-H for manufacturer hybrid cars only (art. 1.1, 2014 technical regulations). - 4 different hybrid power categories are established: 2MJ; 4MJ; 6MJ; 8MJ corresponding to the limit of power released from Motor Generator Unit (MGU) during the equivalent of one lap of Le Mans circuit (art. 5.2.3 and Appendix B, 2014 technical regulations). - The quantity of fuel allowed is inversely proportional to the hybrid system power. A limitation is established concerning the fuel mass flow (art 5.1, 2014 technical regulations). - All competitors must integrate a fuel flow meter into the fuel system to control fuel flow (art. 6.2.1, 2014 technical regulations). - Limit to two ERS systems per car (art. 5.2.1, 2014 technical regulations). - Overall: hybrid system controlled to reduce the fuel consumption (FIA press release, 2013).
2015	**Incremental and restrictive**	**Used in the field, restrictive rules:** - New definition of Motor Generator Unit (MGU) (art. 1.21, 2015 technical regulations). - New rules regulating the rear part of the car bodywork (art. 3.4, 2015 technical regulations).

TABLE 5
Summary of firm and environment level codification

		2012	2013	2014	2015
Environment level	*Magnitude* of regulation change	Radical	Incremental	Radical	Incremental
	Direction of regulation change	Permissive	Permissive	Restrictive	Restrictive
Firm level					
	First Ranked (winner)	**Audi R18 e-tron**	**Audi R18 e-tron**	**Toyota TS040**	**Porsche 919**
	Magnitude of innovation				
	Core subsystem innovation	Incremental	No change	Radical	Incremental
	Peripheral subsystem innovation	Radical	Incremental	Incremental	Incremental
	Prior Knowledge				
	General knowledge	Peripheral	Peripheral	Peripheral and Core	Periph. + Core
	Specialized knowledge	Core	Periph. + Core	Peripheral and Core	Periph. + Core
	Second ranked	**Toyota TS030**	**Toyota TS030**	**Audi R18 e-tron**	**Audi R18 e-tron**
	Magnitude of innovation				
	Core subsystem innovation	Incremental	Incremental	Incremental	No change
	Peripheral subsystem innovation	Radical	Incremental	No change	Incremental
	Prior Knowledge				
	General knowledge	Periph. + Core	Periph. + Core	Peripheral	Peripheral
	Specialized knowledge	Core (minor)	Periph. + Core	Periph. + Core	Periph. + Core
	Third ranked	-	-	**Porsche 919**	**Toyota TS040**
	Magnitude of innovation				
	Core subsystem innovation	-	-	Radical	Incremental
	Peripheral subsystem innovation	-	-	Radical	No change
	Prior Knowledge				
	General knowledge	-	-	Periph. (minor) + Core (minor)	Periph. + Core
	Specialized knowledge	-	-	Periph. (minor) + Core (minor)	Periph. + Core

REFERENCES

Abernathy, W.J., Clark, K.B., 1985. Innovation: Mapping the winds of creative destruction. Research Policy 14, 3-22.

Abernathy, W.J., Utterback, J.M., 1978. Patterns of industrial innovation. Technology review 80, 40-47.

Aggarwal, A., 2000. Deregulation, technology imports and in-house R&D efforts: an analysis of the Indian experience. Research Policy 29, 1081-1093.

Amable, B., Ledezma, I., Robin, S., 2016. Product market regulation, innovation, and productivity. Research Policy 45, 2087-2104.

Andriopoulos, C., Lewis, M.W., 2009. Exploitation-exploration tensions and organizational ambidexterity: Managing paradoxes of innovation. Organization Science 20, 696-717.

Ansari, S.S., Krop, P., 2012. Incumbent performance in the face of a radical innovation: Towards a framework for incumbent challenger dynamics. Research Policy 41, 1357-1374.

Ashford, N.A., Ayers, C., Stone, R.F., 1985. Using regulation to change the market for innovation. Harvard Environmental Law Review 9, 419-466.

Audi, 2015. New 2015 Spec Audi R18 e-tron quattro Even More Efficient. Fortitude.com http://fourtitude.com/news/motorsport_news_6/new-2015-spec-audi-r18-e-tron-quattro-even-more-efficient/.

Aversa, P., Berinato, S., 2017. Sometimes, less innovation is better. Harvard business review May-June, 95, 38-39.

Aversa, P., Cabantous, L., Haefliger, S., 2018. When decision support systems fail: Insights for strategic information systems from Formula 1. The Journal of Strategic Information Systems Forthcoming.

Aversa, P., Furnari, S., Haefliger, S., 2015. Business model configurations and performance: A qualitative comparative analysis in Formula One racing, 2005–2013. Industrial and Corporate Change 24, 655-676.

Balconi, M., 2002. Tacitness, codification of technological knowledge and the organisation of industry. Research Policy 31, 357-379.

Baldwin, C.Y., Clark, K.B., 2000. Design rules: The power of modularity. The MIT Press.

Banbury, C.M., Mitchell, W., 1995. The effect of introducing important incremental innovations on market share and business survival. Strategic Management Journal 16, 161-182.

Benner, M.J., Tushman, M., 2002. Process management and technological innovation: A longitudinal study of the photography and paint industries. Administrative Science Quarterly 47, 676-707.

Benner, M.J., Tushman, M., 2003. Exploitation, Exploration, and Process Management: The Productivity Dilemma Revisited. The Academy of Management Review 28, 238-256.

Bennetts, 2015. The History of Honda's V4 Obsession. Bennetts.co.uk https://www.bennetts.co.uk/bikesocial/news-and-views/features/bikes/honda-v4-history.

Blind, K., 2012. The influence of regulations on innovation: A quantitative assessment for OECD countries. Research Policy 41, 391-400.

Blind, K., Bührlen, B., Menrad, K., Hafner, S., Walz, R., Kotz, C., 2004. New Products and Services: Analysis of Regulations Shaping New Markets: Study Funded by the European Commission, DG Enterprise/Innovation Policy Unit, in the Framework of the Innovation/SMEs Programme, Part of the Fifth Research Framework Programme.

Blind, K., Petersen, S.S., Riillo, C.A., 2017. The impact of standards and regulation on innovation in uncertain markets. Research Policy 46, 249-264.

Blundell, R., Griffith, R., Van Reenen, J., 1999. Market share, market value and innovation in a panel of British manufacturing firms. The review of economic studies 66, 529-554.

Bothner, M.S., Kang, J.-h., Stuart, T.E., 2007. Competitive crowding and risk taking in a tournament: Evidence from NASCAR racing. Administrative Science Quarterly 52, 208-247.

Bothner, M.S., Kim, Y.-K., Smith, E.B., 2012. How does status affect performance? Status as an asset vs. status as a liability in the PGA and NASCAR. Organization Science 23, 416-433.

Bourgeois, L.J., Eisenhardt, K.M., 1988. Strategic decision processes in high velocity environments: Four cases in the microcomputer industry. Management Science 34, 816-835.

Brown, S.L., Eisenhardt, K.M., 1997. The art of continuous change: Linking complexity theory and time-paced evolution in relentlessly shifting organizations. Administrative Science Quarterly, 1-34.

Brusoni, S., Marengo, L., Prencipe, A., Valente, M., 2007. The value and costs of modularity: a problem-solving perspective. European Management Review 4, 121-132.

Brusoni, S., Prencipe, A., 2001. Managing knowledge in loosely coupled networks: exploring the links between product and knowledge dynamics. Journal of Management Studies 38, 1019-1035.

Brusoni, S., Prencipe, A., Pavitt, K., 2001. Knowledge Specialization, Organizational Coupling, and the Boundaries of the Firm: Why Do Firms Know More Than They Make? Administrative Science Quarterly 46, 597-621.

Buysse, K., Verbeke, A., 2003. Proactive environmental strategies: A stakeholder management perspective. Strategic Management Journal 24, 453-470.

Cabigiosu, A., Camuffo, A., 2012. Beyond the "mirroring" hypothesis: Product modularity and interorganizational relations in the air conditioning industry. Organization Science 23, 686-703.

