RACING CAR DESIGN
AND DEVELOPMENT

RACING CAR DESIGN and DEVELOPMENT

by
Len Terry
and Alan Baker

ROBERT BENTLEY
Cambridge, Massachusetts

Fifth printing 1980
Library of Congress Catalog Card Number 73-85159
ISBN 0-8376-0080-4
Manufactured in the United States of America

Published and distributed by
Robert Bentley, Inc.
872 Massachusetts Avenue
Cambridge, Massachusetts 02139

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Introduction

NO-ONE CAN BECOME a successful racing-car designer simply by reading a book, so RACING CAR DESIGN AND DEVELOPMENT should not be considered as a passport to fame and fortune by any budding Chapman or Tauranac. As Len Terry explains in Chapter 1 the requirements for success in this specialised field are both numerous and varied, and so any knowledge of racing car technology gained from a bookshelf can only provide one of the necessary ingredients.

Nevertheless, the structure and content of this book has been planned to provide motor-racing enthusiasts in general and students of racing-car design and technology in particular with as broad an insight as possible into an activity which probably falls somewhere between an art and a science.

The decision to divide the authorship between two engineers, one an internationally known and highly experienced racing car designer, the other a technical writer and editor of equally wide experience in the automotive field, was an important part of the plan to produce a book which would contain the correct blend of practical and theoretical discussions and conclusions. On many occasions during the formative stages of the book one of the authors became the ideal foil for the other, and it is believed that through their many discussions – and indeed on occasions their arguments – they achieved a flexibility of thought which has enhanced their manuscript considerably. Racing-car design is an activity in which the dogmatic approach rarely achieves lasting success, and so it is no coincidence that it has been avoided scrupulously as the authors have presented their thoughts and advice.

Len Terry has designed racing cars which have won world acclaim, and others which have been less than successful. But with refreshing frankness and modesty he has not shied away from exposing the weaknesses of his less successful efforts with as much clarity as he has explained the strengths of his winners. In this field perhaps more than most one tends to learn by the mistakes of others, and Terry has provided readers with the benefit of lessons which he has learnt the hard way. At the same time he has not been slow to point out when in his opinion his designs have failed to achieve a level of success they deserved because of circumstances outside his control.

Alan Baker has provided a detailed biographical sketch of his co-author in Chapter 2, but his own career is not without interest. A BSc (Eng) and a Fellow of the Institution of Mechanical Engineers, he worked with Scammell Lorries and Bristol Aeroplane Co before joining the RAFVR as an engineer officer during the second world war, and on his release he developed a career in technical sales.

He moved into journalism in 1953 when he became technical editor of *Motor Cycle*, transferred to *Automobile Engineer* in 1958 and became its assistant editor in 1961. The following year he left to become the first editor of *Automotive Design Engineering*, and after four years in that post he was promoted to group managing editor, with responsibility for a series of technical magazines.

Since 1969 he has been a freelance writer, specialising in the lubricants, industrial and vehicle-design fields, and has a widely recognised skill of making technicalities comprehensible to the layman, an ability which is evident in his treatment of the highly complex theory of handling characteristics in Chapter 5.

Between them, Terry and Baker have covered all major aspects of racing-car technology beyond the confined area of the engine-transmission package, which today must be considered a bought-out item obtainable from the recognised specialist manufacturers.

Whilst they have not attempted to produce a mathematically orientated textbook, but rather an interesting-to-read, broadly based study of racing-car technology, they have provided by way of Appendices a series of mathematical formulae and working examples concerned with the fundamentals of chassis and suspension design, together with a table of materials-by-usage and a detailed buyers' guide of specialist companies whose products and services should prove invaluable to any prospective racing car constructor.

The drawings (by Len Terry) and photographs have been selected specifically to illustrate and perhaps clarify points raised in the text, and they provide an interesting picture-essay of the development of racing-car design over the most rewarding period of its history.

PUBLISHER'S NOTE

Throughout the chapters which follow the words of Len Terry appear in **bold** type and those of Alan Baker in medium type. In the interest of clarity this rule has been followed both for complete chapters and for sections within a chapter.

1

The anatomy of a racing car designer

A RACING CAR DESIGNER is born rather than made, for beyond a certain point no man can train to become one. To achieve any success in this specialized field he must have a draughtsman's background to which he must add his own ingredients of imagination and inventiveness controlled by common sense. Essential tools of his trade are a thorough historical knowledge of racing car technology and the utmost awareness of the work of his contemporaries; in this way he will see the potholes as well as the signposts on his road.

Since nothing is really new these days, designing a racing car can become largely an intuitive process once sufficient knowledge has been acquired. It is then primarily a question of co-ordinating as many as possible of those features known to be successful. Compromise is inevitable, and the better designer is he who makes the better compromises. In this way, racing car design is more of an art than a science, though the application of scientific principles and data is an essential part of it.

An ordinary road car can be designed by a committee without serious detriment; the resulting lack of individuality is today not necessarily a disadvantage. The committee-designed racing car, however is basically a paradox and so is foredoomed to failure. Even in the sports-racing categories, design by committee is unlikely to succeed unless one strong-minded individual is able to put in a lot of work on it – as was the case with the Ford GT40 and Lola cars.

Accepting that a racing car must be a one-man concept, the designer is at once faced with the problem of delegation. He cannot squeeze a quart of work into the day's pint pot, and the start of a racing season cannot be held back if his new baby is still at the foetal stage. In theory a designer can safely delegate an important matter to someone in whom he has complete confidence. But this implies that the assistant is as good at this job as the designer, and what strong individualist is going to admit that he has an equal, except perhaps in certain specialist areas such as stressing? Alternatively the designer can delegate to someone of lesser stature and accept the consequences. This is satisfactory for non-critical items, but so few components of a racing car fall into that category; virtually every part affects others, so inadequacy in one is likely to set up a chain reaction.

There is also the difficulty of communication. Few people find it easy to put over their ideas in detail to someone else, yet it is a principle of good delegation that the recipient should understand not only what he has to do but also where and how it fits into the overall picture. Thus delegation often results in a loss of time rather than a saving, because after two people have been involved at the explanatory stage, the assistant may still take longer to do the job than the designer might have done.

