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Technological Discontinuities and Competitive Advantage:

A Historical Perspective on Formula 1 Motor Racing 1950 - 2006

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Abstract

This paper considers the interplay between technological discontinuities and competitive performance. Much of the work on technological discontinuities has focused on macro levels of analysis such as industries and technologies rather than specific firms. This study uses a historical perspective on Formula 1 motor racing to explore the dynamics between firm level performance and technological discontinuities over a 57 year period. The study supports the findings of previous research that suggest that incumbent firms are often unable to adapt to the impact of exogenous shocks. However the study also reveals situations where a relatively small number of firms are able to sustain their competitive superiority through a number of successive discontinuities. We suggest that, in addition to dynamic capabilities, these firms possess sustaining capabilities - munificent resource configurations which extend the time available for firms to adapt to technological changes – thereby allowing them to remain competitive across discontinuities.

Keywords

Technological discontinuities, innovation, historical analysis, competitive advantage, dynamic capability, motorsport, Formula 1

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The removal of the competitive advantage enjoyed by incumbent firms in the face of technological change is a well established proposition in the literature on technological innovation and strategic management. The notion of competence destroying technological discontinuities (Tushman & Anderson 1986) suggests that such changes can transform the competitive landscape in ways that often disadvantage incumbent firms. These discontinuities can create disruptive effects that undermine the structure and integrity of the industry (Ehrnberg 1995), allowing new entrants to establish innovative dominant designs (Abernathy & Utterback, 1978). As a result, discontinuities often stimulate high rates of innovation and market performance (Anderson & Tushman 1990). At the level of firm performance the highly potent resources that underpin the strengths of competing firms may quickly become weaknesses in the face of disruptive technologies and new capabilities evident in new entrants (Leonard-Barton 1995). Disruptive technologies are therefore more likely to be created by new firms and incumbents often prove unable or unwilling to respond to them by improving and even rebuilding their existing capabilities (Bower & Christensen 1995; Christensen 1997).

Much of the work in this area has focused on industry and technology levels of analysis, such as electricity (Hargadon & Yellowlees 2001), minicomputers, cement, airlines (Anderson & Tushman 1990), watches (Glasmeier 1991) and cochlear implants (Garud & Van de Ven 1989). This is wholly appropriate where research questions are focussed on technological shifts and rates of technological development, but it is less useful when research questions are concerned with how firms perform and the nature of the competitive advantage that generates this performance.

Some studies have looked specifically at the firm level of analysis. For example, Rothaermel's (2000) study of firms in the biotechnology sector showed that collaboration can counter the impact of disruptive technologies on incumbent firms. Tripsas and Gavetti (2000) focussed on a single firm in their study of how the Polaroid Corporation attempted (and failed) to shift from analogue to digital imaging. In a similar vein Henderson and Clark (1990) and Rosenbloom and Christensen (1994) analysed the role of managerial mindsets and established business models in explaining why incumbent firms were unable to respond adequately to technological challenges from new entrants. Such studies are important contributions to our understanding of the dynamics of technological discontinuities, but they typically focus on internal barriers to change rather than considering the interplay between incumbent firms and new entrants in dealing with technological discontinuities and fighting for competitive advantage.

A historical perspective on the development of industries and firms offers the opportunity for us to consider the impact of such discontinuities at the firm level of analysis, while also considering the interplay between incumbent firms and new entrants. This is an area of particular interest when looking at how organisations adapt and create new resources to deal with changing environments through dynamic capabilities (Teece, Pisano & Shuen 1997) and ambidexterity (Gibson & Birkinshaw 2004) – where firms are simultaneously able to exploit existing resources and explore future sources of advantage. It also relates to the notion of time based competition where organisations need to speed up their change processes relative to environmental shifts, and those of their competitors (Eisenhardt 1989; Fine 1998).

In order to explore the interplay between technological discontinuities and competitive performance we have focused on the specialist area of Formula 1 (F1) motor racing. F1 provides a unique opportunity to explore the competitive performance of complex organisations. F1 firms design, manufacture and race their own cars and require a balance of technology, capital and human resources to achieve a very clear performance outcome. Furthermore the increasing levels of technological change which have characterised this sector (Read 1997; Wright 2001) provide an appropriately turbulent context in which to consider the changing nature of competitive advantage. F1 teams have to both develop their own innovations and imitate those of their competitors to remain competitive. It is this continual pressure to be aligned to the existing environment and to adapt to future environments that makes F1 a particularly rich context to study competitive performance and change. Indeed, F1 has been studied to better understand organisational phenomena such as innovation and technology transfer (Foxall & Johnston 1991), technology trajectories (Jenkins & Floyd 2001), brand marketing (Verity 2000), clusters and regional performance (Henry & Pinch 1999) and also to extract general managerial lessons from its highly competitive context (Jenkins 2004; Jenkins, Pasternak & West 2009).

In this study we focus on Grand Prix wins as the competitive outcome. The winning performance of F1 teams has a direct impact on their value as a business, both by providing sponsors with more exposure and by entitling the team to a greater proportion of the media royalties that are distributed on the basis of performance (Jenkins, Pasternak & West 2009).

Research Design

This paper is based on a detailed study of individual F1 teams or 'constructors' during the period 1950-2006. This time period is chosen as it was from 1950 that grand prix racing was brought under a consistent set of regulations to compete for an annual drivers and constructors world championship. It also allows us to identify and examine seven successive periods which are punctuated by technological change created by new regulations. We take a historical perspective to gain insight into the long-term dynamics of competitive advantage and technological discontinuities. This is a historical account of an industry in which outcomes can be measured and compared over time. We are looking for repeated patterns of industrial evolution that can only be observed at historical timescales (Fine, 1998). A historical perspective allows us to explore the changes and cycles which can occur in multiple levels of organising (Callinicos 1995). Historical accounts have been used to promote organisational and managerial insights into areas of technological development (Hargadon & Yellowlees, 2001; Cusumano et al, 1992) and managerial perspectives (Tripsas & Gavetti 2001). It also allows us to explore emergent principles and to examine the highly contextual relationships between exogenous discontinuities and firm level performance. Some of the best examples of historical theory development draw on single context cases (Allison 1971; Burgelman 1983).

The study utilises secondary data sources spanning a 57 year period. These include public archives, accounts in specialist books and periodicals, autobiographies and motorsport data records which feature information on race performance such as drivers, car types, qualifying times and positions, race times and positions. In addition, ten in-depth interviews were undertaken with team principals, technical directors and other influential individuals working within the teams during this time. The respondents were selected on the basis of their involvement with major innovations and technological changes in Formula 1. These interviews were conducted between 1998 and 2004 and were undertaken to explore a range of research questions all of which are connected to the broad remit of this paper. The interviews were focused on past events and therefore allowed the respondents to reflect more openly than in situations where contemporaneous interviews may necessitate 'impression management' (Hargadon & Yellowlees 2001). These interviews were transcribed and key sections of the transcript were coded and analysed using a grounded approach (Glaser & Strauss 1967). Emerging categories and concepts were related to the seven periods and enabled key issues and connections to be identified. Table 1 summarises the respondents, their involvement with particular F1 teams and the timing of the interviews.

INSERT TABLE 1 ABOUT HERE

The analysis is constructed in seven periods covering the history of F1 from its inception in 1950 until 2006. Each period is delineated by a major change in the regulations for F1 racing which created a technological discontinuity and, with it, the opportunity for a change in the basis of competitive advantage. In some instances the change heralded the demise of incumbent firms and the advent of innovative new entrants. The approach of using such exogenous regulatory interventions has been used to good effect as a basis for studying how organisations respond to discontinuous change in the railroad industry (Barr, Stimpert & Huff 1992).