Cabigiosu, A., Zirpoli, F., Camuffo, A., 2012. Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry. Research Policy.

Carter, J., 2015. LMP1 Going with the flow. fiawec.com http://www.fiawec.com/en/news/lmp1-going-with-the-flow_3166.html.

Castellucci, F., Ertug, G., 2010. What's in it for them? Advantages of Higher-Status Partners in Exchange Relationships. Academy of Management Journal 53, 149-166.

Castellucci, F., Podolny, J.M., 2017. The dynamics of position, capability, and market competition. Industrial and Corporate Change 26, 21-39.

Child, J., 1972. Organizational structure, environment and performance: the role of strategic choice. Sociology 6, 1-22.

Choy, D., 2014. Porsche 919 LMP1 Specs: Everything You Need To Know About The Turbo V4 Hybrid Engine. iMotorTimes.com http://www.imotortimes.com/porsche-919-lmp1-specs-everything-you-need-know-about-turbo-v4-hybrid-engine-report-23993.

Christensen, C., 1997. The innovator's dilemma: when new technologies cause great firms to fail. Harvard Business School Press, Boston.

Codling, S., 2012. Live Blog: the 2012 Le Mans 24 Hours. Autosport.com http://www.autosport.com/free/feature/4536/live-blog-the-2012-le-mans-24-hours/.

Codling, S., 2013. The art of Le Mans Racing: 90 years of speed. Motorbooks, London, UK.

Cohen, W.M., Levinthal, D.A., 1990. Absorptive Capacity: A New Perspective on Learning and Innovation. Administrative Science Quarterly 35, 128-152.

Cohen, W.M., Levinthal, D.A., 1994. Fortune Favors the Prepared Firm. Management Science 40, 227-251.

Collins, S., 2013a. Audi R18 e-tron quattro. Racecar Engineering http://www.racecar-engineering.com/cars/audi-r18-ultra-e-tron-quattro/.

Collins, S., 2013b. Toyota TS030 Racecar Engineering http://www.racecar-engineering.com/cars/toyota-ts030-2013/.

Collins, S., 2014. Toyota TS040. Racecar Engineering http://www.racecar-engineering.com/cars/toyota-ts040/

Collins, S., 2015. Porsche 919 (9R9-2014). Racecar Engineering http://www.racecar-engineering.com/cars/porsche-919/.

Collins, S., 2017. Porsche 919 (9R9 MY15-MY17). Racecar Engineering http://www.racecar-engineering.com/cars/porsche-919-9r9-my15/.

Congrega, C., 2011. Premier essai Peugeot 3008 Hybrid4: Les trois vies de l'Hybrid 4. L'Automobile Magazine http://www.automobile-magazine.fr/tous-les-essais/article/10077-essais-peugeot-peugeot-3008-hybrid4.

D'Aveni, R., 1994. Hypercompetition: Managing the dynamics of strategic maneuvering. Free Press

D'Aveni, R.A., Dagnino, G.B., Smith, K.G., 2010. The age of temporary advantage. Strategic Management Journal 31, 1371-1385.

Davis, J.P., Eisenhardt, K.M., Bingham, C.B., 2009. Optimal structure, market dynamism, and the strategy of simple rules. Administrative Science Quarterly 54, 413-452.

Dierickx, I., Cool, K., 1989. Asset Stock Accumulation and Sustainability of Competitive Advantage. Management Science 35, 1504-1511.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research Policy 11, 147-162.

Eggers, J., 2012a. Falling flat: Failed technologies and investment under uncertainty. Administrative Science Quarterly 57, 47-80.

Eggers, J.P., 2012b. All experience is not created equal: learning, adapting, and focusing in product portfolio management. Strategic Management Journal 33, 315-335.

Eisenhardt, K.M., 1989a. Building Theories from Case Study Research. The Academy of Management Review 14, 532-550.

Eisenhardt, K.M., 1989b. Making fast strategic decisions in high-velocity environments. Academy of Management Journal, 543-576.

Emme, T., 2012. Le Mans: La Toyota TS030 sera finalement une propulsion. Le Blog Auto http://www.leblogauto.com/2012/05/le-mans-la-toyota-ts030-sera-finalement-une-propulsion.html.

Endurance-Info.com, 2013. Gérard Neveu fait le point sur le FIA WEC. Edurance-info.com http://www.endurance-info.com/fr/actualite-endurance-18971/.

English, S., 2010. Grapevine: Porsche to use Williams hybrid system. Autosport.com https://www.autosport.com/f1/news/81402/porsche-to-use-williams-hybrid-system.

European Commission, 2016. Reducing CO2 emissions from passenger cars. ec.europa.eu http://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

Fagnan, R., 2016. Technique - The MGU-K and MGU-H explained. Motorsport.com https://www.motorsport.com/f1/news/technique-the-mgu-k-and-mgu-h-explained-791187/.

Fleming, L., 2001. Recombinant uncertainty in technological search. Management Science 47, 117-132.

Florea, C., 2015. 2015 Audi E18 e-tron quattro. TopSpeed.com https://www.topspeed.com/cars/audi/2015-audi-r18-e-tron-quattro-ar168367.html.

Garud, R., Tuertscher, P., Van de Ven, A.H., 2013. Perspectives on innovation processes. The Academy of Management Annals 7, 775-819.

Gavetti, G., Rivkin, J.W., 2007. On the origin of strategy: Action and cognition over time. Organization Science 18, 420-439.

Geroski, P.A., 1995. What do we know about entry? International Journal of Industrial Organization 13, 421-440.

Gino, F., Pisano, G.P., 2011. Why leaders don't learn from success. Harvard business review 89, 68-74.

Gioia, D.A., Corley, K.G., Hamilton, A.L., 2012. Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. Organizational Research Methods 16, 15-31.

Goodwin, G., 2012. Season Preview: The FIA World Endurance Championship. Le Mans Race. http://lemansrace.com/motorsport-news/2012-season-preview-fia-world-endurance-championship/

Grant, R., 1996. Prospering in Dynamically-Competitive Environments: Organizational Capability as Knowledge Integration. Organization Science 7, 375-387.

Gupta, A., Smith, K., Shalley, C., 2006. The interplay between exploration and exploitation. Academy of Management Journal 49, 693-706.

Gurses, K., Ozcan, P., 2015. Entrepreneurship in regulated markets: framing contests and collective action to introduce pay TV in the US. Academy of Management Journal 58, 1709-1739.

Hamel, G., 1991. Competition for Competence and Inter-Partner Learning Within International Strategic Alliances. Strategic Management Journal 12, 83-103.

Hammond, R., 2012. The Richard Hammond test drive: Peugeot's 3008 Hybrid4 fails to hit the mark. Mirror.co.uk http://www.mirror.co.uk/lifestyle/motoring/peugeot-3008-hybrid4-the-richard-hammond-749021.

Hanlon, M., 2014. Inside Porsche's 919 hybrid LMP1, and a closer look at the competition. Newatlas.com http://newatlas.com/porsche-919-hybrid-lmp1-vs-audi-r18-e-tron-quattro-vs-toyotats040/31081/.

Hart, S.L., Ahuja, G., 1996. Does it pay to be green? An empirical examination of the relationship between emission reduction and firm performance. Business strategy and the Environment 5, 30-37.

Hartnell, G., 1996. The innovation of agrochemicals: regulation and patent protection. Research Policy 25, 379-395.

He, Z.-L., Wong, P.-K., 2004. Exploration vs. Exploitation: An Empirical Test of the Ambidexterity Hypothesis. Organization Science 15, 481-494.

Henderson, R.M., Clark, K.B., 1990. Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. Administrative Science Quarterly 35, 9-30.

Hoisl, K., Gruber, M., Conti, A., 2016. R&D Team Diversity and Performance in Hypercompetitive Environments. Strategic Management Journal 37, forthcoming.

Hoisl, K., Gruber, M., Conti, A., 2017. R&D team diversity and performance in hypercompetitive environments. Strategic Management Journal 38, 1455-1477.