A broad mechanical engineering background can be invaluable to a racing car designer. My own earlier experience covered such varied aspects as aircraft, reinforced concrete, pipework and even a heart-and-lung machine. Knowledge of aircraft or aerospace structural techniques can be very useful if the designer keeps his mind clear as to the essential differences. Safety factors have to be rethought, and contrary to popular belief cost *is* important, while durability criteria are less stringent since the life of some components may be as little as just one race.

Again, the time scale is very different. A project may have to be completed in a couple of months rather than five years, and the bogey of obsolescence is breathing down your neck. If time is to be saved on design and construction in order that the car shall be racing, and therefore earning money, sooner, a practical simplicity of approach is vital. In this respect, the designer listens to any ideas from the shop floor, because the men who are actually building the car will sometimes spot a manufacturing simplification that has been missed. But sometimes the best solution to a problem cannot be seen until the car has been completed, so the cold, hard look of objectivity is particularly necessary at that stage.

The weight saving essential on a racing car comes primarily from an attitude of mind; think light from the start and it will be light. If lightening holes can subsequently be drilled through a part, generally one could say that it had been over-designed in the first place. However, slight conservatism in such vital areas as wheel hubs or wishbones is preferable to optimistic under-design which could have fatal consequences. Following on from my earlier comments on striving for simplicity, the simplest design solution is often also the lightest.

Obviously the designer must have the basic mathematical knowledge to enable him to calculate such things as spring rates and shaft diameters. He does not have to be a stress expert, as indicated earlier, so long as he knows whom to approach or which reference books to study. Also, as his experience grows, so will his need for calculations diminish.

First-hand competition driving experience is a great help to a racing car designer, as is witnessed by the successful cars that have emanated from the McLaren and Brabham/Tauranac workshops. Although my own experience was more limited, it has given me a greater insight than I would otherwise have into both the requirements of the car and the problems of the driver. A race is, after all, won by the best combination of man and machine.

The designer must keep a constant watch on himself for any signs of 'tunnel vision', the narrowing down of the imaginative and creative front. If this takes hold he will find himself centring each design on one idea instead of aiming for the best overall compromise, and something else must suffer as a result. A certain CanAm car was a good example of the narrow approach. Its designer was obsessed with minimising the frontal area, so he designed around 10 inch front wheels, but as a result the brakes were not big enough to cope with the heat input under racing conditions and inevitably the car was not competitive.

Accepting that design takes place on the drawing board as well as in the designer's mind it is essential that he be a more than competent draughtsman, and it is also advantageous for him to possess the ability to draw perspective views freehand. In this respect, I am fortunate in being blessed with this gift which was sharpened by my two years of technical illustrating.

Of necessity, the designer must also have forward vision so that, rather like a chess-player, he can anticipate and identify all the ramifications of the features that he wishes to incorporate into his design. His fertile imagination must be tempered, too, with the strength of will to freeze the design at a given point, otherwise the car will never reach the 'in the metal' stage because the designer keeps dreaming up new and better ideas! Also, it is necessary for the designer to be a planner if the car is to be built in a reasonable period of time. Certain items, for various reasons, must be dealt with at an early stage, otherwise completion of the vehicle may be held up for the want of vital parts. The designer therefore has need to know the 'lead-time' on these vital components and to plan his design schedule accordingly.

It is also advantageous for the designer to possess some practical workshop experience, and it is noteworthy that the majority of contemporary top-line racing car designers rose from the ranks of the special-builders. Chapman, Broadley, Tauranac, Phillippe, the late Derrick White and even Sir Alec Issigonis were all one-time special-builders, as was the writer. All these men are just as familiar with tin-snips, hacksaw, file and welding torch as they are with the drawing pencil and slide-rule.

From the foregoing it will be seen that the successful designer must be a methodical man if he is to achieve his target in the normally short time available. Although not absolutely essential, it can be of advantage if he is also a student of value-engineering; apart from the previously mentioned cost aspect, there is often the need for parts to be made or repaired in the field, and obviously simplicity helps on these occasions. It is clear, too, that a 'nine-to-five' mentality will be a barrier to success in the highly competitive and progressive world of motor racing. To a very great extent, therefore, our man will have very few real interests outside this particular field.

Although possessing a fair amount of self-assurance and self-confidence he must also be prepared to acknowledge and learn from any mistakes that inevitably will be made, and to be self-analytical in the process. In fact he must be analytically minded generally, as it is all too easy to jump to conclusions when a particular idea does or does not work. The individual facets of a racing car are so interlinked that when one particular item is changed or modified it can affect many others. As an example, a change in front-end ride height will alter the front roll centre and consequently the roll axis; it will change the height of the centre of gravity and most likely will affect the static camber as well as the effective swing-arm length. It may also slightly modify the effective spring rate (if any progression is built in) and it will almost certainly influence the aerodynamics. Any anti-dive or anti-squat characteristics will also be slightly modified by this seemingly simple change. It is understandable, therefore, that the cardinal rule when testing is to make only one alteration at a time!

Finally, the designer has to be something of an opportunist. Each project on which he embarks will be circumscribed by regulations, and it is up to him to see that he gives away nothing in his interpretation of the rules. Furthermore, he must be constantly on the alert for deletions or amendments, in case he can turn these to his own advantage in terms of the overall performance of his design.

2

Len Terry – a biographical sketch

FOLLOWING LEN TERRY'S survey of the inherited and acquired characteristics, functions and motivation of a racing car designer, it is interesting to consider how he gained the necessary knowledge and experience in his own career. His commercial involvement in design began in 1947 when, shortly after leaving the RAF (in which he was officially designated an Instrument Repairer but was in fact a draughtsman), he joined the Ever Ready electrical company. In addition to designing various types of batteries he was also required to build the prototypes, so already he was learning that the designer must not work in a vacuum but must remember that the things he draws also have to be made. He had always been handy with the pencil, so technical illustrating became a part of his duties at Ever Ready.

He quickly acquired proficiency in this type of drawing and decided to turn it to good account in his spare time. A long-standing enthusiasm for high-performance cars gave him an obvious outlet and soon he had some work accepted by the weekly magazine *Autosport.* A number of his drawings were published during the next few years, then in 1952 he became a full-time technical illustrator with The Metal Box Company. But although the experience there was useful, the scope for advancement proved to be very limited, and so he soon moved on again.

