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Formula 1 Technology

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Foreword

Anyone interested in Formula One has endless sources of information, including specialist publications, books, television programs, and the daily press. However, none of these gives much idea about how modern Formula One cars really work. These sources touch on various technical details, but the overall picture remains a mystery. As a result, some of the most interesting aspects of Formula One are lost to all but the initiates who actually work in the paddock.

This book is likely to change all that. It is the first systematic explanation of the technical side of modern Grand Prix racing. As such, it will be essential reading for any serious follower of Formula One and of immense help to aspiring drivers and engineers in other forms of racing.

The FIA receives letters and e-mails from all over the world with suggestions, comments, and criticisms. Unfortunately, most of these miss the point because of lack of technical information and understanding. This book is capable of providing what has been missing. I think it will have a significant impact.

*Max Mosley, President
Fédération Internationale de l'Automobile
July 2000*

Introduction

History shows that engineering (using an idea without necessarily understanding it) usually gets the drop on science (understanding an idea without necessarily having any idea what to do with it).

—Philip Whiteman

I am extremely fortunate to have been involved in motor racing during the last 35 years of the first half-century of Formula 1. During that time, I have worked directly for Formula 1 teams for 22 years, and the remainder of the time on relevant technologies: aerodynamics, composites, and closed-loop control systems. I have witnessed firsthand the most technically stimulating and challenging period, and I have seen the industry grow enormously in both size and sophistication. It has been a period during which the technology and engineering has evolved from mechanical systems—most of which you could hold in the hand, look at closely, and see how they should work, even if you could not always understand why they did not—to systems dominated by silicon wafers so small you hardly see them and which often cannot be totally understood by a single human brain.

When I joined BRM straight from university in 1967, it was a World Championship winning team which, unusually for a British one, designed and built its own engines and transmissions. Tony Rudd, BRM's chief engineer and team manager, led an engineering department that consisted of one engine designer, one chassis designer, and one gearbox designer, plus two draftsmen. I became the R&D department once it was established that anything I designed was too expensive to make. All calculations were made on slide rules or using logarithm tables, which inhibited carrying out extensive analysis, especially stressing. Suspension geometry was plotted on the drawing board using fishing line; the instantaneous center was always off the board and sometimes stretched to the other side of the drawing office. In the workshops, highly skilled panel beaters wheeled magnesium skins to form the bodywork, and machinists achieved astonishing tolerances on old milling machines and jig-borers. Engine test beds were located on an old airfield several miles away, where a pair of ex-Tiger Moth, de Havilland Gipsy Major engines was used to drive propellers to vent the test beds. This was the state of the Formula 1 art.

Today, Formula 1 teams such as McLaren or Williams are housed in gleaming, modern buildings and are staffed with 200 to 300 persons (Fig. 0.1). The 30-person design department is equipped with CAD stations, feeding design information directly to CNC machining centers, sometimes served only by robots. The 25 engineers in R&D are linked to design and racing by an integrated network of databases and analysis software connected to the race cars, rigs, and their on-site 50% wind tunnel. The composite department, with its autoclaves and five-axis pattern cutting machines, dominates manufacturing. Engine manufacturers, such as Ford-Cosworth and Mercedes-Ilmor, are approximately the same size, but they have more machining capability and rows of engine test beds instead of wind tunnels and seven-post rigs. The 500-person Scuderia Ferrari combines both team and engine manufacturer. When the team, its engine supplier, and major sponsor go to a Grand Prix, the 30+ tons of equipment is transported in six or more articulated trucks. Three or four double-decker hospitality vehicles look after guests and the 60 team personnel running the cars. BRM took only one converted bus to races 30 years previously. Instead of the roomy pit complexes at modern circuits, the paddock where the cars were worked on, was exactly as the name implies: a grass paddock.