Jacobides, M.G., MacDuffie, J.P., Tae, C.J., 2016. Agency, structure, and the dominance of OEMs: Change and stability in the automotive sector. Strategic Management Journal 37, 1942-1967.

Jaffe, A.B., Palmer, K., 1997. Environmental regulation and innovation: a panel data study. Review of economics and statistics 79, 610-619.

Jansen, J.J., Van Den Bosch, F.A., Volberda, H.W., 2006. Exploratory innovation, exploitative innovation, and performance: Effects of organizational antecedents and environmental moderators. Management Science 52, 1661-1674.

Jenkins, M., 2010. Technological Discontinuities and Competitive Advantage: A Historical Perspective on Formula 1 Motor Racing 1950–2006. Journal of Management Studies 47, 884-910.

Jenkins, M., 2014a. Do regulations place innovation in a straitjacket or give it wings? Virgin.com Blog https://www.virgin.com/disruptors/do-regulations-place-innovation-straitjacket-or-give-it-wings.

Jenkins, M., 2014b. Innovate or Imitate? The Role of Collective Beliefs in Competences in Competing Firms. Long Range Planning 47, 173-185.

Jenkins, M., Floyd, S., 2001. Trajectories in the evolution of technology: A multi-level study of competition in Formula 1 racing. Organization Studies 22, 945.

Jenkins, M., Pasternak, K., West, R., 2016. Performance at the limit: Business lessons from Formula 1 motor racing (Third Edition). Cambridge University Press, Cambridge, UK.

Joest Racing, 2014. Audi R18 e-tron quattro 2014. Joest-Racing.de http://www.joest-racing.de/en/index.php/cars/single/der-naechste-audi-r18-e-tron-quattro.

Kim, C., 2012. Insider's Look at the Toyota TS030 Hybrid Le Mans Effort. Road and Track http://www.roadandtrack.com/motorsports/news/a18309/insiders-look-at-the-toyota-ts030-hybrid-le-mans-effort/.

King, A.A., Tucci, C.L., 2002. Incumbent entry into new market niches: The role of experience and managerial choice in the creation of dynamic capabilities. Management Science 48, 171-186.

La Pierre, D.B., 1976. Technology-forcing and federal environmental protection statutes. Iowa L. Rev. 62, 771.

Lamarche, F., 2014. Neel Jani se confie sur sa saison 2014. SuisseAutomag.ch http://www.suisseautomag.ch/2014/12/wec-neel-jani-tire-bilan-saison-porsche/

Lane, P.J., Lubatkin, M., 1998. Relative Absorptive Capacity and Interorganizational Learning. Strategic Management Journal 19, 461-477.

Lanjouw, J.O., Mody, A., 1996. Innovation and the international diffusion of environmentally responsive technology. Research Policy 25, 549-571.

Lavrinc, D., 2014. Toyota's New Hybrid Racer Is a 1,000 Horsepower Beast. Wired.com https://www.wired.com/2014/03/toyota-ts040/.

Lee, C.-H., Venkatraman, N., Tanriverdi, H., Iyer, B., 2010. Complementarity-based hypercompetition in the software industry: Theory and empirical test, 1990–2002. Strategic Management Journal 31, 1431-1456.

Lee, J., Veloso, F.M., Hounshell, D.A., 2011. Linking induced technological change, and environmental regulation: Evidence from patenting in the US auto industry. Research Policy 40, 1240-1252.

Leonard-Barton, D., 1992. Core Capabilities and Core Rigidities: A Paradox in Managing New Product Development. Strategic Management Journal 13, 111-125.

Levinthal, D., March, J.G., 1981. A model of adaptive organizational search. Journal of Economic Behavior & Organization 2, 307-333.

Levinthal, D.A., 1997. Adaptation on rugged landscapes. Management Science 43, 934-950.

Mahon, J.F., Murray, E.A., 1981. Strategic planning for regulated companies. Strategic Management Journal 2, 251-262.

March, J., 1991. Exploration and exploitation in organizational learning. Organization Science 2, 71-87.

Marino, A., Aversa, P., Mesquita, L., Anand, J., 2015. Driving performance via exploration in changing environments: Evidence from Formula One racing. Organization Science 26, 1079-1100.

McCarthy, I.P., Lawrence, T.B., Wixted, B., Gordon, B.R., 2010. A multidimensional conceptualization of environmental velocity. Academy of Management Review 35, 604-626.

Meiners, J., 2012. Audi Unveils R18 e-tron Quattro and Upgraded R18 Ultra Le Mans Prototypes. CarandDriver.com http://blog.caranddriver.com/audi-unveils-r18-e-tron-quattro-and-upgraded-r18-ultra-le-mans-prototypes/.

Mercier, L., 2013. Nicolas Lapierre and the Toyota Hybrid: "No one expected us to be at that level". Motorsport.com http://www.motorsport.com/wec/news/nicolas-lapierre-and-the-toyota-hybrid-no-one-expected-us-to-be-at-that-level/.

Mercier, L., 2014a. Audi unveils the new R18 e-tron quattro. Endurance-info.com http://www.endurance-info.com/en/audi-unveils-the-new-r18-e-tron-quattro/.

Mercier, L., 2014b. Audi welcomes LMP1 efficiency regulations. Endurance-info.com http://www.endurance-info.com/en/audi-welcomes-lmp1-efficiency-regulations/.

Miller, F., 2013. Toyota reveal 2013 LMP1 Challenger at Paul Ricard. fiawec.com http://www.fiawec.com/en/news/toyota-reveal-2013-lmp1-challenger-at-paul-ricard_954.html.

Miller, F., 2014. FIA and ACO Technical Briefing on new LMP1 regulations. fiawec.com http://www.fiawec.com/en/news/fia-and-aco-technical-briefing-on-new-lmp1-regulations_1777.html.

Miller, P., 2015. Automotive Lithium-Ion Batteries. Johnson Matthey Technology Review 59, 4-13.

Moldrich, C., 2016. How Mercedes made F1's best hybrid engine - and why it's looking forward to 2016. Alphr.com http://www.alphr.com/cars/1002748/how-mercedes-made-f1-s-best-hybrid-engine-and-why-it-s-looking-forward-to-2016.

Morris, N., 2000. Vial bodies: conflicting interests in the move to new institutional relationships in biological medicines research and regulation. Research Policy 29, 149-167.

Mourao, P.R., 2017. The Economics of Motorsports. The Case of Formula One. Palgrave Macmillan, U.K.

Murmann, J.P., Frenken, K., 2006. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. Research Policy 35, 925-952.

Nadkarni, S., Narayanan, V.K., 2007. Strategic schemas, strategic flexibility, and firm performance: The moderating role of industry clockspeed. Strategic Management Journal 28, 243-270.

Narayanan, K., 1998. Technology acquisition, de-regulation and competitiveness: a study of Indian automobile industry. Research Policy 27, 215-228.

Noah, J., 2015. Toyota reveals updated TS040 Hybrid LMP1 for 2015 Autoblog.com http://www.autoblog.com/2015/03/26/2015-toyota-ts040-hybrid-lmp1-videos-official/.

Noble, J., 2017. Honda hurt by time away from F1, says former chief. Motorsport.com https://www.motorsport.com/f1/news/f1-news-lack-experience-honda-downfall-926191/.

Novak, M., 2014. 15 Years Of Virgin Galactic's Failed Space Age Promises. Gizmodo.com https://www.gizmodo.com.au/2014/05/15-years-of-virgin-galactics-failed-space-age-promises/.

O'Reilly, C.A., Tushman, M., 2007. Ambidexterity as a Dynamic Capability: Resolving the Innovator's Dilemma. SSRN eLibrary.

Ozcan, P., Gurses, K., 2017. Playing cat and mouse: Contests over regulatory categorization of dietary supplements in the US. Academy of Management Journal Forthcoming, amj. 2015.1221.

Palmer, K., Oates, W.E., Portney, P.R., 1995. Tightening environmental standards: The benefit-cost or the no-cost paradigm? The Journal of Economic Perspectives 9, 119-132.