He joined the Institution of Electrical Engineers, to become illustrator of that august body's various technical publications, but the institutional life and methods did not appeal, and the fledgling designer felt the need to stretch his wings in less rarified air. So in 1954 he became a design engineer with a firm of general consultants, Tricorn Designs. In addition to the wide range of activities he mentioned in the last chapter, he began at last to get his teeth into the automotive cake, doing sub-contract design work for Vauxhall, Aston Martin and ERA (Engineering Research & Applications - no longer English Racing Automobiles, though still at the Dunstable establishment).

The Vauxhall tasks were confined to bodywork fittings, but for Aston Martin Terry produced the body contour drawings for the rare fixed-head notched-back DB2. At ERA he was involved in a fascinating but unfortunately still-born project for the British Motor Corporation - a rear-engined car with such advanced features as air suspension and electronic control of the automatic transmission.

These designing activities in the motor industry took him into 1956 when he switched back to technical illustrating in a London studio handling general industrial work. As at Metal Box, though, his creativity had little scope there, so he exercised it in his spare time by designing and building his first competition car, the Terrier Mark 1. Limitations of time, money and physical resources demanded the simple, straightforward approach which has characterized all of Terry's work. The Mark 1, which is described and illustrated later, did well enough on the track to establish its designer's ability.

By 1957 technical illustration was palling rapidly as a livelihood, so Len moved into commerce by joining Falcon Shells as sales manager. At that time Falcon were one of the leading suppliers of glass-fibre-reinforced plastic bodies for 'special' builders, and the Terry task comprised nearly as much advisory work as selling. After about three months, though, he found himself increasingly at variance with the man at the top, and since this discovery coincided with a vacancy at the Lotus establishment, then still at Hornsey in North London, Terry took his next big step forward. By this time (1958) Colin Chapman was really beginning to go places and had recently caused something of a furore with that most handsome coupe, the all-GRP Elite (Lotus 14).

Work at Hornsey was hard, interesting and varied, and Len was involved with the Lotus 15 and 16 as well as later models of the 11, 12 ('bathtub') and Elite. He also did some work on the Lotus 17, condemned its short-strut suspension but was overruled; the design went through, and the car was not a great success so his criticism was justified.

Despite the increasingly responsible nature of his work at Lotus, where he had quickly become chief draughtsman, Terry was still playing second-fiddle, so understandably, though rather rashly, he devoted his limited leisure time to the busman's holiday of designing, building and racing his Terrier Mark 2, which proved highly successful in the hands of Brian Hart, who also footed the bills. Equally understandably, Colin Chapman decided that the bible was right about no man being able to serve two masters, so in 1959 Terry had to go.

Continuing his upward progress he went straight into the chief designer's berth at Gilby Engineering, run by the father-and-son team of Sidney and Keith Greene. Here at last he had full freedom of action plus reasonable resources. During the next two years he designed an 1100 cc sports car and a 1½ litre Formula 1 car. Both were raced successfully by Keith Greene, and it is significant that they were planned as monocoque structures (in 1961) although manufacturing difficulties subsequently forced a change to orthodox space-frame construction. It is worth recording here that Peter Ashcroft, later to become Ford's competitions manager in Britain, was at that time chief mechanic to the Gilby team.

Len Terry's work at Gilby ended abruptly as a result of a personal tragedy. While practising in a Terrier Mark 2 at Oulton Park in the wet, Terry slid off a patch of oil into a tree and sustained a compound fracture of the leg. Complications included pneumonia and a coronary thrombosis, from which he reckons he was lucky to recover, and while he was doing so, the Greenes sold Gilby Engineering to Cope Allman, who decided to drop the racing car side of the business.

Back as a freelance again after his convalescence, Terry undertook a complete design for the French Alpine company who wanted a small sports car for Le Mans. The car eventually was built and raced, though in a considerably modified form; apparently Alpine thought they knew better on various aspects of the design, although their optimism was not justified by results! Terry also carried out some work for his old boss Colin Chapman, including the preparation of proper production drawings for the Lotus 22 chassis frame and for the cylinder head of the Ford/Mundy/Ansdale Twin-Cam engine used in the Lotus Elan, the Ford Lotus-Cortina and later the Escort Twin-Cam. Chapman apparently was pleased with these efforts because, when Mike Costin left him towards the end of 1962 to rejoin Keith Duckworth in Cosworth Engineering, he invited Terry to return, this time as chief designer. He held this position for nearly three eventful years.

The company's first monocoque, the Lotus 25, was already in existence but certain structural troubles had occurred, so here was an urgent first task. Its successful completion helped Jim Clark to win the world championship in 1963, and to set his record of seven Grand Prix wins in one year. Two new cars were brought out that year - the Lotus 27 Formula Junior monocoque and the first Indianapolis car, the Lotus 29. As a change from exotica, Terry spent some time in early 1963 working on Chapman's design for the original Lotus-Cortina rear suspension. He recalls that it bore a marked resemblance to his own layout for the Terrier Mark 2, but had suffered slightly in the translation!

1964 was quite a successful year, though Jim Clark narrowly lost the world title to Graham Hill and had his famous spot of tyre trouble at Indianapolis. But in 1965 he made up for his misfortune by winning both the World Championship and the famous 500-mile race. On top of that Lotus won the Formula 2 British and European manufacturers' titles and the British Saloon Car Championship. During 1964 Terry also designed the Lotus 19B - virtually a one-off car for Dan Gurney. Although outwardly similar to the original Lotus 19 rear-engined sports car, with which it shared the same body panels, the 19B was in fact a completely new design, and it was during this period that Terry's later association with Gurney was first conceived.

Immediately after the 1965 Indianapolis race Terry left Lotus to join Dan Gurney's All American Racers organization, as chief designer. This may seem an odd time for him to have quit, but disagreements between Terry and Chapman on design policy seemed to be building up to a level that could affect the end products, the racing cars. Gurney had just set up shop at the Weslake engineering establishment at Rye, in Sussex, where the Formula 1 Eagle's V12 engine was to be designed and built, and he was also opening a workshop in California for the US side of the AAR activities. Terry's job was to help organize these two shops as well as design a dual-purpose Formula 1/USAC Indianapolis monocoque car. To relieve him of some of the first task he took on John Lambert, who had been at Lotus during both Terry's periods with the company, more recently in charge of racing car development and the building shop, and for whose abilities Terry had formed a high regard.