These particular discontinuities are selected as they cover both a significant time period and demonstrate an impact on the basis of competitive advantage by shifting the relative position of the key competitors. The changes are defined by the regulatory body the Fédération Internationale de l'Automobile (FIA) – and have been introduced for reasons such as reducing costs, improving safety, increasing competition and keeping the technical criteria in line with external market trends. Table 2 provides a summary of the major regulatory changes used to define the periods in the study. As they are delineated by regulatory interventions the time periods are not uniform, but range from four to fifteen years. These proposed interventions were shared with two industry experts who confirmed their selection as being important milestones in the technological development of F1.

INSERT TABLE 2 ABOUT HERE

1950 – 1960: Engines, Italians and the entrance of the Garagistes.

This period describes a number of shifts in competitive superiority. It starts with the Italian dominance of the early 1950s based around large, 4.5 litre, twelve cylinder engines positioned at the front of the car. This dominance is threatened by the challenge of Mercedes Benz which ends with their withdrawal from motorsport following an accident at Le Mans. Ferrari, in particular, continue to dominate through to the late 1950s, but at this point a new threat emerges – the English constructors led by Cooper Cars.

The British Grand Prix on 13 May 1950 was the first event in the newly created World Drivers' Championship. It brought together a series of autonomous Grand Prix races across Europe and the USA under the auspices of the FIA. It was attended by King George VI and Queen Elizabeth and was referred to as 'Royal Silverstone' (Rendall 1993). Despite the patriotic theme of the event it was dominated by cars designed and built in Italy by Alfa Romeo, Maserati and Ferrari. All of these cars were designed with the engine in front of the driver and built within a relatively small area around Modena in the region of Emilia Romagna in north eastern Italy. These were primarily 'works' cars where the racing teams relied on the resources of their parent companies to fund their construction and development.

Through the 1930s and 1940s Grand Prix racing had been the domain of the large manufacturers such as Alfa Romeo, Mercedes and Auto Union, often supported by government funding. Specialist operations, distinct from the core business, created the F1 racing cars. However, the actual racing activity was often undertaken by independent organisations using the nomenclature of thoroughbred horse stables – 'scuderia' in Italy and 'écurie' in France (Lawrence 1998). For example, Scuderia Ferrari (SF), founded by former Alfa Romeo works driver, Enzo Ferrari, began life in Modena, Italy in November 1929. SF focused on the preparation and competition of racing cars for enthusiasts, thereby creating one of the first specialist motorsport companies. In Germany both Auto Union and Mercedes had been banned from racing following WW2. However with the creation of new F1 regulations in 1950 and a need to develop a strong line up of racing cars, Germany were readmitted and Mercedes started to plan their return (Rendall 2000). The 'works' cars prepared and raced by the factory or their appointed scuderia also competed with privately entered cars:

purchased and raced by individuals who were either independently wealthy or had a wealthy benefactor. At the San Remo Grand Prix of 1950, there were six works Ferraris, six works Maseratis, nine privately entered Maseratis, and a single works Alfa Romeo, which subsequently won the event (Lawrence 1998).

The early 1950s were dominated by Alfa Romeo's supercharged Alfetta 158 which had been racing since before WW2 and had won every race entered between 1947 and 1951. However the supercharged cars used pre-war engine designs that had very poor fuel consumption and were at the end of their development cycle (Rendall 2000). In 1952 Alfa Romeo withdrew from F1.

In 1954 Mercedes Benz entered F1 with their own factory based team. The Mercedes 196 Streamliner used state of the art fuel injection and laid the engine on its side to keep the centre of gravity as low as possible (Lawrence, 1998). They were first and second in their first race: the French Grand Prix of 4th July. However Mercedes' path to F1 domination was halted in 1955 when motor racing's worst ever accident claimed the lives of 81 spectators and driver Pierre Levegh. Levegh's Mercedes sports car crashed into the crowd at the Le Mans 24-hour sportscar race. Mercedes Benz withdrew from motor racing at the end of the year.

After the withdrawal of Mercedes, Maserati and Ferrari resumed their rivalry, with Ferrari dominating in 1956. Difficult financial conditions in Italy led Maserati to pull out of F1 in 1957 (Beck-Burridge & Walton 2000). The predominant design philosophy during this period was to position the engine in front of the driver, primarily because of the problem of locating a large 4.5 litre engine. The leading designers of the time were engineers such as Alberto Massimino (Alfa Romeo/Ferrari/Maserati), Giaocchino Colombo (Ferrari/Maserati/Alfa Romeo), Carlo Chiti (Ferrari, Alfa Romeo), Vittorio Jano (Lancia/Ferrari). All of them were skilled engineers, but their background and primary expertise was in engine design, underlining the Italian philosophy that car performance was based around the power of the engine.

Throughout the 1950s a number of British motoring clubs had emerged racing hand-built cars assembled from various components of standard cars and motorcycles on the many disused airfields in the UK following WW2. These included locations such as Silverstone in Northamptonshire, which was an RAF Operational Training Unit, and Snetterton in Norfolk, the wartime base of the 96^{th} USAF bomber group. Many of the cars used in these clubs were manufactured by the Cooper Car Company run by father and son Charles and John Cooper. They used suspension components from the Fiat Topolino car to construct a chassis, along with a range of scrap materials from air-raid shelters, aircraft and boat engines, for this reason they were described as ‘cunning blacksmiths’ (Lawrence 1998). Cooper used a single cylinder JAP motorbike engine to provide the power, the short chain drive to the rear wheels requiring that the engine was located in a ‘mid’ position, directly behind the driver (Jones 1996). These cars were hugely successful and by the end of 1951 Cooper were producing a car a week, an unprecedented volume for a racing car manufacturer (Lawrence 1998).

From these early beginnings Cooper progressed to F2. In F2 a 2.0 litre engine was used, but often the cars raced alongside the larger, more powerful 4.5 litre F1 cars. In

1958 the first race of the year, the Argentine GP, was won by Stirling Moss in a Cooper Climax, beating the works Ferraris. This victory was the first time a mid-engine F2 car had won an F1 Grand Prix. In the same year a new British constructor made its debut at Monaco. It was an inauspicious beginning for Lotus: they started at the back of the grid, one car retired and the other finished last, 13 laps behind the leader. Despite the fact that the British built, mid engine Coopers were beating the competition, Lotus founder Chapman persevered with front engine layout, and it was not until he imitated the Cooper concept to create the mid engine Lotus 18 in 1960 that their fortunes changed (Crombac 1986). The Lotus 18 has been described as a ‘scientific’ Cooper (Lawrence 1998) since Chapman had used calculus to create a well-designed space-frame. He explained why the design of a racing car needed to start with the chassis rather than the engine in the following terms:

"If the starting point is the car rather than the engine, the point at which all "grip" is lost can be deferred by design that is aimed at keeping as much rubber on the road as possible. The limit of adhesion is extended by independent suspension to all four wheels, which helps to distribute the weight equally and by designing a car that is not only light, and structurally efficient, but also "wind cheating". (Chapman 1958, p72)

Chapman’s philosophy put him in direct contradiction with the Italian F1 teams such as Ferrari. Driver Nigel Mansell, who had worked for both organisations observed: *"Enzo Ferrari believed that the engine was the most important part of the racing car; Colin* [Chapman] *believed it was the chassis."* (Mansell 1996, p126). Enzo Ferrari initially resisted the trend being pioneered by the British constructors, whom he referred to as *‘garagistes’* (Couldwell 2000) or *‘assemblatori’* (Beck-Burridge &

Walton 2000), using the analogy that the horse had always pulled not pushed the cart (Nye 1977).

During this period a number of factors can be discerned regarding the characteristics of technological development and the distinctive trajectories followed by different firms. First is the dominant design of the Italian cluster based on powerful, well designed, proprietary engines, an approach that was also followed by Mercedes prior to its withdrawal from F1 racing in 1955. During this period an alternative design philosophy emerged from the British constructors and, while it did not achieve competitive superiority during this period, it established its race winning potential.