Piezunka, H., Lee, W., Haynes, R., Bothner, M.S., 2018. Escalation of competition into conflict in competitive networks of Formula One drivers. Proceedings of the National Academy of Sciences.

Porsche, 2010. 911 GT3 R Hybrid Celebrates World Debut in Geneva. Porsche Official Website http://www.porsche.com/uk/aboutporsche/pressreleases/pag/?pool=international-de&id=2010-02-11.

Porter, M.E., 1980. Competitive Strategy: Techniques for Analyzing Industries and Competitors. Free Press.

Porter, M.E., Van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. The Journal of Economic Perspectives 9, 97-118.

Posen, H.E., Levinthal, D.A., 2012. Chasing a moving target: Exploitation and exploration in dynamic environments. Management Science 58, 587-601.

Powell, T.C., Lovallo, D., Caringal, C., 2006. Causal ambiguity, management perception, and firm performance. Academy of Management Review 31, 175-196.

Prince, M., 2014. The Toyota TS040 Hybrid is a 1000-hp AWD Le Mans Kaiju. Road and Track http://www.roadandtrack.com/motorsports/a7473/2014-toyota-ts040-hybrid/http://www.roadandtrack.com/motorsports/a7473/2014-toyota-ts040-hybrid/.

Pruett, M., 2012. 2012 Le Mans Hybrids. Road and Track http://www.roadandtrack.com/motorsports/videos/a18176/2012-le-mans-hybrids/.

Racecar-Engineering, 2012. Toyota TS030 LMP1 hybrid revealed. Racecar Engineering http://www.racecar-engineering.com/news/toyota-ts030-lmp1-hybrid-revealed/.

Ramaswamy, K., Thomas, A.S., Litschert, R.J., 1994. Organizational performance in a regulated environment: The role of strategic orientation. Strategic Management Journal 15, 63-74.

Reed, R., DeFillippi, R.J., 1990. Causal ambiguity, barriers to imitation, and sustainable competitive advantage. Academy of Management Review 15, 88-102.

Reger, R.K., Duhaime, I.M., Stimpert, J.L., 1992. Deregulation, strategic choice, risk and financial performance. Strategic Management Journal 13, 189-204.

Rochet, J.-C., Tirole, J., 2005. Competition Policy in Two-Sided Markets. Advances in the Economics of Competition Law, MIT Press, Cambridge, MA, USA.

Romanelli, E., Tushman, M.L., 1994. Organizational Transformation as Punctuated Equilibrium: An Empirical Test. The Academy of Management Journal 37, 1141-1166.

Rothaermel, F.T., Deeds, D.L., 2004. Exploration and exploitation alliances in biotechnology: a system of new product development. Strategic Management Journal 25, 201-221.

Rügheimer, U., 2013. The Audi R18 e-tron quattro. Audi-MediaCenter.com https://www.audi-mediacenter.com/en/press-releases/the-audi-r18-e-tron-quattro-803.

Sierzchula, W., Bakker, S., Maat, K., Van Wee, B., 2012. The competitive environment of electric vehicles: An analysis of prototype and production models. Environmental Innovation and Societal Transitions 2, 49-65.

Simon, H.A., 1962. The Architecture of Complexity. Proceedings of the American Philosophical Society 106, 467-482.

Simon, H.A., 2002. Near decomposability and the speed of evolution. Industrial & Corporate Change 11, 587–599.

Smith, K.G., Grimm, C.M., 1987. Environmental variation, strategic change and firm performance: A study of railroad deregulation. Strategic Management Journal 8, 363-376.

Soda, G., Furlotti, M., 2014. Bringing Tasks Back In An Organizational Theory of Resource Complementarity and Partner Selection. Journal of Management, 0149206314535435.

Soda, G., Furlotti, M., 2017. Bringing tasks back in: an organizational theory of resource complementarity and partner selection. Journal of Management 43, 348-375.

Spender, J.-C., 1989. Industry recipes. Basil Blackwell Oxford.

Spicer, A., 2015. How could VW be so stupid? CNN.com http://edition.cnn.com/2015/09/23/opinions/spicer-vokswagen/.

Stewart, L.A., 2010. The impact of regulation on innovation in the United States: A cross-industry literature review. 1-29.

Stewart, R.B., 1993. Environmental regulation and international competitiveness. The Yale Law Journal 102, 2039-2106.

Stigler, G.J., 1971. The theory of economic regulation. The Bell journal of economics and management science 2, 3-21.

Stoklosa, A., 2014. Porsche 919 Hybrid Le Mans Prototype. CarandDriver.com http://www.caranddriver.com/reviews/porsche-919-hybrid-le-mans-prototype-auto-shows.

Strauss, A., Corbin, J.M., 1990. Basics of qualitative research: Grounded theory procedures and techniques. Sage Publications, Inc.

Suarez, F., Lanzolla, G., 2005. The half-truth of first-mover advantage. Harvard business review 83, 121.

Suarez, F., Lanzolla, G., 2007. The role of environmental dynamics in building a first mover advantage theory. Academy of Management Review 32, 377-392.

Sylt, C., Reid, C., 2010. Formula Money. Money Sport Media Limited, London, UK.

Tallman, S., Jenkins, M., Henry, N., Pinch, S., 2004. Knowledge, clusters, and competitive advantage. The Academy of Management Review 29, 258-271.

Teece, D.J., 1986. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research Policy 15, 285-305.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strategic Management Journal 18, 509-533.

Timiraos, N., 2017. Business Leaders Send Donald Trump Their Deregulation Wish List. The Wall Street Journal https://www.wsj.com/articles/business-leaders-send-donald-trump-their-deregulation-wish-list-1487845980.

Timiraos, N., Benoit, D., Paletta, D., 2016. Donald Trump's New Appointments Shake Up Trade, Regulation. Wall Street Journal http://www.wsj.com/articles/trump-names-pete-navarro-to-head-house-national-trade-council-1482353955.

Toyota, 2013. Toyota Racing Reveals Updated TS030 Hybrid for 2013. Toyota Motorsport GmbH http://www.racingbytmg.com/toyota-racing-reveals-updated-ts030-hybrid-for-2013/.

Toyota, 2014. New era for Toyota Racing with TS040 Hybrid. Racing By TMG http://www.racingbytmg.com/.

Toyota-Global.com, 2016. History - Challenging Motorsport. "The 24 Hours of Le Mans". Toyota Global website http://www.toyota-global.com/events/motor_sports/history_01/.

Tripsas, M., Gavetti, G., 2000. Capabilities, cognition and inertia: Evidence from digital imaging. Strategic Management Journal 21, 1147-1162.

Tushman, M., Anderson, P., 1986. Technological discontinuities and organizational environments. Administrative Science Quarterly 31, 439-465.

Tutu, A., 2015. Porsche's 2015 Le Mans: 2nd Generation 919 Racecar in 3 Liveries, Future Hybrid 911 Refferenc. Autoevolution.com https://www.autoevolution.com/news/porsche-s-2015-le-mans-2nd-generation-919-racecar-in-3-liveries-future-hybrid-911-refference-93739.html.

Ungson, G.R., James, C., Spicer, B.H., 1985. The effects of regulatory agencies on organizations in wood products and high technology/electronics industries. Academy of Management Journal 28, 426-445.

Vijayenthiran, V., 2013. 2013 Audi R18 e-tron quattro Ready To Defend Le Mans Title. MotorAuthority.com http://www.motorauthority.com/news/1083393_2013-audi-r18-e-tron-quattro-ready-to-defend-le-mans-title.

Volberda, H., 1996. Toward the flexible form: How to remain vital in hypercompetitive environments. Organization Science 7, 359-374.

Wan, M., 2010. Lancia Fulvia Coupe HF (1965). Autozine.org http://www.autozine.org/Archive/Lancia/classic/Fulvia.html.

Watkins, G., 2015. Porsche reveals its 2015 919 Hybrid LMP1 car for WEC and Le Mans. Autosport.com http://www.autosport.com/news/report.php/id/117379.