In September 1965, Lambert went to Santa Ana to get the Californian workshop under way. Design and construction of the Eagle continued quite briskly there, though it proved impossible, in spite of the use of different gauges of aluminium for the monocoque structure, to make the car competitively light for Formula 1 while keeping it strong enough for Indianapolis.

By the time the development stage was reached, however, relations between Terry and Dan Gurney had become decidedly strained. This was due to a clash of personalities as much as of methods - perhaps it would be fairer to say that there was a complete lack of communication between the two men. Anyway, he decided to leave AAR in September 1966, as soon as the 3 litre Formula 1 version of the Eagle was completed; John Lambert, having found the Californian situation equally unsettling, had departed from AAR and Santa Ana six months earlier.

As a bit of psychotherapy after this frustrating chapter in his career, Terry turned his creative talents to designing and making furniture for his home at Hastings. Then early in 1967 came an approach from Frank Nichols of Elva fame; it resulted in the two of them forming Transatlantic Automotive Consultants, at Hastings, initially to design a CanAm car for Carroll Shelby. This incorporated a number of novel features, particularly in the suspension layout (see next chapter) but the car never emerged from the 'ugly duckling' phase because those in charge insisted on racing it before it was properly developed.

Next came the Tasman P126 project for BRM. These cars did better than the CanAm effort, but again development seemed to be inadequate and on the wrong lines, not least because the people at Bourne insisted on 'going it alone', with virtually no liaison with the Terry/Nichols *ménage.* The relative failure of two apparently promising designs inevitably caused friction between these two strong personalities who already were not seeing eye-to-eye on all matters.

So TAC was disbanded towards the end of 1967 and Terry decided the time had come to run his own show. The original objective, once again, was to design to order, and preferably to build at least the prototype cars if a batch was envisaged. His old colleague John Lambert was by then living and working in the Poole area, an expanding town where business rentals were still low, so since Terry no longer had any ties at Hastings he decided to move to Dorset. The result was Design Auto, set up late in 1967 in a small factory on a new industrial estate on the outskirts of Poole, with Terry in charge of the design operation and Lambert looking after the car construction.

They had little trouble getting off the ground, and the first assignment was the prototype Gulf Mirage 3 litre, with BRM engine, for JW Automotive Engineering, John Wyer's ex-Ford establishment at Slough. This car was built at Poole but developed almost entirely by JW Automotive.

Then John Surtees, after severing his connection with Eric Broadley's Lola company, asked Terry to design and build him a near-replica of the Honda Formula 1 car, with Honda's approval. Various modifications were incorporated; some were to simplify the rather complex design of certain features, while others, such as the adoption of Terry's own parallel-lower-link rear suspension (since used increasingly on other *marques*) were straightforward improvements on the originals.

Almost as soon as this project was finished, Terry contracted with Nathan Racing to design a Formula 5000 car, but when the design and construction of this were almost completed the deal fell through, in September 1968. Fortunately, John Surtees came along at the critical moment with a request for a Formula 5000 design and was offered and accepted the ex-Nathan car which, with a few modifications, became the well-known and successful Surtees TS5. Over the next few months four cars were built for Team Surtees, together with three chassis monocoques and a number of spares of various kinds. Terry feels that this was one of his best designs, not least because the only changes required were minor strengthening modifications.

By the time the TS5 design work was completed, BMW were hammering on the Design Auto door with a request for a Formula 2 car, to be built in Germany by Dornier, the aircraft company. The car was raced in 1969 with some success but was less competitive than Terry feels it should have been. He attributes this to three factors. One was that BMW insisted on the use of some components - hubs and brakes among them - from the existing Lola-BMW car, and this compromised the design to some extent. Another factor was a major constructional modification imposed by Dornier: they converted Terry's full monocoque into a cross between a monocoque and a 'bathtub' (open-top structure) which was less stiff and probably impaired the handling qualities. Finally, once again there was a lack of liaison during the development phase.

Designed more or less simultaneously with the BMW was a Cosworth-Ford-powered version of the JWA Gulf Mirage. The front end of this was much the same as before, but the back was converted to a composite monocoque/space-frame layout to accommodate the shorter but wider engine, and there were other minor differences. Development of this car tended to be deferred by JWA because of John Wyer's concentration in 1969 on the Gulf-Ford GT40, culminating in its win at Le Mans. However, the second Gulf Mirage car became a winner towards the end of the 1969 season when Terry assisted with the development work.

By the spring of 1969 Terry had decided that there were disadvantages in working to the orders of another company or individual. Even in those cases where the cars had been built in his own shop, he had never been brought deeply enough into the subsequent development work to get the best out of them. Also, once all the drawings, jigs and patterns had been handed over to the client, normally he had no further access to them as a possible means of speeding-up the next project of a similar nature. The answer, clearly, was for him to become a constructor rather than a consultant - to design, build and sell the cars of his own choice. He and John Lambert therefore established Leda Cars Ltd as a company to make and market the vehicles that Design Auto laid out.

Formula 5000 was obviously going to be a big feature of 1970 racing, so the Leda 5000 was quickly designed but there was not enough in the kitty to provide the £6000 - £8000 needed to build the first car. Terry went to Indianapolis for the 1969 race, partly as a refresher course and partly to look for customers with ready cash. He was unsuccessful in the latter respect but Dan Gurney asked him to design an Indianapolis car for 1970. Though this meant temporarily going back on his newly made decision, Terry felt that he must refill the coffers, so he agreed. He must have done a good job since Gurney drove the car into third place. The fee was still insufficient to finance the Formula 5000 car but fortunately the Malaya Garage Group, who were appointed sole concessionaires, offered a merger since they were interested in going Formula 5000 racing themselves. So the car was built and presented to the press in February 1970, having run for the first time earlier that month.