Many of the firms which were evident in 1950-1960 such as Alfa Romeo, Maserati, Vanwall and, to some extent Cooper, were unable to successfully continue beyond this period. Of the firms that survived, Ferrari and Lotus went on to become two of the most successful Grand Prix teams of the 57 year period. It was in this formative period that both of them established the managerial and design philosophies that were to sustain these organisations over multiple discontinuities.

INSERT TABLE 3 ABOUT HERE

1961-1965: Chassis Technology dominates

The second period involved a shift away from the dominant design of engine based development to one which emphasized the construction of the chassis. New regulations introduced in 1961 focused on smaller power units which encouraged the technological shift to mid, as opposed to front, engine cars. This was partly in response to the need to encourage new entrants into F1 as it allowed cars based on the smaller F2 regulations to compete in F1. The established engine manufacturers such as Ferrari, BRM and Coventry Climax all developed new engines to deal with the change in regulations. The change also encouraged the introduction of two major new entrants, Honda and Porsche, who both developed F1 cars around new 1.5 litre power units.

By 1961 the dominance of the mid engine cars was clear, and Ferrari had to build such a design themselves, which they did using a highly effective V6 engine. The Dino 156 or ‘shark nose’ dominated 1961 and gave Ferrari a further world title. However during 1961 Lotus was working on a new design of racing car in which Colin Chapman took chassis development a stage further with the Lotus 25 monocoque chassis, first raced in 1962. The monocoque concept remains the dominant design to this day, and involves the chassis being formed as a structure fabricated from sheet material (aluminum was the favoured option at the time). This made the monocoque lighter and more rigid than the traditional tubular space-frame. The monocoque was not a new concept, since it had been the basis for aircraft design for many years (Vincenti 1990), but it was revolutionary for single seat racecars and was derived from Chapman’s parallel interest in aircraft design (Crombac, 1986). The Lotus 25 and its successor, the Lotus 33, won the world championship for Lotus in 1963 and 1965. The advances Lotus made in chassis construction were in an area that was a low priority to Ferrari (Nye 1977) and, as a result, they became increasingly uncompetitive and had to resort to imitating their British competitors. In 1964 the Ferrari 158 was launched with a similar monocoque type chassis to the Lotus 25 of 1962.

The most popular engines amongst the British constructors during this period were those produced by Coventry Climax. Climax produced powered water pumps for fire engines which required engines that were powerful, compact and light, the ideal combination for a racing car application. A total of 697 'racing fire-pump' engines were built (Beck-Burridge & Walton 2000) and they enjoyed significant success on the track when combined with a Cooper or Lotus chassis. However in 1963 the FIA announced that the engine regulations would change from 1 January 1966, with an increase in capacity from 1500cc to 3000cc for a normally aspirated engine or 1500cc for a turbo-charged one. Coventry Climax made the decision in 1965 not to develop a 3000cc engine on the basis that the costs would be prohibitive. This left Cooper, Lotus and other constructors such as Brabham looking for an engine supplier from 1966 onward.

This period represents a transition from the earlier technologies of the 1950s, which drew on pre-war design philosophies, to modern concepts in racing car design related to the use of lightweight materials, low drag design and aerodynamics. This shift embodied both architectural and radical innovation (Henderson & Clark 1990) where new component areas of technology are both introduced (radical) and rearranged (architectural) in a way that proved challenging for many incumbents to both recognize and respond to. These innovative shifts meant that certain firms only made short appearances during this transitional period (Porsche and Honda) and others which had been strong in the previous period now struggled to remain competitive (Cooper). In contrast, other firms were finding greater momentum and competitive success (BRM), there were new entrants who embraced these new approaches (Brabham) and well-established rivals, Ferrari and Lotus had been able to both stimulate and adapt to these changes. These different patterns of performance suggest very different resource endowments and different dynamic capabilities within these firms.

INSERT TABLE 4 ABOUT HERE

1966 – 1980: The Ford DFV, the Ferrari Flat 12 and ground-effect

The third period contains one of the most influential events in the history of F1: The Ford DFV engine was introduced in response to changes in the regulations on engine size for 1966. The impact of this innovation was to create an entire swathe of new entrants, all based in the UK and all focusing on chassis and aerodynamic technologies. It also presented a major threat to those teams who had developed bespoke expertise in engine design and development.

The Ford DFV 'V8'engine was first used competitively in a Lotus 49 at the Dutch Grand Prix in 1967 and caused a sensation by winning its first race (Robson 1999). The concept was not simply about a better performing engine; the engine was also used as a critical part of the structure, substituting for a major section of the chassis, to create a lighter, high-powered racecar. The Ford DFV was created by a joint venture between the Ford Motor Company, who funded the project, Cosworth Engineering, who designed and built the engine and Lotus Cars who designed and built the Lotus 49 around the engine. Given the extreme competitiveness of the engine Ford made the decision not to give Lotus exclusive use of the engine and made it available to other teams in 1968. It quickly became the technological imperative for all the constructors:

"*...for ten years that engine pretty well ruled the roost. Anyone with enough money, and in the first year*[1968] *it was only £7,500, went to Cosworth and came* *away with an engine that was capable of winning the next race. That went on for many years which is the reason why there are so many British Formula One teams,."* (Ken Tyrrell, F1 Team Principal 1968-1998).

In 1968 Lotus was joined by McLaren and Matra in using the Ford DFV. The Brabham team followed in 1969. During the early seventies F1 was dominated by the Ford powered 'kit-car'. In this case 'the kit' included the Ford DFV engine, manufactured by Cosworth Engineering, and the gearbox built by Hewland Engineering (Beck-Burridge and Walton 2000) with the chassis and suspension designed and manufactured by the constructor. In 1969 and 1973 a car with a Ford DFV engine won every Grand Prix, the only time in the history of F1 that a single engine totally dominated.

With these light, powerful cars, designers were increasingly searching for ways to improve grip – the extent to which the car is able to transfer power from the engine to speed on the track. One line of development was the application of aerodynamic principles using aerofoils or 'wings'. If driver skill is excluded, the performance of a racing car is a function of three factors: the power created by the engine and transmission, the drag of the car moving through the air and the grip provided by the tyres and suspension system to allow the power to be applied to the track (Wright 2001). Wings on F1 cars enhanced grip by generating downforce from forward motion, the opposite effect of the lift generated by an aircraft wing. Wings were quickly adopted in F1 with Lotus using front wings made from inverted helicopter blades at the Monaco Grand Prix on 26 May 1968 (Crombac 1986). Both Ferrari and Brabham then introduced cars with rear aerofoils at the Belgian Grand Prix held at

Spa-Francorchamps on 9 June 1968 (Rendall 1993). This innovation diffused quickly throughout the teams and by 22 September 1968, at the Canadian Grand Prix held at St Jovite, every car on the grid was using some form of wing.

The availability and low cost of the Ford DFV meant that F1 teams, like Ferrari and BRM, who were vertically integrated - building their own engines and gearboxes - were at a disadvantage. In response to the proposed regulation changes of 1966 Ferrari had developed their Flat-12 engine, originally designed by Mauro Forghieri as an aircraft engine. This had 12 horizontally opposed cylinders creating a wide, flat power unit. The late sixties were a difficult period for Ferrari, both financially and technologically. In 1969 it 'merged' with Italian automotive manufacturer Fiat. Fiat took a 50% stake in Ferrari which provided a huge injection of cash to support Ferrari's research and development activities. This allowed for the construction of a private Grand Prix circuit at Fiorano, close to the SF factory at Maranello. The technical team used this facility to engage in a period of intensive development focusing on the Flat-12 engine.

These increased resources and development time enabled Ferrari to leverage its way back to the top of F1, winning world championships in 1975, 1976 and 1977. Ferrari's success led many of the Ford DFV teams to look to alternative sources of power and, in particular, to 12 cylinder engines. In 1975 Brabham reached an agreement with Alfa Romeo to supply a Flat-12 engine developed by engine specialist Carlo Chiti, who had formerly worked for Ferrari. In contrast, two other constructors, Tyrrell and Lotus, retained the Ford DFV, but developed more radical chassis designs. Tyrrell created a six-wheel car with four small wheels at the front designed to reduce drag and enhance grip at the front of the car. In contrast, Lotus undertook a longer term project that was to emphatically establish the importance of aerodynamics for F1 performance.