Whereas one man such as Tony Rudd could understand the whole car—chassis, engine, and gearbox—and could relate to his drivers because he too had raced, the size of the engineering task is now so large and complex that specialists are required for every aspect. Room remains for an overall engineering view, and those individuals who have the instinct of McLaren's Adrian Newey for what makes a race car fast, still succeed the most often. The technology of Formula 1 has, however, almost completed the transformation from the black art of the 1950s and 1960s to the science of the 2000s. Black art allows success to come to those who have some science, are able to extrapolate intuitively, and have the luck to be able to just "do it." Computer science enables every solution to be evaluated, with ultimate convergence on the solution. The way a race car works is nearly understood, but pockets of complexity remain and the computer models have not yet unraveled their inner workings. Turbulent rotating airflows, tires, and the motion, thermodynamics, and chemistry of the gases inside a combustion chamber that fires 150 times per second are among them.

Until the 1950s, Grand Prix cars were configured similarly to road cars. The engine placement, size, and type were similar, although more powerful; the chassis layout, suspension, and wheel and tire sizes were sometimes even derived from road cars; bodywork was more streamlined, mudguards were dispensed with, and the passenger seat was discarded. A sporting driver of road cars would recognize the controls and be quite able to drive the cars. In the 1960s, 1970s, and 1980s, a series of inventions and technological advances transformed Formula 1 cars such that the average motorist would have trouble identifying many of the components and probably would be unable to drive the cars, even if he could withstand the physical forces it imposed. The performance of the cars has increased greatly and would have done so even more but for regulatory restrictions on both the type and quantity of the technologies permitted. This book examines what, how, and why this has happened during this period.

Fig. 0.1 Organizational structure of a typical British Formula 1 team.

In his book *Innovation* (Ref. 0.1), William Kingston defines the stages of innovation. The originator who postulates the idea is the dreamer. The person who describes it in visual terms is the artist. Finally, the person who takes the visual form and produces a working demonstration of the idea is the inventor. Perhaps Kingston also could have given credit to the person who authorized the expenditure that enabled the idea to be exploited successfully and become known. That person is often the one who has the vision and means not only to employ people with the ability to innovate, but also to enable the inventions to reach fruition. Formula 1 is full of claims to the ideas that have worked, but little has been patented and thus those claims have never had to be tested in law. In most cases, if A had not invented something, B would have done so shortly afterward. The invention occurs when the need is apparent and is thus almost inevitable. I have tried to avoid the issue of which individual deserves the credit for the key ideas and technologies, but rather to concentrate on which organization pioneered those ideas in racing and how and why the inventions came about when they did.

In his book *Guns, Germs and Steel* (Ref. 0.2), Jared Diamond, professor of physiology at the University of California Medical School, has written about the conditions conducive to the development and diffusion of technology within societies. The conditions he describes are as relevant to the Formula 1 environment as to the primitive societies that invented the wheel and the alphabet. He states that most inventions are borrowed and adapted from another society in close proximity, because this is nearly always easier than reinventing independently and it results in a more rapid spread of the idea. To adopt an invention, a society must be willing to see, learn from, and be receptive to the idea; otherwise the society will tend to become disadvantaged by the lack of it and will eventually be overwhelmed. Once something has been invented and examples exist, it becomes much easier to reinvent it independently. For example, the process for making fine porcelain in Europe was developed more or less independently by Meissen, Sèvres, Wedgwood, and Spode, nearly a thousand years after the Chinese had perfected it. The Europeans were assisted by having examples of Chinese porcelain to inspire them, although they did not know the formula for the clay or the details of the firing process. Diamond claims that the development of technology is an autocatalytic process; that is, it speeds up at a rate that increases with time because the process catalyzes itself. This is certainly what has happened in Formula 1. When active suspension required the installation of servo-hydraulics and a chassis computer on the cars, numerous other chassis control systems quickly followed, adapting the active technology and hardware. Diamond's analysis seems to be particularly relevant when considering why the British motorsport industry has been so successful.