During the 1970 season the Leda suffered more misfortunes than Terry can recall with any other of his cars - a veritable chapter of mishaps and accidents! The highlights were major handling problems, which caused the rejection of two cars by a customer, and four nearly write-off crashes by Malaya's drivers Mac Daghorn and

Roy Pike, two of them in practice and two in races. The car was considerably redesigned, as the Mark 2, during the summer, in an endeavour to overcome the various troubles, and by the end of the season things seemed to be going better.

Terry worked like a beaver through the winter, designing and building the Leda Mark 3, or LT25 as it was called in deference to the current fashion for labels rather than names. The LT25 differed considerably from its predecessors, and Terry had high hopes for it. But again these were not borne out on the circuits during 1971, primarily because of chronic oversteer. This was eventually cured, whereupon Trevor Taylor crashed at Oulton Park, through no fault of the car, injuring himself in the process and severely damaging the LT25.

For 1972 Malaya Garage signed up New Zealander Graham McRae, one of the top Formula 5000 drivers and a practical engineer of some repute. Part of the deal was that Leda Cars would build him a Formula 5000 car to his own requirements and basic specification. This was done, and the combined abilities of the two men resulted in an immediately successful vehicle, the LT26, with which McRae won the 1971-2 Tasman series in Australia and New Zealand against strong opposition. When Graham continued his winning ways in and around Britain in the early months of the 1972 season, it looked as though Terry's fortunes had finally taken an upswing, but not a bit of it! Malaya decided in July that they had had enough of racing, although one would have thought that, since they had survived the storm so far, they would stick around for a while in the calmer waters and do a bit of cashing-in. With virtually no reference to Terry they sold the Poole establishment lock, stock and barrel to McRae so that he could build and sell replicas (called GM1s) of the car that was doing so well.

In hardly a cheerful frame of mind, Terry transferred Design Auto to his attractive self-designed home above nearby Wimborne. He had already started work on a Formula 1 car for the German Eifelland organization who wanted a replacement for the much-modified March 711 that Rolf Stommelen had been racing with scant success. By September this new car, which was to have a Cosworth-Ford V8 engine, was well advanced and Terry felt that it had real possibilities. But once again he was to be frustrated as Eifelland were taken over and the new management decided to have nothing more to do with motor racing.

Terry's consequent enforced idleness did bring one advantage in that it gave him the time to prepare many of the drawings and sketches that appear in the pages of this book. And, of course, his designer's brain was still ticking busily. Just after Christmas 1972 he introduced the Design Auto Plan-a-Car scheme – a serious and carefully thought-out endeavour to make racing-car ownership possible at a substantially reduced cost. In essence, he would provide the 'home constructor' with a full set of plans together with a comprehensive parts list specifying companies able to supply the necessary materials and components – anything from a complete monocoque tub to a clevis pin.

The plan sets covered six single-seater categories – Formulae 5000, 2, 3, Atlantic, B (USA) and Super-Vee – and Terry fixed their prices, by guess and by God, at what seemed a very reasonable level. Since many components were standardized across the range, and the cars were designed for construction without any specialized equipment, he estimated that the cost of a rolling chassis should be 50 per cent or even more below that of an 'off-the-shelf' assembly from one of the regular constructors. At the time these words were written the scheme was already off the ground, several sets of plans having been sold, and Terry was thinking of extending the range to embrace Formula 1, USAC Championship, CanAm and sports cars.

3

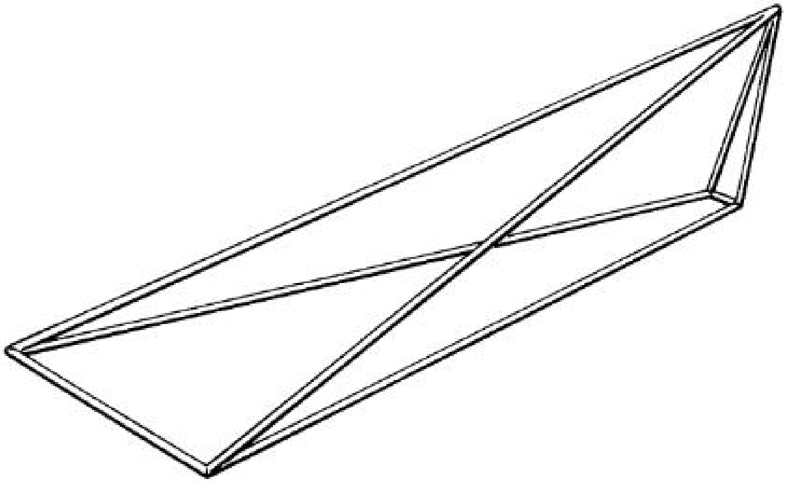
A pack of Terriers

A survey of the racing cars designed by Len Terry between 1957 and 1972

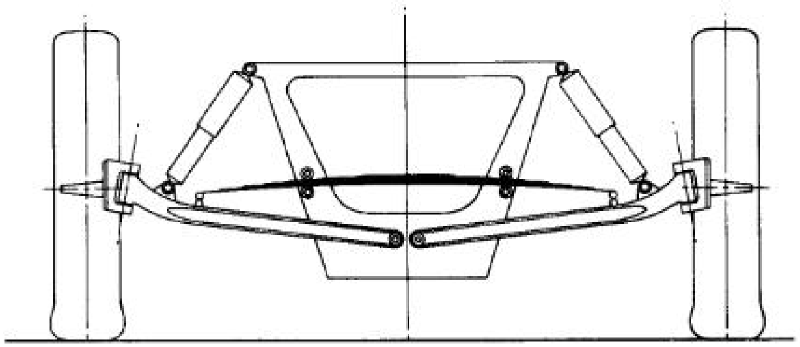
TERRIER MARK 1 (1957-8)

The first of an impressive line of Terrier racing and sports cars was derived from a vehicle Terry bought second-hand in 1955 from John Teychne in order to go racing. It was built by Teychne - who never raced it - at the premises of his small London company, Progress Chassis, which produced the early Lotus models for Colin Chapman; in fact the car was a contemporary of the Lotus 3b sports car, which it resembled in a number of chassis and suspension respects. The power unit was one of the then-popular Ford E93A 1172 cc side-valve engines which were cheap to buy, easy to work on and reasonably strong, although inevitably their power output was limited.