In 1974 the unusually poor performance of the Lotus team led owner Colin Chapman to ask Technical Director, Tony Rudd, to revisit the entire concept of a racecar to see where performance gains could be made. Rudd, along with aerodynamicist, Peter Wright, explored the prospect of producing ground-effect in an F1 car. Ground-effect had been developed as a theoretical concept, but its practical application in F1 was unproven. It was achieved by a breakthrough in using 'skirts' -- strips down the sides of the car that effectively sealed the underbody area – and, as with many great discoveries, it came almost by accident.

"...the [wind-tunnel] *model was so decrepit we started getting variable results. It would be modified so often, it was made of card and plastic and clay and tape and what have you. We got inconsistent results and we couldn't figure out why and then I noticed that the side pods were sagging. We thought maybe it's the gap at the edge* [between the car and the ground], *so we put some card down the edge in a little tiny gap and wumph! We couldn't believe it! We had to re-do* [the test] *four times before we believed it."* (Peter Wright, Former Lotus Aerodynamicist.)

The Lotus design proved to be the most effective technological change in breaking Ferrari's dominance of the mid-seventies. The Lotus 79 won the 1978 world championship establishing ground-effect technology as a dominant concept in F1 and many constructors subsequently attempted to imitate the design. Since the majority of constructors used the same engine configuration as Lotus [Ford DFV], their imitations focused on a re-design of the chassis. However, Ferrari's commitment to a Flat-12 engine meant that it was unable to create the narrow chassis profile needed to locate the ground-effect venturi (aerodynamically shaped tunnels which created the low pressure area needed for ground-effect) on either side of the engine. The same problem also applied to Brabham which had shifted to the Alfa Romeo Flat-12 in 1976. In contrast the narrow Ford V8 was ideally suited to this application.

This problem prompted Brabham's Technical Director to position a large fan at the rear of the car in an attempt to create artificial ground-effect by sucking the air from underneath the car. The Brabham BT46B 'fan-car' was a product of this innovative period and won the Swedish Grand Prix in 1978. Ultimately, it was banned because it was deemed to be outside of the regulations and due to the potential danger of debris being sucked through the fan and hitting following cars.

As Brabham was attempting to find ways to achieve ground-effect with a Flat-12 engine, Ferrari appeared to ignore the phenomena and concentrated on developing its engine and chassis along the same lines as 1974. However, its efforts left Ferrari hopelessly uncompetitive against the ground-effect cars. "*Maranello's* [location of Ferrari factory] *Flat-12, still a magnificent racing engine, is incompatible with modern chassis.* [Drivers] *Villeneuve and Scheckter were competing in yesterday's cars.*" Roebuck (1980). It was not until the appointment of Dr Harvey Postlethwaite, an English engineer who had already designed ground-effect cars, that the extent of Ferrari's myopia became clear. "*Everyone else had them* [ground-effect aerodynamics] *for years, but until I arrived* [1981] *it was quite firmly believed that they didn't exist.*" (Roebuck 1999, p29)

Williams Grand Prix Engineering designer, Patrick Head, imitated the ground-effect concept developed by Lotus. It proved to be a simple, but highly effective interpretation of the concept. As the Lotus reached the technical limit of the ground-effect concept, the Williams FW07 was considered to be the optimal application of the concept to a F1 car. Williams' development of the technology was undertaken with an emphasis on simplicity and reliability. Williams developed a championship winning car for 1980 in the FW07B, a car which effectively took them from the back to the front of the F1 grid.

Although ground-effect had created significant advances in performance, safety concerns were increasing due to higher cornering speeds and situations when a collision would send the car airborne when the ground-effect downforce was suddenly lost (Watkins, 1996). In 1980 the FIA announced that sliding skirts would be banned from 1981 onwards, and followed this up two years later by determining that all cars would have totally flat underbodies. The ground-effect revolution was over.

The change in the competitive environment created by the Ford DFV engine significantly reduced barriers to entry and led to a flood of new entrants who were able to design and manufacture the chassis and aerodynamic elements of F1 cars. It meant that a larger number of firms were able to produce Grand Prix winning cars and, as a consequence, this period saw the highest number of different Grand Prix winners as shown in Table 5. The period also underlined the evolutionary nature of innovation across competitors with the Ford DFV creating the need for improved grip from aerodynamics, which in turn led Ferrari to respond through improvements to the Flat-

12 engine and, ultimately, to the development of ground-effect aerodynamics by Lotus.

The introduction of the Ford DFV stimulated the development of new capabilities, most notably around the use of aerodynamics and specialist infrastructure such as moving-ground wind tunnels. Perhaps the most surprising aspect of this period was that although it created many new entrants, it did not cause the immediate demise of incumbent firms. Ferrari, in particular, was challenged by these new technologies and, yet, its commitment to engine development throughout the Flat-12 design meant that it remained competitive and enjoyed one of its most successful periods between 1975 and 1979. We therefore see two areas of capability – engine development and aerodynamics working off each other in order to establish supremacy, but neither being sufficient in isolation and therefore allowing different balances of these capabilities at the firm level.

INSERT TABLE 5 ABOUT HERE

1981 – 1988: Composites and turbo-charging

This period saw the development of a new area of engine technology which, prior to this point, had been regarded as an uncompetitive option. Renault had won the first ever Grand Prix (as opposed to F1 race) in 1906 and had a strong racing heritage to draw on. Its entry in 1977 with a turbo-charged car was greeted with both surprise and cynicism by the incumbent teams. It was their belief that Renault's technology would not challenge the established normally aspirated engines.

The development of ground-effect aerodynamics in the previous period provided the impetus for a number of constructors to look at alternative materials to use in the construction of the car. Carbon composite had developed out of a variety of aerospace initiatives in the USA, the UK and Japan into a new generation of super-stiff, lightweight materials by the 1960s (McBeath 2000). In 1976 it was used by Brabham in the construction of brake discs. Team Lotus had also become aware of the possibilities of this new material and developed a hand laid carbon composite monocoque for the Lotus 81 which was first raced in March 1981. It was followed a month later by the McLaren MP4/1 which became the dominant design in F1.

John Barnard, McLaren's Technical Director, wanted to create a complete molded monocoque but, in order to do so, a rapid shift in the current approach to manufacturing composite materials was required. Until that time, carbon-fibre had been used in small sections or had been hand-laminated, as was the case with the Lotus (Crombac 1986). The advantage of molding was that it would provide a more complete composite structure that would be stronger and therefore could be of a lighter construction. However the molding process required access to a large specialist oven or autoclave. Despite leading-edge work being undertaken in the UK aerospace industry, there was no interest in this kind of project from the established UK companies and Barnard had to look further afield, eventually finding aerospace technology firm Hercules in Salt Lake City, USA. The molding process enabled the completion of the first Project Four McLaren: the MP4/1 that was raced in April 1981. The fact that McLaren had developed the first molded monocoque gave it a major technological advantage that contributed to its winning the 1984 and 1985 World

Championships. More than twenty years later every F1 car is still constructed using a molded carbon composite monocoque.

In 1977 Renault had entered F1 as a manufacturer developing both the chassis and engine themselves. Unusually at the time Renault had decided to build a 1.5 litre turbocharged engine, a specification that had existed in the regulations since 1966, but had not been considered a competitive option. It took Renault until 1979 to win a Grand Prix and, although it was unable to win a world championship before withdrawing from F1 in 1985, it had performed sufficiently well to encourage other manufacturers such as Ferrari, Honda, Porsche and BMW to develop their own turbocharged F1 engines.