Compared to the almost *formula libre* of the early years of Formula 1, and indeed before that also, it is extremely regulated formula. Before the development of wings and ground effect, there was only a perceived need to regulate engine size and weight. Performance did not escalate out of hand, and safety was not an issue. Motor industry, or indeed national participation, was primarily on the basis of promoting and displaying technical supremacy. The cars resembled the low-volume, exotic road-going products of the manufacturers, and the public following was so small in today's terms, in the absence of television, that the racing results had

little marketing effect on mass-produced cars. Aerodynamic downforce, wide and slick tires, turbocharging, aerospace materials, and computer-control systems added so much performance potential that regulation to control speeds was inevitable. Other influences, including safety awareness, costs, the sporting spectacle, and the need to modify circuits to suit television, all have contributed to the current Fédération Internationale de l'Automobile (FIA) Technical Regulations and the way the permitted technologies have evolved. Most vehicles—whether they are road cars, trucks, civilian and military aircraft, or ships and spaceships—compete with each other in absolute terms, subject only to safety and environmental regulation. Their economics are an inherent competitive factor. Race cars compete in relative terms, almost unencumbered by cost constraints but with the performance technologies greatly limited by regulations. It is a somewhat unnatural environment, necessary to maintain motorsport as a contest among humans and one that has had a significant effect on the way it has evolved technically.

Only five main parameters determine the performance potential of a race car: power, weight, tire grip (coefficient of friction), drag, and lift (or downforce). Until Chaparral, greatly assisted by Chevrolet R&D, demonstrated the significance of lift by generating downforce aerodynamically, it had been largely ignored and designers had concentrated on only the first four parameters. Tire grip did not increase significantly until the 1960s, when tread widths started to increase; wear rate of the narrow treads was a more critical factor until then. Formula 1 technology is about how to maximize these five parameters as much of the time as possible, and to enable the driver to use as much of them as possible all of the time. Hundreds of technologies are involved, not merely in the makeup of the car and its systems but also in the means by which the components are manufactured and in the systems for testing and racing the cars. This book is about some of the most important of these technologies.

Making up these hundreds of technologies are thousands of details that go into the design, the manufacturing, and the development processes involved. This book is not about these details because they embody the main intellectual property of the companies employing them. Formula 1 has become so competitive and the stakes have become so high that the companies involved have procedures that attempt to protect their secrets. Even if they allowed the cars to be photographed regularly with the body panels removed, little would be revealed because the important secrets are embedded in the fine detail of piston crown shapes, anti-friction surface coatings, damper valving, hydraulic circuits, and software. None of these are ever disclosed. The cars are retained at the end of a season in team museums or, if sold to collectors, they are stripped of their secret components. The opportunity to inspect and describe a Formula 1 car, as could be done 20 years ago, is gone. Many companies involved in Formula 1 instruct technical personnel never to discuss anything technical with either the press or people from competing companies. It is all too easy to reveal information useful to a competitor simply by indicating an interest in a particular technology.

The basic principles and fundamental technologies described in the following chapters are not secrets. They are known and understood by most designers and engineers in Formula 1 and any of the major racing series. They may not be known and understood by technically oriented

people outside racing, even within the automobile industry. This book is written for those who are interested in and follow Formula 1, and who wonder what the designers are trying to achieve and why they follow a particular trend. I have tried to avoid using formulae and equations to describe the concepts upon which the technologies depend, but that is not always possible. Race cars must follow Newtonian laws, and I believe that stating simple equations is sometimes necessary to illustrate how fundamental are some of the concepts that reside behind all the technical sophistication.