Terry raced the car for about three years, making various improvements during this time, but gradually it became outclassed by the better-handling cars such as the Lotus 9 and 11. He decided to produce something better, but shortage of money dictated the use of the existing engine and running gear for which he designed and built a space-frame chassis and body. Torsional stiffness was the crux of the chassis concept; even this early in his career Terry was convinced that a stiff frame was essential for



Because of its full triangulation, and therefore high stiffness, this tetrahedron form was adopted for the backbone of the Terrier Mark 1 space-frame



Terrier Mark 1 swing-axle front suspension; the halfway-out roller location of the leaf spring gave a high roll-stiffness without over-firmness on bumps good roadholding, although in his search for it he went for a more complex layout than he would have tolerated in later years.

The basis of the frame was a built-up backbone of tetrahedron shape, chosen for its inherent rigidity. From this projected the rest of the chassis, of conventional space-frame layout. The mid-section panels of the full-width aluminium body were rigidly attached by pop-riveting. They were therefore stressed and contributed quite a lot to the overall stiffness of the structure.

Having no workshop facilities at my North London home, I marked out the frame shape on the floor of the living room, where I cut and mitred all the tubes. This was done in conjunction with a perspective sketch on which all the tubes were numbered; the corresponding numbers were also marked on the actual tubes, to ensure correct assembly. I enlisted the help of a welder friend in nearby Hornsey, and the two of us spent our holiday building up the frame. When finished it weighed 59 lb (just under 27 kg), which was quite light in view of its complexity, but I reckon in fact it was strong enough to have taken an engine of up to 3 litres.

The rear suspension was orthodox - 4.9:1 Austin Seven live axle (located by a radius arm on one side and an A-bracket on the other, with the torque tube in the middle), coil springs and telescopic dampers - but the front-end layout was an interesting cross between Leslie Ballamy's and John Cooper's ideas. It comprised a divided Ford axle - the halves being pivoted close together at the middle - and a transverse leaf spring which was mounted so as to give additional roll stiffness. This was done by replacing the normal central anchorage by two widely spaced pairs of rollers, the spring being sandwiched between each pair. On bump or rebound the spring adopted a simple curvature, but in cornering it assumed a reflex or S shape, in which mode of bending it was naturally considerably stiffer.

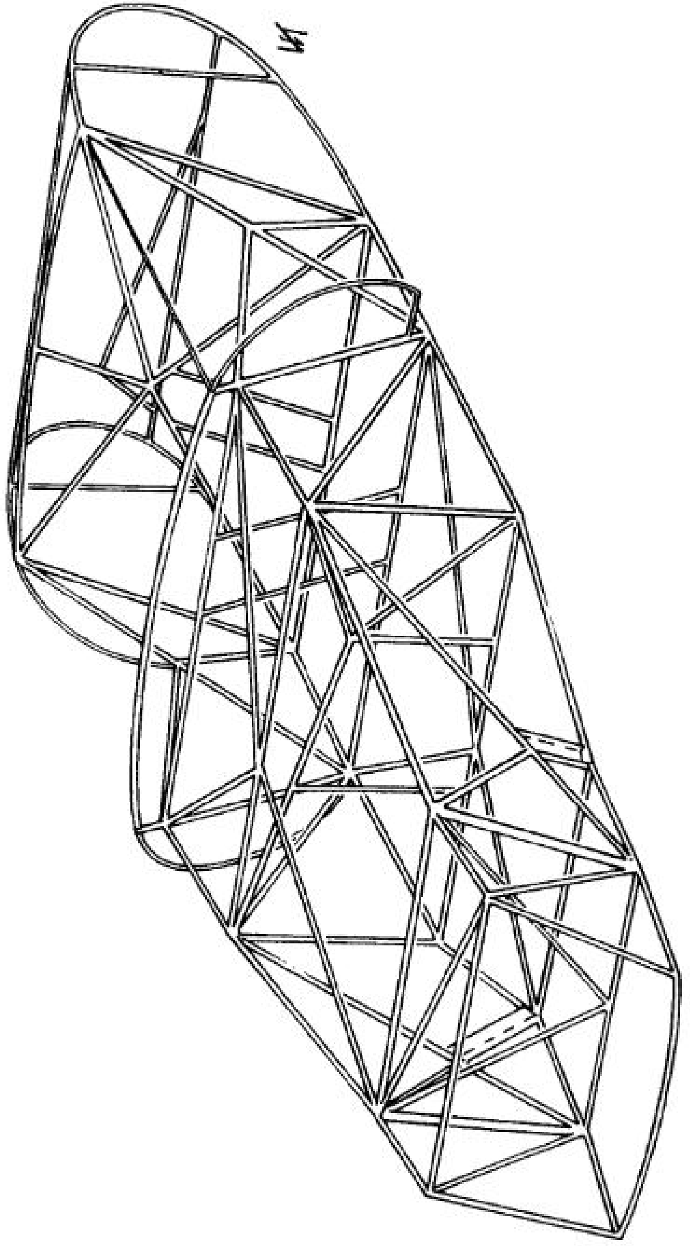
The steering system was based on an Austin Seven reduction box but a bell-crank linkage was employed, similar to that of the 1969 Lotus Formula 1 and Indianapolis cars. Also of Austin Seven type, the wire wheels were transferred from the Teychne car; they were built originally by West London Wheel Company and carried second-hand Dunlop R4 tyres, bought cheap from one of the 500 racing lads. Terry recalls them as being rather deficient in wet-roadholding qualities!

To keep the cost down, the duck-tailed body was designed so that only the nose portion had double curvature, and the panel beating for the nose was carried out by a friend on a wooden former made by Terry. Commercial-grade aluminium was used for the body panels, 20 swg for the nose and 22 or 24 swg for the rest.

At this time I was earning the princely sum of £12 a week at Lotus, so the Terrier Mark 1 had to serve me as personal transport as well as a racing machine. I even used it for holidays. Because of the car's dual function, engine tuning had to be moderate and did not extend much beyond the use of the Ford Eight cylinder-head which, because of the smaller clearance volumes, gave a compression ratio of about 8.0:1 instead of the standard 6.5:1. Also I had to be very careful not to shunt the car - hence my deep feelings about the wet-road grip of the R4 tyres! Total cost of the conversion, excluding the original purchase price, was about £100.