Honda entered F1 as an engine manufacturer in 1983 in partnership with Williams, having previously entered as a full manufacturer to take advantage of the regulation changes in 1961 (Hilton, 1989). Importantly the engines were supported by a significant commitment from Honda in terms of both people and resources. They used the relationship as an opportunity to develop some of their most talented engineers and to transfer F1 design and development capabilities to their production car programme. In the mid eighties the Williams/Honda partnership was very successful, but at the end of 1986 it moved to supply both McLaren and Lotus for the 1987 season. By the end of the year it had dropped Lotus to focus solely on McLaren.

In 1988 the Honda powered McLaren MP4/4 car was the fastest and most reliable car on the circuit, winning an unprecedented 15 out of 16 Grand Prix.

Escalation in the performance of the turbo-charged engines was causing concerns both in terms of safety and costs. Teams were using a single engine specifically for qualifying for the race in excess of 1200 horsepower; these engines were designed to last for only a few laps and an alternative specification engine would be used for the race itself. Various regulations had been introduced to reduce the power and performance of the turbo engines, but their performance and costs were rising inexorably. In 1987 the FIA made the decision that, from the 1989 season on, turbo engines would be banned and all power units would be normally aspirated.

This period was in many ways the most significant in terms of shifting the balance from one set of dominant teams (Lotus, Brabham, Tyrrell) to a group of new entrants (Williams, Renault) and in particular new engine suppliers (Porsche, Honda, BMW). Lotus went into terminal demise, marking the end of a team that had successfully competed across four competitive periods. For many the reason for its inability to adapt to the turbo era was the loss of its entrepreneurial founder, Colin Chapman, who had died from a heart attack in 1982. In contrast, a number of teams were able to make a very successful transition to the turbo era: Ferrari had been developing turbo technology since Renault entered F1 in 1977 and McLaren was particularly successful in working with new suppliers such as Porsche and Honda to maintain its competitive position.

INSERT TABLE 6 ABOUT HERE

1989 – 1993: Driver aids and the gizmo car

This period saw the continued domination of McLaren which continued its success from the previous period by finding new engine partners following the withdrawal of

Honda. However, sources of competitive advantage shifted from the engine to control systems and related technologies, placing the emphasis on enhancing the ability of the car to respond to the various inputs provided by the driver.

The McLaren Honda combination dominated F1 from 1988 through 1991. However, in September 1992, Honda confirmed that it was pulling out of F1 racing, bringing its domination to an end. Williams had resurrected its fortunes by creating an alliance with Renault to supply engines and focussed on creating competitive advantage through a range of innovations on the car. These included the adoption of semi-automatic gearboxes (originally developed by Ferrari), drive-by-wire technology and its own active suspension system (Lotus had also developed its own system at the same time). As a senior manager at Williams F1 put it:

"*I think we actually were better able to exploit the technology that was available and led that technology revolution. We were better able to exploit it to the full, before the others caught up… it wasn't just one thing but a combination of ten things, each one giving you another 200/300th of a second, if you add them up you a get a couple of seconds of advantage*." (David Williams, General Manager Williams F1 1999).

The Williams FW14B of 1992 won the first eight Grand Prix of the season which led to a second successful period for the constructor. However, despite Williams' success with what was often referred to as their 'gizmo' car, there was increasing concern that technology was replacing the skill of the driver. While F1 was undoubtedly a technologically driven form of competition, many felt it had gone too far in negating the role of the driver and other human factors. This led the FIA to introduce regulations in 1994 which banned the various forms of active suspension systems, driver aids such as traction and launch control and re-introduced refuelling through pit-stops made during the race.

For Ferrari this proved to be a particularly difficult period. Enzo Ferrari passed away in 1988 at the age of 90. He had remained highly influential in the operation of the team up to his death and his passing meant that control of the team passed to Fiat who installed a succession of their senior managers in the team, none of whom appeared to grasp the essentials of how different an F1 team was from an automotive manufacturer.

Although this particular period was relatively short, it was significant in the history of F1 since it involved a shift away from the core technology components of engine, chassis and aerodynamics to bring greater emphasis on the integrating technologies of control systems which linked the component areas. These systems included, for example, 'fly-by-wire' throttle systems, which enhance the link between the driver and the power of the engine, and active suspension systems, which enhance the link between chassis dynamics and aerodynamics. In this sense the period represents a highly significant discontinuity which is underlined by the marked shift in competitive performance – notably the growing domination of McLaren and Williams and the relative decline of Ferrari.

INSERT TABLE 7 ABOUT HERE

1994 – 1997: Growth

The subsequent short period underlined a different kind of transition for F1. The banning of many of the driver aids from the start of 1994 meant that the basis of advantage shifted again. The emphasis moved to engine power as the critical element and Williams' partnership with BMW, and Benetton's with Renault, meant that they moved to dominant positions. During this time both McLaren and Ferrari were in the process of rebuilding their organisations, McLaren through a new partnership with Mercedes Benz, and Ferrari moving to a more integrated and co-located approach for the design and manufacture of their cars.

1994 was a disastrous year for F1 with the deaths of drivers Roland Ratzenberger and Ayrton Senna at the San Marino Grand Prix. Images of Senna's fatal accident were shown across the world and prompted widespread condemnation of F1 and its safety standards. Ironically worldwide outrage also created global exposure for F1 and viewing figures climbed significantly through the 1990s with the F1 teams increasing in size by a factor of three or four due to the increased revenue streams (Collings 2002).

In 1995 the Benetton team eclipsed the Williams' domination. Benetton had developed a car using many of the technological innovations used by Williams (with the help of ex-Williams designer, Ross Brawn). In addition Renault's ambitions to match Honda's previous domination of the sport as an engine supplier from 1986 to 1991 led it to supply Benetton, as well as Williams, with its engines. 1995 was the year in which Benetton and Michael Schumacher broke the three year run of success for the Williams team.

This period represents a further transition between the focus on innovative control systems of the previous period to a more conservative ethos where the design regulations further reduced the opportunity for more radical designs. The amount of funding for F1 increased significantly, thereby increasing investment in facilities and technologies which, in turn, underlined the commitment to particular technological trajectories and related investment patterns. This was a period of strong growth and also convergence to a dominant design. The organisations placed greater emphasis on getting existing technological systems to work more reliably as opposed to ‘changing the rules of the game’ through more radical innovations.

INSERT TABLE 8 ABOUT HERE

1998 – 2006: Integrated operations and the car manufacturers

The final period was characterised by a further convergence in dominant design, driven by further increases in investment by the car manufacturers and incremental regulatory changes in an attempt to reduce variation in performance and also costs.

Towards the end of the 1990s a shift in ownership began to take place. Renault acquired the Benetton team in 2001. DaimlerChrysler bought 40% of McLaren’s holding company and a similar proportion of their specialist engine supplier Ilmor. Both Honda and Toyota also explored the potential of creating their own F1 teams. Toyota entered F1 in 2002 and Honda became a full constructor in 2006 when it acquired the BAR racing team.

This period was characterised in the first part by Ferrari's comeback to dominate F1 racing once again. In 1996 Ferrari recruited two times world champion Michael Schumacher from the Benetton team. It followed this appointment by hiring the two main members of the technical team at Benetton. As had been the case at Benetton, Ferrari split the technical roles between a chief designer, Rory Byrne, who had overall responsibility for designing the car, and Ross Brawn, who managed the entire technical operation. The new arrangement also meant that Byrne and Brawn faced the task of building a design department from scratch which initially included around 50 people who were based in Italy. One of the most important tasks for the new team was to take advantage of the fact that Ferrari made its own engines by integrating the design of the engine, chassis and aerodynamics as early in the process as possible. Ferrari's historic emphasis on the engine was replaced by a focus on integration, summarised by Ross Brawn as follows: *"it's not an engine, it's not an aero-package it's not a chassis. It's a Ferrari"*. (Ross Brawn, Ferrari Technical Director 1987-2006).

The rejuvenated team provided the basis for Michael Schumacher's dominance of F1. In 2000 Ferrari secured both championships, 21 years after its last world championship victory in 1979. In 2002 Schumacher and Ferrari were so dominant that a series of regulation changes was introduced to try to make F1 racing more competitive.