Wholey, D.R., Brittain, J., 1989. Characterizing environmental variation. Academy of Management Journal 32, 867-882.

Wittemeier, R., 2012. Projektstart: Ein weißes Blatt mit Antrieb. Motorsport-Total.com http://www.motorsport-total.com/wec/news/2012/10/Projektstart_Ein_weisses_Blatt_mit_Antrieb_12100601.html.

Yin, R., 2008. Case study research: Design and methods. Sage Publications, Inc.

Young, J., 2002. Induced innovation and energy prices. The American Economic Review 92, 160-180.

Zahra, S.A., George, G., 2002. Absorptive Capacity: A Review, Reconceptualization, and Extension. Academy of Management Review 27, 185-203.

Zhou, K.Z., Wu, F., 2010. Technological capability, strategic flexibility, and product innovation. Strategic Management Journal 31, 547-561.

Zirpoli, F., Camuffo, A., 2009. Product architecture, inter-firm vertical coordination and knowledge partitioning in the auto industry. European Management Review 6, 250-264.

FIRM TECHOLOGICAL RESPONSES TO REGULATORY CHANGES:

A LONGITUDINAL STUDY IN THE LE MANS PROTOTYPE RACING

APPENDIX

SUPPLEMENTAL MATERIALS FOR REVIEW
(suggested for online publication only)

APPENDIX A

TABLE A1
Glossary of technical terms

Automobile Club de l'Ouest (ACO): The largest automotive club in France that organises the race of the 24 hours of Le Mans as well as the WEC Championship in cooperation with the FIA.

Energy Recovery System (ERS): A kinetic energy recovery system (often simply termed as KERS, or ERS) is an automotive system for recovering a moving vehicle's kinetic energy under braking (KERS) or from exhaust pipes (ERS). The recovered energy is stored in a reservoir (for example a flywheel, high voltage batteries or a supercapacitor) for later use on acceleration.

Fédération Internationale de l'Automobile (FIA): The largest automotive association in the world that has organizes and licenses the Formula 1 championship, the Word Rally Championship and the Word Endurance Championship.

Le Mans Prototype 1 (LMP1): The category of the most powerful and technologically advanced endurance cars used in the WEC. Prototype describes a type of car that is only designed for racing in contrast with Grand Tourer that is used to describe a racing car elaborated from a road car. The hybrid sub-category in LMP1 is called LMP1-H.

Flywheel system: The mechanical system that stores energy by the use of a rotor spinning at a very high speed. The energy is redirected to an MGU.

Megajoule (MJ): The megajoule (MJ) is equal to one million (10^6) joules, or approximately the kinetic energy of a one megagram (tonne) vehicle moving at 160 km/h. One kilowatt hour of electricity is 3.6 megajoules.

Motor Generator Unit (MGU): Device that converts mechanical and/or heat energy to electrical energy. In a second time, it sends back the energy created to the powertrain.

MGU-H: It converts heat energy from exhaust gases to electricity.

MGU-K: It converts kinetic energy from breaking to electricity.

Supercapacitor: A system that stores energy electrochemically on the surface of electrodes allowing a fast energy absorption and delivery. However, the amount of energy storage is relative to the surface used limiting the storage. The energy is redirected to an MGU.

World Endurance Championship (WEC): Edurance world championship organised by the ACO and the FIA.

TABLE A2
Detailed qualitative codification of innovation at the firm level

		2012	2013	2014	2015
Environment level	*Magnitude* of regulation change *Direction* of regulation change	**Radical** **Permissive**	**Incremental** **Permissive**	**Radical** **Restrictive**	**Incremental** **Restrictive**
	First Ranked (winner)	**Audi R18 e-tron**	**Audi R18 e-tron**	**Toyota TS040**	**Porsche 919**
Firm level	*Core Subsystem* innovation	**Incremental:** - Improved carbon fiber monocoque coupled from previous versions, with a modified chassis to host the hybrid powertrain	**Incremental:** - No structural re-design but several changes mostly aimed at reducing the overall weight.	**Radical:** - Radically new chassis made with lightweight materials and new aerodynamic package. - The car is 10cm narrower and with narrower tyres as well and a new overall concept. It also features new safety items such as wheel tethers, a rear crash structure, new requirements for driver visibility and side-impact reinforcement.	**Incremental:** - The basis of the chassis structure remains unchanged but it is lighter and more rigid. - Three aerodynamics packages to adapt to each track.
	Peripheral Subsystem innovation	**Radical:** - Innovative flywheel ERS "borrowed" from the sister	**Incremental**: - Improved hybrid structure; new rear wing	**Radical:** - Brand-new engine (from 3.4 to 3.7 liters) and ERS system coupled to	**Incremental:** - Hybrid system modifications to increase the

	company Porsche. - First use of a diesel-electric combination to design the first four-wheel drive in a racing series. . - Moderate evolution of the 2011 3.7 liter V6 TDI engine. - New carbon-fiber composite gear-box to reduce the weight.	design and new exhaust system.	an additional MGU transforming the car to a four-wheel drive with 998 hp. The TS040 was the first car in endurance racing that could recover energy from the four wheels.	power released (from 6MJ in 2014 to 8MJ in 2015)
Second ranked	**Toyota TS030**	**Toyota TS030**	**Audi R18 e-tron**	**Audi R18 e-tron**
Core Subsystem innovation	**Incremental:** - New carbon-fiber monocoque coupled with a highly modified chassis to support the hybrid system.	**Incremental:** - Lighter chassis based on the older 2012 design, and some minor updates for the aerodynamic package. - Reorganized the space by pushing back and re-centralizing the driver position that	**Incremental:** - Brand new chassis and bodywork to reduce weight and increase rigidity.	**Incremental:** - Aerodynamic drag reduced with large air inlets in the front wheel arches.

		incrementally improved the prototype's mass displacement.		
Peripheral Subsystem innovation	**Radical:** - Supercapacitor used as a storage system for the first time in a motor sport series. - Normally aspirated 3.4 liter V8 engine coupled with an ERS releasing energy to the rear axle allowing additional boost use at any speed.	**Incremental**: - New supercapacitor components designed by the partner Denso. - Removal of the deactivated MGU in front axle.	**Incremental:** - Traditional engine 4.0 liter V6 TDI.	**Incremental:** - Storage system capacity increased and doubled power released by the hybrid system (from 2MJ in 2014 to 4MJ in 2015).
Third ranked	-	-	**Porsche 919**	**Toyota TS040**
Core Subsystem innovation	-	-	**Radical:** - Innovative and complex car with unique and complex suspension system, and new aerodynamics.	**Incremental:** - Chassis and suspension system improvement to reduce tire wear and some aerodynamic updates. - Redesigning

				the front end, the aerodynamics package has been thoroughly revised, the suspension reconfigured and extra weight has been cut. - Two aero kits: one for high-speed circuits with reduced drag, and the other for tighter tracks requiring increased downforce.
Peripheral Subsystem innovation	-	-	**Radical:** - New 2.0-liter engine pioneering a V4 architecture coupled to a double hybrid system. - Groundbreaking hybrid system combining two ERS systems. The first one collecting kinetic energy from braking; the second one	**No change:** -

		collecting waste heat from exhaust gases, allowing the car to continuously recover energy al through the race.	