TERRIER MARK 2 (1958-9)

The Mark 1 was raced regularly by Terry during 1958 and performed twice more at the beginning of the 1959 season. During the intervening winter, though, he met



Complete space-frame of Terrier Mark 2, showing the high degree of triangulation

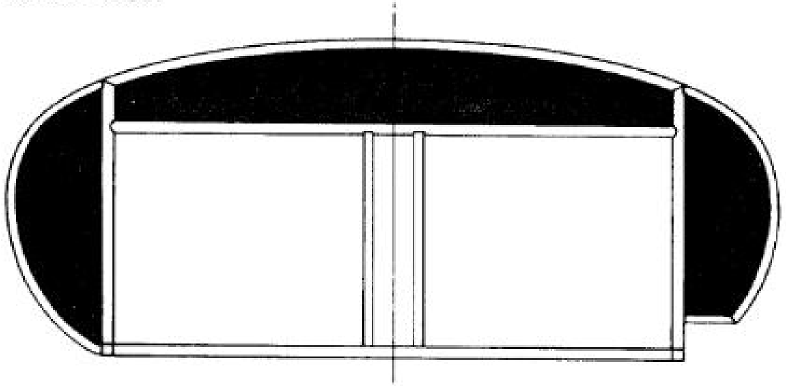
Brian Hart - later a name to be reckoned with in Formula 2 racing-engine building - and arranged to construct a new car for him. Since Brian could afford £400-£500 - quite a worthy sum in those days - Terry decided he could start from scratch. In taking on this major spare-time task he had no option but to neglect his own Mark 1 which in any case was beginning to show signs of mechanical senility.

Although I began with a 'clean sheet', I realized that an economical approach on the chassis side was essential if the kitty was also to pay for such essentials as engine, gearbox and final drive. I was helped here by working at Lotus, since this enabled me to incorporate a number of existing components which I could buy at a reasonable discount. Further savings were made by obtaining other bits and pieces through Brian's father who owned a garage with a BMC distributorship.

Because of the inescapable fact that undue weight puts the cost up and the acceleration down, an unusually short wheelbase of 6 ft 10 in (2083 mm) was adopted. The space-frame was a simpler concept than that of Terrier Mark 1, primarily to facilitate building, and in fact turned the scales at a mere 52 lb (23.6 kg). It was not quite as stiff as the first effort but subsequently it proved able to cope with 1½ litre engines giving well over 100 bhp.

This time the building of the frame was 'farmed out' to Frank Coltman, who was to become the boss of Racing Frames Ltd, but Brian and I made the body except for the nose, which again had double curvature and so was entrusted to a professional panel-beater. Another 'repeat' was the pop-riveting of the skin to the centre-section of the frame, as a means of increasing torsional stiffness. So far as I

know, this was the first car to have a diaphragm-type instrument-panel bulkhead as a further twist-reducer – an idea of mine which received wider acclaim later when it was featured on Chapman's first Formula 1 car, the front-engined 2½ litre Lotus 16 of 1961.



On Terrier Mark 2's central bulkhead, Terry introduced sheet-metal diaphragms to increase torsional stiffness; they are indicated here by shading

The body constituted one of the major conceptual differences from the Mark 1, which had a full-width shell. To save weight, an exposed-wheel layout was adopted for the Mark 2, and the combination of a wedge-shape profile and cycle-type mudguards extending down in front of the wheels resulted in a fairly low drag coefficient, as evidenced by a maximum speed of well over 100 mph.

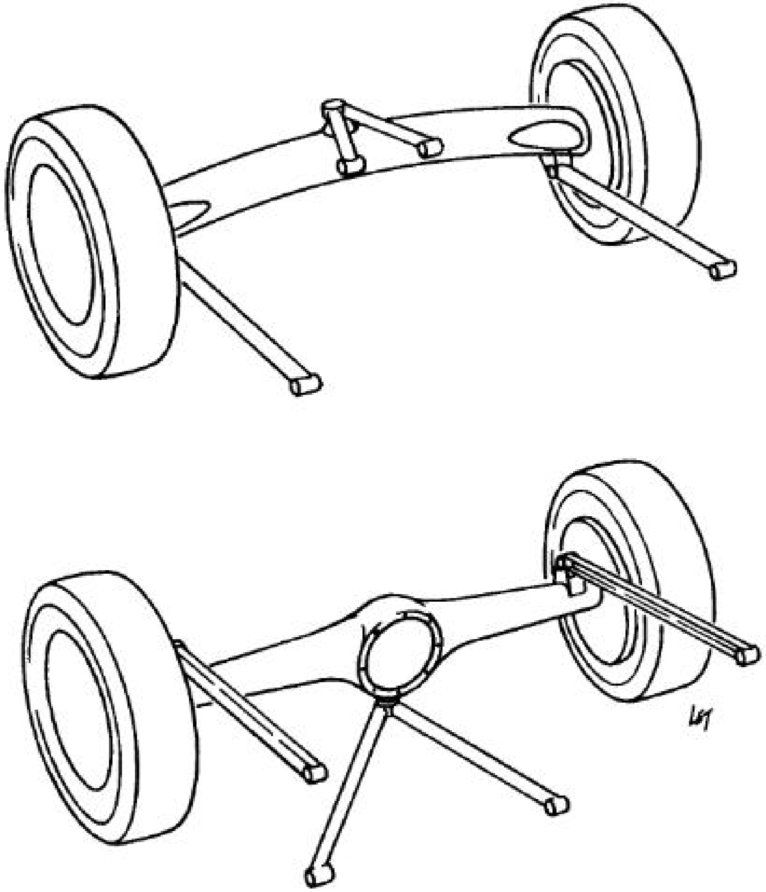
The double-wishbone front suspension of the Terrier Mark 2 had a basic similarity to that of the Lotus Seven, and incorporated a number of common components. However, the geometry was altered in line with Terry's own thinking, and the lower wishbones were reversed so that the brake-loaded member was in compression; one arm of the upper wishbones was formed by the anti-roll bar. A further change was to increase the track as a means for raising the cornering power. The steering was through a Lotus-modified Morris Minor rack-and-pinion system.