In 2005 and 2006 the competition became much stronger and, despite being competitive, Ferrari lost the drivers' and constructors' titles to Renault (formerly Benetton). Renault benefited from the rising talent of Fernando Alonso who proved a match for Schumacher. In 2005 changes in the regulations meant that tyres were required to last for the whole race which favoured the Michelin technology used by Renault and the damping device it had fitted to the car to improve the performance of their tyres. Ferrari was left struggling towards the end of the race on its Bridgestone tyres. In 2006 a more drastic change to the regulations meant that the constructors had to shift from 3.5 litre V10 engines to smaller V8's. Despite a much smaller budget than some of its major rivals, Renault F1 was able to create a very effective F1 package with the engine, car and tyres working together to outperform the major competition.

In overall terms this period was characterised by the dominance of Ferrari, the only F1 team who had been involved since the inception of F1 in 1950. Ferrari's dominance was in part due to their ability to transform the organisation from one which had been a technological philosophy that focused on the engine as the primary component of the system, to one which had become far more balanced between the core components of engine, chassis and aerodynamics. In many ways this period could be characterised as a 'back to basics' shift in which firms that focused on the core elements and optimised their integrated performance were most likely to be successful.

INSERT TABLE 9 ABOUT HERE

Discussion

This study identified a total of 27 firms which achieved Grand Prix wins during a 57 year period. Of these more than half (15) only did so during one of the periods delineated by the regulatory changes identified in Table 2. An analysis of the performance of the most successful firms over the entire period (Table 10) indicates that only four of the 27 teams - Ferrari, McLaren, Williams and Lotus - were able to win Grand Prix in more than three periods.

INSERT TABLE 10 ABOUT HERE

The impact of these regulatory discontinuities on the competitive population was more significant in some cases than others. In 1966 – 1980 there were a total of 12 new Grand Prix winners compared to the previous period; whereas in 1989 – 1993 there were none. Ten of the 18 Grand Prix winners in 1966 to 1980 failed to continue their success into the following period; whereas all of the five teams winning in 1989 – 1993 did so. It can therefore be discerned that the identified discontinuities had differing effects on the competitive population at different points in time. In particular the regulatory changes made in 1961, 1966, 1981 and 1998 appeared to have the most significant impact on competitive dynamics and the performance of individual firms.

At the industry level these findings support Anderson and Tushman's (1990) assertion that the entry of new firms during a period of ferment is contingent on how the discontinuity impacts existing competences, competence destroying discontinuities creating a greater influx of new entrants. We see evidence here of some discontinuities creating far more new entrants than others. It is also clear from this study that exogenous discontinuities create shifts in the relative competitive performance of incumbents, the resource configurations of some firms proving to be less effective in winning races.. Figure 1 presents a graphical illustration of the performance of the top three teams in each time period from 1950 – 2006.

INSERT FIGURE 1 ABOUT HERE

In the first period, 1950-1960, firms such as Alfa Romeo, Maserati, Mercedes Benz and Vanwall had their only Grand Prix wins, and Cooper enjoyed 13 of their 16 Grand Prix victories during this time. Similarly in 1961-1966 BRM scored 11 of their 16 victories and both Porsche and Honda were only successful as full manufacturers in this period alone (although Honda later returned in 2006). From 1966-1980 Lotus were particularly dominant as were McLaren, Tyrrell, and Brabham. Many firms enjoyed a single Grand Prix victory during this period including Shadow, Hesketh and Penske, all attributable to the availability of the Ford DFV engine. Renault's entry using turbo technology created an important technological shift during the 1981-1988 period which also saw the further ascension of McLaren and Williams, whereas 1994-1997 saw the rise of the Benetton team. In 1998–2006 Renault became a strong challenger to Ferrari and McLaren who had largely sustained their position from the previous period.

Although there is evidence that particular firms dominate a time period and then fail to adapt to new technological environments, we can also identify firms that have been able to adapt over successive time periods. In some instances, their success extended over four or five periods as was the case for Lotus from 1950 through 1988, for McLaren from 1966 through 2006, and for Williams from 1966 through 2006. In other cases, teams managed to sustain their winning streaks for two or three periods as for Cooper and BRM (1950–1980), Tyrrell and Ligier (1966–1988) and Benetton (1981–1997). These patterns suggest that a limited number of firms can deal with certain kinds of technological discontinuities more effectively than others. There are a number of potential explanations for this finding. First, the type of discontinuity may be framed within an established broad technological trajectory (Jenkins & Floyd, 2001), making it less disruptive for firms that have a range of capabilities within this trajectory, such as chassis construction and aerodynamics in the case of Lotus, composite manufacturer and recruiting bespoke engine partners in the case of McLaren, and systems integration in the case of Williams. A second and potentially complementary explanation is that the architectural knowledge of these firms is sufficiently 'loose' to enable them to adapt across particular kinds of discontinuities, the implication being that these firms are more adaptable and less likely to develop the 'core rigidities' referred to by Leonard-Barton (1995). Such an explanation infers that such firms may have a broader absorptive capacity (Cohen & Levinthal, 1990) allowing them to recognise radical innovations and their implications more easily than other firms, suggesting that they have a greater capacity for building dynamic capabilities during these periods.

The most intriguing case is that of Ferrari which was able to remain in the top three places in every time period, suggesting that some firms may hold unique resources that enable them to remain competitive through many different technological regimes. Ferrari dominated the first and last periods of this study with the number of overall Grand Prix wins being almost twice that of its closest competitor. However, in the periods 1961-65, 1981-88 and 1989-93 Ferrari's performance was relatively poor. This historical pattern suggests a different kind of adaptation than that observed in those firms whose technological trajectories enable them to adapt between periods. Ferrari's adaptation appears to be more radical and more emphatic in terms of achieving competitive advantage, although it made its shift over an extended period of time. This is particularly evident in the shift between 1950-1960 and 1961-1965 and also between 1981-1988 and 1998-2006, where Ferrari was able to survive between periods when its major competitors did not.

One potential explanation is that Ferrari is a truly 'ambidextrous' organisation (Gibson & Birkinshaw 2004): they are able to simultaneously align to their existing environment and adapt to changes created by discontinuities. However if we consider the Ferrari story there are several examples that suggest it struggled to adapt to changes such as the monocoque chassis and ground-effect aerodynamics, not characteristics that would be associated with a firm which is identifying and developing such new concepts in parallel with existing technologies. An alternative explanation is that Ferrari's strength of resources such as finance (from Fiat), the Ferrari brand and its political skills in working with the regulatory body – the FIA - allowing it to better anticipate and influence the implementation of these changes (Yates, 1991) - enabled it to better weather these changes than less well endowed organisations. Ferrari did adapt but often not as fast as other firms and often in ways that required greater levels of organisational upheaval and change.

Our findings suggest that there are two distinct sets of resources at play when organisations are able to sustain their performance through technological discontinuities. The first set allows for adaptation and change of their existing resource base through dynamic capabilities (Teece, Pisano, & Shuen 1997) but the second is a set of sustaining capabilities which provide the organisation with the space and time to make these changes and which are not available to other competitors. This could be described as a form of organisational slack (Cyert & March 1963), where resources exist in excess of current needs to provide a cushion against environmental jolts. However, the phenomenon we discern here is distinct in that it not only provides a buffer protecting the technical core from the environment (Thompson 1967) but also requires a change in the technical trajectory and related resource configurations to meet these environmental changes. In this sense we see a combination of sustaining resources which are combined with dynamic capabilities in order to create the transformation needed to change the basis of competitive advantage. Sustaining capabilities give the organisation additional time to adapt relative to their competitors. In effect they enable the organisation to slow down the clockspeed of the industry (Fine, 1998) relative to their own speed of change. This study suggests that, over the long term, dynamic capability is insufficient in isolation to break through technological discontinuities. Firms also need sustaining capabilities to provide the time and space necessary for them to reconfigure their resource base and to respond to new competitors.