TABLE A3a
Toyota's general and specialised knowledge (2012-2015)

			2012		2013		2014		2015	
Firm	**Subsystem**	**Main technologies adopted**	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).
TOYOTA	**Peripheral subsystems**	*ERS: Super capacitor*	From other series: inspired by Toyota Supra 2007.	n.a.	From other series: inspired by Toyota Supra 2007.	From LMP1: optimizations designed by DENSO (Toyota's company) to deliver up to 300ps.	From other series: inspired by Toyota Supra 2007.	From LMP1: Improved design of the technology used in 2013.	From other series: inspired by Toyota Supra 2007.	From LMP1: prior technology.
		Transmission, 4 Wheel Drive, Gearbox	n.a.	n.a.	n.a.	n.a.	n.a.	From LMP1: 4 wheel drive ERS powered by	n.a.	From LMP1: prior technology.

								two MGU previously tested in 2012.		
	Core subsystems	*V8 engine*	From other series: Toyota Super GT 3.4-liter V-8 for Japanese series.	n.a.	From other series: Toyota Super GT 3.4-liter V-8 for Japanese series.	From LMP1: Same 2012 engine with updates for increasing power.	From other series: Toyota Super GT 3.4-liter V-8 for Japanese series.	New, bigger engine derived from the former V8 used in 2012 and 2013.	From other series: Toyota Super GT 3.4-liter V-8 for Japanese series.	From LMP1: prior technology.
		Chassis, Aerodynamics	From Formula 1: Exhaust design and others in line with Toyota F1 car.	From LMP1: General design widely inspired by Peugeot 908 Hybrid4 LMP1	From Formula 1: Exhaust design and others in line with Toyota F1 car.	From LMP1: Revised aerodynamics package including updated	From Formula 1: Exhaust design and others in line with Toyota F1 car.	From LMP1: Major evolution of the 2013's model with ambitious aerody	From Formula 1: Exhaust design and others in line with Toyota F1 car.	From LMP1: improvement of prior aero package.

			(2011) .	monoc oque.	namic s.	

TABLE A3b
Audi's general and specialised knowledge (2012-2015)

			2012		2013		2014		2015	
Firm	**Subsystem**	**Main technologies adopted**	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).
AUDI	**Peripheral subsystems**	*ERS: Flywheel*	From other series: Borrowed from 2010 Porsche 911 GT3-R hybrid system (formerly developed by Williams F1).	n.a.	From other series: Borrowed from 2010 Porsche 911 GT3-R hybrid system (formerly developed by Williams F1).	From LMP1: 2012 Flywheel with slightly increased capacity.	From other series: Borrowed from 2010 Porsche 911 GT3-R hybrid system (formerly developed by Williams F1).	From LMP1: design of a Porsche-inspired rear ERS from exhaust pipes (not implemented).	From other series: Borrowed from 2010 Porsche 911 GT3-R hybrid system (formerly developed by Williams F1).	From LMP1: Prior year ERS now upgraded to 4MJ.
		Transmission, 4 Wheel Drive, Gearbox	From standard roadcars: Four-wheel inspired fom	n.a.	From standard roadcars: Four-wheel inspired fom	From LMP1: 2012 4 Wheel drive transmission.	From standard roadcars: Four-wheel inspired fom	From LMP1: Lighter electric motor on the front axle.	From standard roadcars: Four-wheel inspired fom	From LMP1: prior technology.

			standard cars Peugeot. Gearbox inspired by F1.		standard cars Peugeot. Gearbox inspired by F1.		standard cars Peugeot. Gearbox inspired by F1.		standard cars Peugeot. Gearbox inspired by F1.	
	Core subsystems	*V6 TDI engine*	n.a.	From LMP1: From 2011's Audi R18 e-tron model (same engine).	n.a.	From LMP1: V6 TDI engine from 2012.	n.a.	From LPM1: Increased size for the 2013, V6 4.0 liter engine .	n.a.	From LMP1: Previous engine, now more powerful. Updated parts from 2014.
		Chassis, Aerodynamics	n.a.	From LMP1: Audi 2011's model.	n.a.	From LMP1: New rear wings inspired by Toyota TS030.	n.a.	From LMP1: Incremental evolutions from 2013's model new front wings and bodyworks elements.	n.a.	From LMP1: new front wings and sideposts.

TABLE A3c
Porsche's general and specialised knowledge (2012-2015)

			2012		2013		2014		2015	
Firm	**Subsystem**	**Main technologies adopted**	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).	**General knowledge** (i.e., road cars, or other racing series).	**Specialised knowledge** (i.e., applied in LMP1).
PORSCHE	**Peripheral subsystems**	*ERS: Lithium-ion Batteries*	n.a.	n.a.	n.a.	n.a.	From high-performance roadcars: A123 Systems lithium-ion batteries, used on Mercedes-Benz S400 Hybrid model and Poråsche 919 Hybrid. Read exhaust ERS is inspire	n.a.	From high-performance roadcars: A123 Systems lithium-ion batteries, used on Mercedes-Benz S400 Hybrid model and Poråsche 919 Hybrid. Read exhaust ERS is inspire	From LMP1: exactly same battery storage than in 2014.

							d by Formula 1 cars.		d by Formula 1 cars.	
		Transmission, 4 Wheel Drive, Gearbox	n.a.	n.a.	n.a.	n.a.	From Formula 1: rear-drive from Hybrid F1.	From LMP1: from MGU drive inspired by Audi and Toyota LMP1.	From Formula 1: rear-drive from Hybrid F1.	From LMP1: Some changes from 2014 but following the same technology. MGU (8MJ) with increased power.

	Core subsystems	*V4 engine*	n.a.	n.a.	n.a.	n.a.	From other series: Lancia Fulvia 1972; motobike industry V4 architecture.	n.a.	From other series: Lancia Fulvia 1972; motobike industry V4 architecture.	From LMP1: Evolution from 2014's model: new twin exhaust systems to make the engine lighter.
		Chassis, Aerodynamics	n.a.	n.a.	n.a.	n.a.	n.a.	From other LMP1 cars: copied general design from Audi and Toyota.	n.a.	From LMP1: Evolution from 2014's model, now in a single piece; also, new nose and other aerodynamics elements.

TABLE A4
Individual race results (2012-2015)

Race	2012 ranking	2013 ranking	2014 ranking	2015 ranking
12 Hours of Sebring	1. **Audi** R18 Ultra TDI 2. **Audi** R18 Ultra TDI 3. **HPD-Honda**	-	-	-
WEC 6 Hours of Silverstone	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 Ultra TDI 3. **Toyota** TS030 Hybrid	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **Toyota** TS030 Hybrid	1. **Toyota** TS040 Hybrid 2. **Toyota** TS040 Hybrid 3. **Porsche** 919 Hybrid	1. **Audi** R18 e-tron Quattro 2. **Porsche** 919 Hybrid 3. **Toyota** TS040
WEC 6 Hours of Spa-Francochamps	1. **Audi** R18 Ultra TDI 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 Ultra TDI	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 e-tron Quattro	1. **Toyota** TS040 Hybrid 2. **Audi** R18 e-tron Quattro 3. **Toyota** TS040 Hybrid	1. **Audi** R18 e-tron Quattro 2. **Porsche** 919 Hybrid 3. **Porsche** 919 Hybrid
24 Hours of Le Mans	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 Ultra TDI	1. **Audi** R18 e-tron Quattro 2. **Toyota** TS030 Hybrid 3. **Audi** R18 e-tron Quattro	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **Toyota** TS040 Hybrid	1. **Porsche** 919 Hybrid 2. **Porsche** 919 Hybrid 3. **Audi** R18 e-tron Quattro
WEC 6 Hours of Sao Paulo	1. **Toyota** TS030 Hybrid 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 Ultra TDI	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro **3. Lola**	1. **Porsche** 919 Hybrid 2. **Toyota** TS040 Hybrid 3. **Audi** R18 e-tron Quattro	-
6 Hours of Bahrain	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **HPD-Honda**	1. **Toyota** TS030 Hybrid 2. **Audi** R18 e-tron Quattro **3. Orica**	1. **Toyota** TS040 Hybrid 2. **Porsche** 919 Hybrid 3. **Porsche** 919 Hybrid	1. **Porsche** 919 Hybrid 2. **Audi** R18 e-tron Quattro 3. **Toyota** TS040 Hybrid