The development of three of the technologies—ground-effect aerodynamics, the use of carbon-fiber reinforced composites in primary structures, and electro-hydraulic control systems (active suspension)—is described in more detail because I had firsthand knowledge of the initial stages of their development. All three started as classic black-art programs and matured into sciences with good theoretical bases now in place for them. Each involved an initial concept demonstrator phase, lasting approximately six to twelve months and having very little financial outlay. They subsequently took another six to twelve months to reach the racetrack. Ground effect required an additional six months before the benefits really showed and, for some inexplicable reason, another year or two before the competition fully caught up. Carbon-fiber reinforced plastic (CFRP), and the processes that enabled it to be used to construct the monocoque, surfaced simultaneously in two teams, and the benefits were immediately apparent to all. Active suspension lapsed due to the death of Colin Chapman and a change in the aerodynamic regulations. It resurfaced four years later, winning Grand Prix's for two teams, but required another five years before dominating Formula 1. Two years later, it was banned. The life cycle for a Formula 1 car is approximately 18 months, but any significant new technology (such as the aforementioned ones or radial tires and turbocharging) tends to require at least three years to mature into race-winning systems. The time scales in Formula 1 are short compared to those of similar industries. That is a function of the participants' willingness to take risks, as well as the gains to be won by introducing something new but unproven which may give an edge in performance over competitors.

As with so much nowadays, the microprocessor and the complex and repetitive tasks it is set to perform have had the biggest effect on technology in Formula 1. Starting in the late 1970s, they first appeared on Formula 1 cars to control engines and manage data acquisition systems. Firmly established on the cars in the 1980s, they also began to play a major part in the design and development processes, as CAD, CAE, and CAM software and specialized applications developed for the aerospace industry began to be exploited by the remainder of industry. By the 1990s, the computer-controlled functions permitted on the cars were severely limited by regulations; nonetheless, the computer had become an integral part of the design, development, manufacturing, and racing processes. The escalation in performance during the last decade—in spite of the FIA applying continuous performance-limiting regulations and no major new, fundamental, technical advances—can be attributed to the ability of the computer to provide understanding through simulation and modeling, and to optimize highly complex systems.

One of the most perplexing aspects of the evolution of motor racing technology is why it took so long for the benefits of aerodynamic downforce to be appreciated. Figure 0.2 shows an airfoil section being tested on a car around the turn of the last century. Although the wing is mounted in such a way as to produce lift, and the rear-facing passenger was noting the magnitude of that lift, another 60 years passed before it was realized that a similarly generated downforce could radically improve the overall performance of a race car. Why did the technology not cross disciplines? The scientific approach used by Chevrolet R&D to measure and analyze race car performance, and the ability of the computer to simulate the effect of new concepts, finally made the now obvious connection. In doing so, Chevrolet heralded the start of the scientific age of motor racing (Refs. 0.3 and 0.4).

*Fig. 0.2 Testing an airfoil section on a car, circa 1900.
(Courtesy of the Cowin Collection)*

In spite of the impact of the computer, anyone who has driven a rear-wheel drive car at or near its limit will have experienced most of the topics discussed in this book, except perhaps for the startling increase in high-speed grip generated by ground-effect downforce. The physics are the same, but the magnitude of some of the accelerations experienced is approximately four to

five times greater. Often, the first experience of a car driven at the limit stimulates an interest in race cars, a desire to understand what makes up that experience, and how a race car driver can deal with a much greater embodiment of it. Some go on to race, while others prefer to delve into the science and engineering of the cars. In writing this book, I have tried to make Formula 1 a little bit more accessible to those people.

In the introduction to his autobiography, *It Was Fun!* (Ref. 0.5), Tony Rudd wrote,

I must, however, repeat the advice I gave to Peter Wright...when some 25 years ago he applied for the job of being my personal assistant—"It will be fun, but there's not much money in it."

Tony was absolutely correct until around the 1980s. I recall Gérard Ducarouge in 1987, then technical director of Team Lotus, saying after an eight-hour day of testing and well into a further eight hours of night work on the cars,

It isn't fun anymore.

By then, a career as an engineer in Formula 1 was already pretty good, compared to other engineering jobs. Now, 34 years after Tony gave me that advice, I suspect that most of the fun has gone out of Formula 1 design and engineering, but there is a lot of money in it now.