Our study is inevitably limited by the particularly specialist context that we have chosen. Our view is that it has allowed us to explore phenomena which otherwise would have been obscured by lack of data and transparency, however the idiosyncratic nature of this industry means that any attempts to generalise from this study should be made with care. Our data has also mainly been taken from the public domain suggesting that there are private aspects to firm level performance that we have not been able to access.

Conclusion

This paper has used a historical perspective on Formula 1 motor racing to consider the interplay between technological discontinuities and competitive performance over a 57 year period. Our findings are consistent with previous research that suggests that incumbent firms are often unable to adapt to the impact of exogenous shocks and that such shocks create opportunities for an influx of new entrants. The evolutionary nature of our data allowed us to observe more subtle shifts in relative competitive performance between incumbents. The central contribution of the study is the identification of a relatively small number of firms which were able to sustain their competitive superiority through several successive discontinuities. We suggest that, in addition to dynamic capabilities – which create new sources of advantage, these firms possess sustaining capabilities - munificent resource configurations which extend the time available for these firms to adapt to technological changes.

The concept of sustaining capabilities provides an interesting avenue for further research. We have used a highly specialised context to explore these issues, but further work could usefully explore whether the concept of sustaining capabilities could apply to other firms and indeed other industries. In his work on clockspeeds Fine (1998) identifies the differences between industries in terms of speed of change required, we are suggesting that such variability applies at the intra-industry level and that some firms may have more time available to create new competences and resources due to their sustaining capabilities. This poses an interesting question linking the work on organisation and industry evolution (Fine 1998) and the area of organisational slack (Cyert and March (1963) with dynamic capability (Teece, Pisano, & Shuen 1977). This also suggests that researchers may benefit from considering the interplay between these different competitive concepts over time, a subject which would particularly benefit from the kind of evolutionary, historical perspective that we have adopted here.

Table 1: Interview Respondents

Respondent	F1 Team Involvements	Date of Interview
David Williams	General Manager, Williams F1 -	9 February 1998
Gordon Murray	Draughtsman – Technical Director, Brabham: 1968 – 1987 Technical Director, McLaren Racing 1988 – 1990	22 September 1999
John Barnard	Technical Director, McLaren Racing 1980 – 1987 Technical Director, Ferrari 1988 - 1997 Technical Consultant to Arrows and Prost F1 teams 1998 - 2001	5 May 1999 25 September 2000
Ken Tyrrell	Team Principal, Equipe Matra International: 1968 – 1969 Team Principal, Tyrrell Racing: 1970 – 1997	20 January 1999
Martin Ogilvy	Various Technical positions through to Technical Director, Team Lotus: 1978 - 1988	18 March 1999
Mauro Forghieri	Various technical positions through to Technical Director, Ferrari 1962 - 1987	18 October 1999
Patrick Head	Technical Director, Williams F1: 1977 - 2004	16 February 2000
Peter Wright	Aerodynamicist – Team Principal, Team Lotus: 1974 - 1994	9 March 1999
Ross Brawn	Various technical positions at Williams: 1978 - 1988 Technical Director Benetton: 1991 - 1996 Technical Director Ferrari: 1997 - 2006	24 June 2004

Table 2: Major Regulatory Discontinuities in Formula 1

Season Regulation Introduced	**Nature of Changes (main reasons)**
1961	Maximum engine size reduced from 2.5 to 1.5 litres. Supercharging now banned. Weight limit introduced (for the first time) of 450kg. (increase competition and provide more tightly defined regulations)
1966	Maximum engine size increased from 1.5 to 2.5 litres. (keep F1 in line with market trend to larger capacity engines)
1981	Use of Ground Effect ‘skirts’ banned. (safety)
1989	Use of Turbo-chargers banned. All engines required to be normally aspirated. (cost reduction)
1994	Removal of automated driver aids. (cost reduction and responding to public demand for increased driver input)
1998	Car maximum width reduced (from 200 to 180cms) and use of slick (untreaded) tyres made illegal. Grooved tyres introduced. (safety – reduce size and speed of cars)

Table 3: 1950 – 1960

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
Ferrari (24) Cooper/Climax (13) Alfa Romeo (10) Mercedes (9) Vanwall (9) Maserati (8) Lotua/Climax (2) BRM (1)	1950 – First Drivers World Championship 1952 – Alfa Romeo withdraw from F1 1954 – Mercedes Benz enter factory based team 1955 – Serious accident at the Le Mans sportscar race leads Mercedes to withdraw from Motorsport 1957 – Maserati withdraw from F1 1958 - Constructors championship introduced	1950 - Engines either 1.5L Supercharged or 4.5L normally aspirated. No weight limitation. 1952 - 2.0L Formula 2 regulations applied in 1952 & 1953 due to lack of F1 designed cars. 1954 - Engines limited to 750cc supercharged or 2.5L normally aspirated. 1957 – cars allowed to use aviation fuel, up to 130 octane.	• Engine design and manufacturing facilities. • Space frame fabrication.

Table 4: 1961 – 1965

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
Lotus/Climax (22) BRM (11) Ferrari (9) Brabham/Repco (2) Cooper/Climax (1) Porsche (1) Honda (1)	1961 - All competitors using mid-engine layout. 1962 - Lotus introduce sheet aluminium monocoque chassis	1961 - Engines limited to 1.5L with no supercharged equivalent. Minimum weight of 450kg introduced.	• Mid engine layout requiring emphasis on weight reduction and distribution • Access to engine design and manufacturing facilities or specialist engine partners. • Monocoque design and fabrication

Table 5: 1966 – 1980

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
Lotus/Ford (47) Ferrari (40) McLaren/Ford (24) Brabham/Ford (21) Tyrrell/Ford (21) Williams/Ford (11) Matra/Ford (10) Ligier/Ford (6) BRM (5) Renault (4) Wolf/Ford (3) Cooper/Maserati (2) March/Ford (2) Hesketh/Ford (1) Honda (1) Eagle/Weslake (1) Penske/Ford (1) Shadow/Ford (1)	1967 - The first non technical sponsor - Imperial Tobacco appears 1968 - The first aerodynamic devices (wings) appear 1969 - Some teams experiment with four wheel drive 1970 - Slick tyres introduced 1977 - Radial tyres introduced + Renault introduce the 1.5L Turbo Engine 1978 - Ground-effect cars appear	1966 - Engine size increased to 3.0L normally aspirated or 1.5L turbocharged. Minimum weight increased to 500kg. 1969 - Regulations introduced to control wing size and height. 1970 – Minimum weight increased to 530kg. 1972 - Engines limited to 12 cylinders or less, minimum weight increased to 550kg. 1973 - 250L tank capacity + minimum weight increased by 75Kg to 575kg. 1974 - Restrictions on rear wings (aerofoils) to make them more durable. 1976 - Air box height and tyre sizes reduced.	• Monocoque chassis design and development. • Design and manufacture of lightweight alloys. • Expertise in aerodynamic principles and design. • Access to specialist aerodynamic testing facilities such as wind tunnels and model making.

Table 6: 1981 – 1988:

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
McLaren/Porsche/Honda (46) Williams/Ford/Honda/ Renault (29) Ferrari (15) Brabham/Ford/Alfa Romeo/BMW (12) Renault (11) Lotus/Ford/ Renault/ Honda (8) Tyrrell/Ford (2) Ligier/Matra (2) Benetton/ BMW (1)	1981 - Carbon composite monocoques introduced 1986 - Computer controlled active suspension introduced	1981 - Sliding skirts banned and minimum ground clearance of 6cm introduced. Minimum weight increased to 585kg. 1982 – Six wheel cars banned. All cars required to have four wheels. 1983 - Ground Effect banned - cars required to have uniformly flat underside 1984 - Maximum fuel load during race 220L, in race refuelling banned 1985 – Maximum fuel capacity limited to 220L, chilling of fuel banned. 1986 – Only turbocharged engines of 1500cc allowed. Maximum fuel capacity reduced to 195L. 1987 – ‘Pop-off’ valves introduced to limit turbo pressure to 4.0bar and thereby restrict performance. 3.5L normally aspirated engines allowed. 1988 – Turbo pressure limited to 2.5bar. Fuel restricted to 150L during race.	Monocoque chassis design and development. Design and manufacture using carbon composite materials. Control systems and instrumentation using hydraulics and electronics. Access to turbo charging engine technologies. Significant financial resources to sustain high usage of engines.