6 Hours of Fuji	1. **Toyota** TS030 Hybrid 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 e-tron Quattro	1. **Toyota** TS030 Hybrid 2. **Audi** R18 e-tron Quattro 3. Lola	1. **Toyota** TS040 Hybrid 2. **Toyota** TS040 Hybrid 3. **Porsche** 919 Hybrid	1. **Porsche** 919 Hybrid 2. **Porsche** 919 Hybrid 3. **Audi** R18 e-tron Quattro
6 Hours of Shanghai	1. **Toyota** TS030 Hybrid 2. **Audi** R18 e-tron Quattro 3. **Audi** R18 e-tron Quattro	1. **Audi** R18 e-tron Quattro 2. **Toyota** TS030 Hybrid 3. **Audi** R18 e-tron Quattro	1. **Toyota** TS040 Hybrid 2. **Toyota** TS040 Hybrid 3. **Porsche** 919 Hybrid	1. **Porsche** 919 Hybrid 2. **Porsche** 919 Hybrid 3. **Audi** R18 e-tron Quattro
6 Hours of Circuit of the Americas	-	1. **Audi** R18 e-tron Quattro 2. **Toyota** TS030 Hybrid 3. **Audi** R18 e-tron Quattro	1. **Audi** R18 e-tron Quattro 2. **Audi** R18 e-tron Quattro 3. **Toyota** TS040 Hybrid	1. **Porsche** 919 hybrid 2. **Audi** R18 e-tron Quattro 3. **Audi** R19 e-tron Quattro
6 Hours of Nürburgring	-	-	-	1. **Porsche** 919 Hybrid 2. **Porsche** 919 Hybrid 3. **Audi** R18 e-tron Quattro

TABLE A5
LMP1 Grand Prix details (2012-2015)

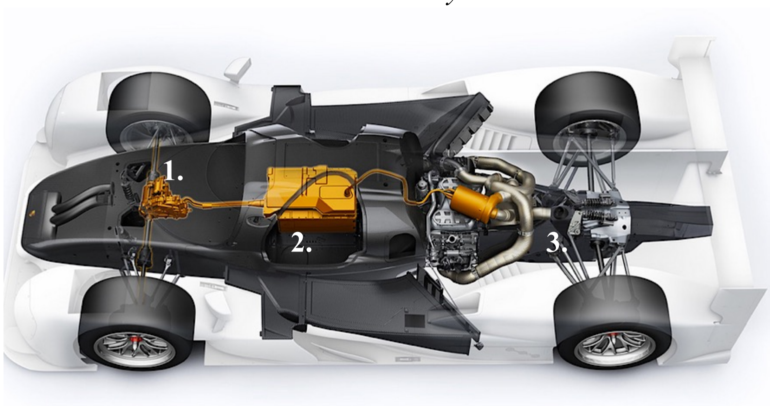
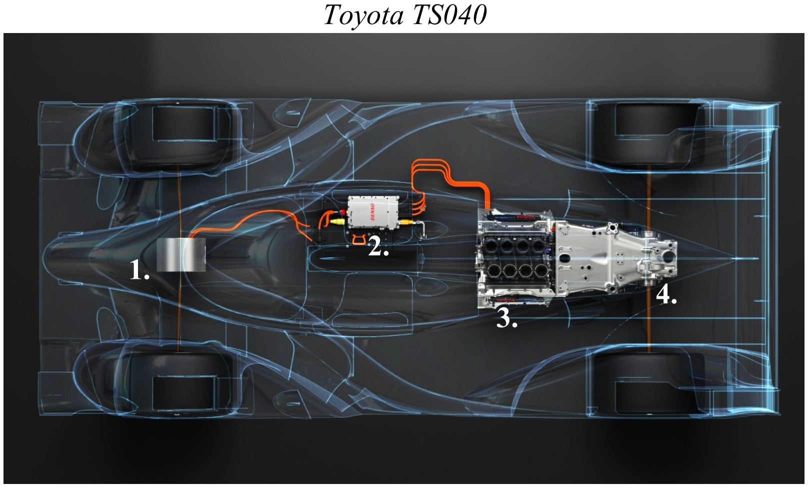
Sequence	Year	Date	Race	Circuit	Length m	Nr. Laps	Distance km
1	2012	17-Mar	Sebring	Sebring	6019	325	1956.175
2	2012	5-May	Spa-Francorchamps	Spa-Francorchamps	7004	160	1120.64
3	2012	17-Jun	Le Mans 24h	Le Mans	13629	378	5151.762
4	2012	26-Aug	Silverstone	Silverstone	5891	194	1142.854
5	2012	15-Sep	Sao Paulo	Interlagos	4309	247	1064.323
6	2012	29-Sep	Bahrain	Bahrain	5412	191	1033.692
7	2012	14-Oct	Fuji	Fuji	4563	233	1063.179
8	2012	28-Oct	Shanghai	Shanghai	5451	191	1041.141
1	2013	14-Apr	Silverstone	Silverstone	5891	197	1160.527
2	2013	4-May	Spa-Francorchamps	Spa-Francorchamps	7004	168	1176.672
3	2013	22-Jun	Le Mans 24h	Le Mans	13629	348	4742.892
4	2013	1-Sep	Sao Paulo	Interlagos	4309	235	1012.615
5	2013	22-Sep	Americas	Americas	5513	187	1030.931
6	2013	20-Oct	Fuji	Fuji	4563	16	73.008
7	2013	9-Nov	Shanghai	Shanghai	5451	190	1035.69
8	2013	30-Nov	Bahrain	Bahrain	5412	199	1076.739
1	2014	20-Apr	Silverstone	Silverstone	5890.8	167	983.764
2	2014	3-May	Spa-Francorchamps	Spa-Francorchamps	7003.9	171	1197.667
3	2014	15-Jun	Le Mans 24h	Le Mans	13629	379	5165.391
4	2014	20-Sep	Americas	Americas	5513	157	865.541
5	2014	12-Oct	Fuji	Fuji	4563	236	1076.868
6	2014	2-Nov	Shanghai	Shanghai	5451	188	1024.788
7	2014	15-Nov	Bahrain	Bahrain	5412	195	1055.34
8	2014	30-Nov	Sao Paulo	Interlagos	4309	249	1072.941

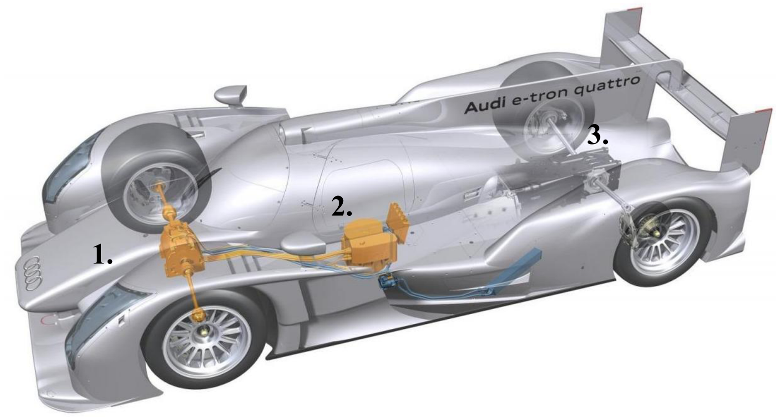
1	2015	12-Apr	Silverstone	Silverstone	5901	201	1186.101
2	2015	2-May	Spa-Francorchamps	Spa-Francorchamps	7003.9	176	1232.686
3	2015	13-Jun	Le Mans 24h	Le Mans	13629	395	5383.455
4	2015	30-Aug	Nürburgring	Nürburgring	5137	203	1042.811
5	2015	19-Sep	Americas	Americas	5513	185	1019.905
6	2015	11-Oct	Fuji	Fuji	4563	216	985.608
7	2015	1-Nov	Shanghai	Shanghai	5451	169	921.219
8	2015	21-Nov	Bahrain	Bahrain	5412	199	1076.988

TABLE A6
LMP1 Championship results and points (2012-2015)

2012			2013			2014			2015		
Team	**Rank**	**Points**	**Team**	**Rank**	**Points**	**Team**	**Rank**	**Points**	**Team**	**Rank**	**Points**
Audi	1	173	Audi	1	207	Toyota	1	289	Porsche	1	344
Toyota	2	96	Toyota	2	142.5	Audi	2	244	Audi	2	264
						Porsche	3	193	Toyota	3	164

TABLE A7
Visual comparison of competing technologies in WEC LMP1-H (2014)

Car model	Hybrid components
Porsche 919 Hybrid  	1. MGU-K recovering the kinetic energy produced while braking. It also supplies power to the front rears. 2. Lithium-ion batteries storing the energy produced by both the MGU-K and MGU-H 3. MGU-H recovering the energy from the exhaust heats. It uses an electric generator powered by the flow of gases and is linked to the turbocharger of the engine.
Toyota TS040  	1. Front MGU-K recovering kinetic energy and supplies power to the front wheels. 2. V-8 engine. 3. Supercapacitor storing the energy produced by the two MGU-K devices. 4. Rear MGU-K with same functionalities than the one on the front but linked to the rear axle.