Table 7: 1989 – 1993:

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
McLaren/Honda/Ford/ Peugeot/Mercedes (34) Williams/Renault/BMW (31) Ferrari (9) Benetton/Ford (6)	1989 – Cars required to carry on-board TV cameras 1990 - Electro-hydraulic gear change introduced 1991 - Carbon-fibre breaks introduced 1992 - Fly by wire' throttles introduced 1993 - Traction control introduced	1989 - Turbo Chargers banned. 3.5 L normally aspirated engines only. Maximum 12 cylinders. 1990 – Front wing (aerodynamics) end plates restricted. 1991 - Points systems amended to emphasise win. 1993 – Maximum car width limited to 200cm. Tyres limited to 38cm.	'Fly-by-wire' control systems using electronic rather than mechanical responses. Further exploration of advanced materials

Table 8: 1994 – 1997:

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
Williams/BMW/Cosworth (31) Benetton/Renault (21) Ferrari (10) McLaren/Mercedes (3) Ligier/Honda (1)	1994 – deaths of Ayrton Senna and Roland Ratzenberger at Imola.	1994 – Active/Reactive suspension systems banned. Driver-aids (traction and launch control) banned. Refuelling re-introduced using standardised fuel rigs. Revised wing dimensions. Fitting of a fixed dimension 'plank' under the cars to raise the ride height. 1995 - Engine size reduced to 3.0 litres normally aspirated. 1996 – All drivers must qualify within 107% of the fastest time.	Regulation removes some of the previous differentiators between teams, making driver skill and access to particular engine packages the key differentiators.

Table 9: 1998 – 2006:

Grand Prix Winning Constructors/engine suppliers	Key events	Summary of Key Regulation Changes	Dominant Resources and Capabilities
Ferrari (79) McLaren/Mercedes (41) Renault (18) Williams/BMW/Cosworth (10) Jordan/Honda (4) Honda (1) Stewart/Ford (1)	2001 – Acquisition of Benetton F1 team by Renault 2002 – Toyota formally enter F1 with team built from scratch 2004 – Sale of Minardi and Jaguar teams to Red Bull 2004 – Sale of Sauber team to BMW 2006 – Agreement between the FIA and the Automotive Manufacturers as to how to establish a future Concorde Agreement from 2008	1998 - Smaller treaded 'grooved' tyres introduced and reduced chassis width to 180cm. 1999 – Number of grooves on front tyres increased. 2000 - Engines have to have 10 cylinders, with a maximum of five valves per cylinder. 2001 – Front wing ground clearance increased. Traction and Launch Control re-introduced. 2002 – Two way telemetry (allowing engineers to make adjustments to the car during the race) introduced. 2003 – Two way telemetry banned. Points system adjusted to include the top eight finishers. Tyre compound regulations relaxed. 2004 – Engine usage limited to one per race weekend. Launch control banned. 2005 – Engine usage limited to one for every two races. Range of aerodynamic changes and limitations on tyre usage. 2006 – Engine size reduced to 2.4L; 8 Cylinders only.	Integrating technologies such as engines, aerodynamics and chassis development.

Table 10: Summary of F1 performance: Twelve most successful teams 1950 – 2006:

Team	Period of Winning Grand Prix	Total Number of Grand Prix Wins	Number of Periods during which wins occurred
Ferrari	1951 – 2006	186	7
McLaren	1968 – 2006	148	5
Williams	1979 – 2004	112	5
Lotus	1960 - 1987	79	4
Brabham	1964 - 1985	35	3
Renault (two separate entries in different time periods)	1979 – 1983; 2003-2006	33	3
Benetton	1986-1997	28	3
Tyrrell	1971 - 1983	23	2
BRM	1962 - 1972	17	3
Cooper	1958 – 1967	16	3
Alfa Romeo	1950-1951	10	1
Matra	1968-1969	10	1

Figure 1: Top 3 Constructors from each time period 1950-2006

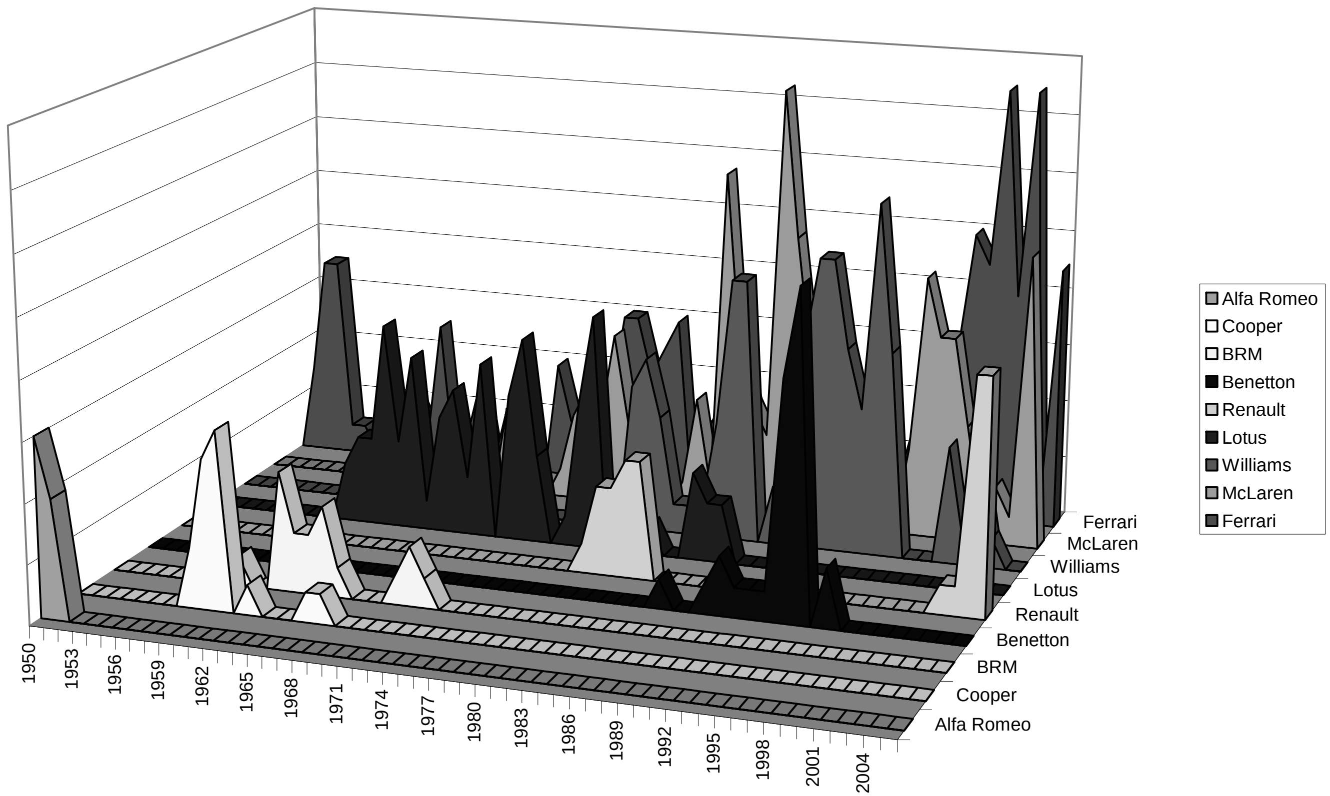

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Figure 1: Top 3 Constructors from each time period 1950-2006