Audi R18 e-tron 	1. MGU-K linked to the front axle. 2. Flywheel using a rotor that mechanically stores the energy recovered by the MGU-K. It also re-direct the energy to the MGU-K. 3. V-6 TDI Diesel engine.

APPENDIX B

MINI CASE STUDIES

AUDI MOTORSPORT

Team History

Audi is a German automotive company, sub-division of Volkswagen Aktiengesellschaft Group (VAG) where Porsche is also one of the brands. The sport department at Audi, called Audi Motorsport, was created in 1979 in Ingolstadt where the headquarter of the brand is still based. Mainly focus on the world rally championship, the department was originally created to develop what made Audi famous for, the so called ‘Quattro system’. This center differential all-wheel drive system established a new technological standard not only in motorsport, but also in the entire automobile industry. After almost a decade of success crowned by two world champion titles in 1982 and 1984, Audi withdrew from rallying in 1986. Later, Audi focused on circuit racing with a first experience in the American TransAm series in 1988 and then in the German touring car series DTM from 1990, where it collected several prizes such as 7 championship titles. Yet, the endurance series is the racing category where Audi has outclassed its competitors during more than a decade with 13 victories in Le Mans between 1999 and 2016.

Audi Motorsport in endurance since 1999

Audi Motorsport took part for the first time in the endurance championship in 1999 with the R8R model. While the overall design and assembly was developed in Ingolstadt, Germany under the direction of Dr. Wolfgang Ullrich—also known as called "Mister Le Mans"—the chassis was developed by the Italian specialist Dallara in Parma. Audi also chose to build its endurance car in association with Joest Racing, a former Porsche's partner in endurance racing. From 2000 and thanks to an advanced development of the R8 model, Audi won almost every edition of the 24 hours Le Mans race, being the first constructor ever in history winning this prestigious and challenging race with a direct injection engine in 2000, with a diesel engine in 2006, and with a hybrid system in 2012. For many experts—and despite the modest R&D budget—Audi's key to success was the ability to innovate and always evolve over and beyond its competitors. Also, Audi always worked with the most experience endurance drivers through its life: Tom Kristensen, Emanuele Pirro André Lotterer and Marcel Fassler, among others.

Main sources

http://www.audi.com/corporate/en/company/history/motorsport.html

https://www.carwow.co.uk/guides/glossary/audi-quattro-system-explained

http://www.veloce.co.uk/shop/graphics/pdf/V4327.pdf

TOYOTA MOTORSPORT GMBH

Team History

Toyota Motorsport GmBh (TMG) is a subdivision of the Japanese automaker Toyota and is currently is based in Cologne, Germany employing around 200 people. This plant was established in 1979 under the name Andersson Motorsport GmbH originally for its World Rally Championship program. By the end of the program in 1999, Toyota had won three rally world championships as manufacturer. In 1998, TMG entered the endurance series with the car model TSO20 but closed its program two years later after losing the 24h of Le Mans in 1999. Meanwhile, TMG developed a Formula One division and entered the F1 Championship in 2002. TMG was one of the few constructors designing and building both car and engine. From 2002 to the end of the program in 2009—and despite the huge resources deployed—Toyota disappointingly did not win any race but finished 13 times on podium. The F1 program corresponded to a heavy investment in Toyota's Cologne facilities. The high performance infrastructures—such as wind tunnels and several test rings—were rented to different F1 teams and motorsport companies between 2009 and 2012. In 2012, TMG returned to the endurance racing with an innovative hybrid car named TS030. Recently, Toyota decided to join all its motorsports activities under the name "Gazoo Racing". This included its endurance program.

TMG endurance team since 2012

TMG was responsible for more than 80% of components in the TS030, the first WEC model presented in 2012. The rest of the car's elements were designed and manufactured back in Japan by few Toyota's partners such as Denso, which was working on the Hybrid System in collaboration with the Toyota's motorsport division based in Higashifuji. Since 2012 and its return in endurance, Toyota has worked in partnership with ORECA Racing, an experienced French team—21 entries at Le Mans—that offered operational support to the Japanese constructor. Not surprisingly, TMG's 9 year experience in F1 allowed the team to adapt several technologies from F1 to the their WEC vehicles. By hiring in 2012 the former F1's driver Sebastien Buemi as well as the endurance specialist such as Stephan Sarrazin as main drivers, TMG made a major investment in experienced sportsmen despite deploying a budget that was inferior to competitors.

Main sources

http://www.autoblog.com/2015/04/10/toyota-gazoo-racing-official/

http://www.toyota-motorsport.com/en/f-heritage

http://www.f1fanatic.co.uk/f1-information/f1-teams/toyota/

http://www.racecar-engineering.com/news/toyota-ts030-lmp1-hybrid-revealed/

http://www.racecar-engineering.com/news/revised-toyota-ts030-shown-off/

http://www.oreca.com/racing-2/

PORSCHE AG MOTORSPORT

Team History

Porsche AG Motorsport is a subdivision of Porsche AG, a German car manufacturer based in Stuttgart. Porsche itself is owned by Volkswagen AG which is also majority-owned by Porsche's Holding since 2012. Porsche is considered as the most successful race car manufacturer in endurance, with 18 victories in the prestigious 24h of Le Mans, the last one won in 2016. Even when Porsche was not competing in the LMP1 top category as official manufacturer, it built and sold different 911 racing models to private teams to compete in the GT category. Porsche had abandoned the factory motorsports program after its success in Le Mans in 1998. This departure corresponded to a period of financial difficulties for the firm, and its cession to the WV group. The latter had already massively invested in Audi's endurance program since 1999, so it was a problem for WV group to enrol Porsche as a competing factory team in LMP1 again its very own Audi. However, in 2005 Porsche worked closely with a private team (the American team Penske) to run a RS Spyder prototype in the LMP2 category. Before its return in the top-category as manufacturer with the prototype 919 Hybrid, Porsche also run two official 911 RSR in the GT category from 2013. In 2014, Porsche came back to the competition with two GT cars and two prototypes equipped with advanced technology. Its objective was to use its endurance program as an R&D lab to develop its future hybrid production cars.

Porsche AG Motorsport in LMP1 since 2014

Industry experts agree that Porsche came back in endurance with the largest budget ever seen in the series—financial resources were comparable to a top team in F1 (i.e., around $300 million per season). In order to develop a competitive car, Porsche invested in new facilities in Weissah and formed a new team from scratch by hiring more than 200 professionals, including several high quality engineers mostly coming from F1. Different specialised companies such as Bosch and A123 worked closely with Porsche on the car's battery system for the hybrid engine. The extraordinary expertise of both suppliers and engineers allowed Porsche to present the most innovative car ever seen since a long time in the series.

Notable former F1 drivers such as Nico Hulkenberg and Mark Webber joined the Porsche AG team in WEC.

Main sources

Porsche AG Motorsporthttp://www.les24heures.fr/index.php/database/palmaresdes24hdumans

http://www.teampenske.com/

https://newsroom.porsche.com/en/motorsports/le-mans-porsche-technology-919-hybrid-911-rsr-11084.html

http://www.evo.co.uk/porsche/911/13127/porsche-911-rsr-races-at-le-mans

http://www.racecar-engineering.com/cars/porsche-919/