At the rear, a live axle was retained for simplicity and predictability of handling. However, it had to be properly located so the suspension system incorporated two upper trailing arms and a lower A-bracket, in conjunction with coaxial coil-spring/damper units of normal type.

The layout was inspired by that of the G Type ERA, though the latter in fact had de Dion suspension. My objection to the ERA version was its too high roll centre, which I overcame by merely inverting the locating linkage; the A-bracket was ball-jointed to the underside of the final-drive housing. This variation, incidentally, has since been copied for several other cars, perhaps the best-known being the original Lotus Cortina and later models of the Lotus Seven.

Terrier Mk 2 resembled its older brother in having a Ford side-valve engine of 1172 cc swept volume, but this time the more advanced 100E unit was used. It had an Aquaplane aluminium cylinder-head and was canted over at 25 degrees from the vertical to enable the inlet tracts to be straightened out, thus improving the breathing through the two modified SU carburettors. As demanded by the regulations, the camshaft was standard. Brian Hart spent a lot of time working on this power unit, his labours including meticulous polishing of the crankshaft and connecting rods in the interests of fatigue resistance and minimum oil-drag.

Brian's best move, though, was to fit a very small crankshaft pulley – about half the standard size. This, of course, greatly reduced the speed of the dynamo and water pump, and hence their power consumption. The gain was estimated to be about 2–3 bhp at peak revs (perhaps 5 per cent of the maximum output) and the fact that neither generator nor pump was very effective at low engine speeds was immaterial in the racing context. Unlike the



Rear-suspension comparison of G Type ERA (above) and Terrier Mark 2; the latter's inverted linkage gives a lower roll-centre

Mark 1 this car was not intended for regular personal transport, although it was used on the road as a 'fun' car and was always driven to meetings. Close-ratio Buckler gears were fitted in the standard Ford three-speed gearbox case. In fact, cars of this type went surprisingly well with only three closely spaced ratios, primarily because the standard camshaft had so little overlap that the low-speed torque was excellent. The Terrier's rear axle was from a Morris Minor and gave no trouble at all.

The combination of Terry handling, an above-average power output and spirited driving enabled Hart to win the One-off and Chapman Trophies in 1959. (Perhaps even more remarkably, the same model in Keith Norman's hands won the Chapman Trophy again eight or nine years later.) The 1959 success caused not a little head-scratching and, apparently, some jealousy because the 750 Club called a special meeting to suggest that the Terrier Mark 2 was 'bending' the regulations in some way. The counter was short, sharp and effective, Hart offering to repeat his best times on any circuit and then to hand the car over to the Club for detailed examination and measurement. No further action was taken!

Because of the success of this one-off, I formed a small company during the latter part of the 1959 season to build a batch for sale. I supervised the construction of the first four in my spare time, but this particular commodity became very scarce indeed when I went from Lotus to Gilby Engineering. As a result, the manufacturing standards began to fall, which was bad for the reputation I was trying hard to build up, so I opted out after most of my small credit balance at the bank had been used up.

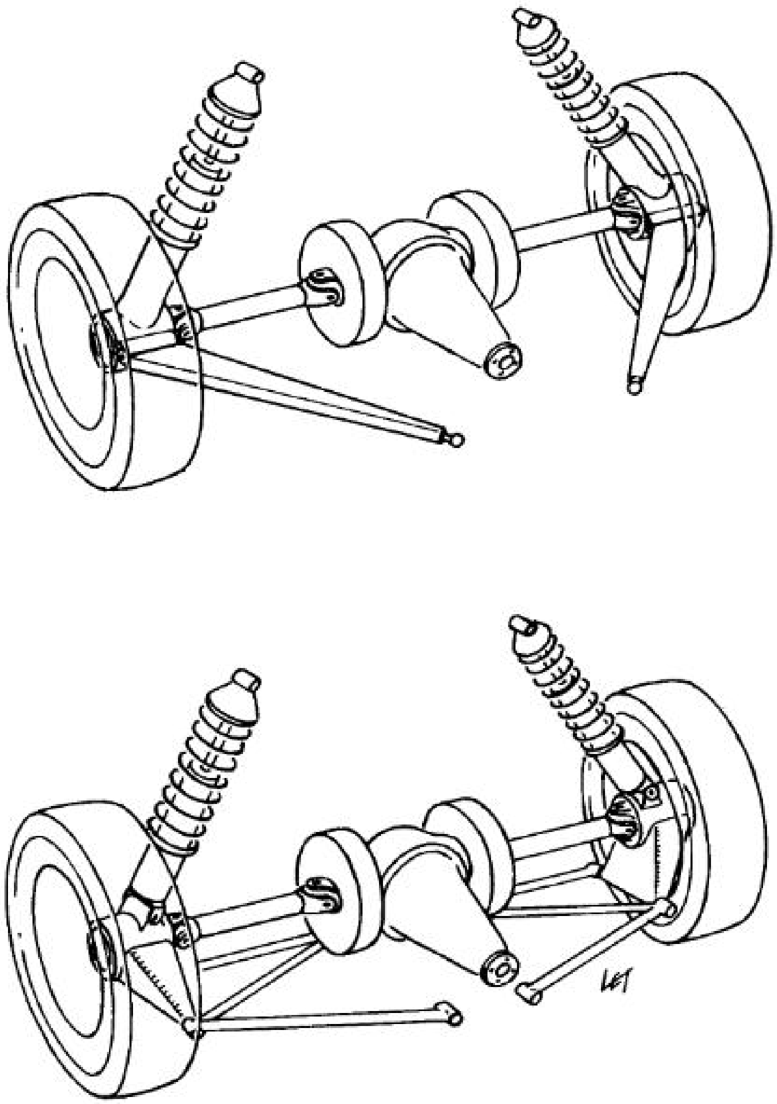
GILBY A TYPE (1960)

In brief, this front-engined 1100 cc sports car had all-independent suspension, a full-width body and a Coventry Climax single-ohc engine. As already mentioned, it was planned initially as a full aluminium monocoque structure but Gilby's sheet-metal facilities were not adequate for such exacting work and Len was not keen to farm-out the manufacture. This is the usual problem of sub-contracting - 'will the other lot make a decent job of it when I'm not there?'

The space-frame designed instead of the monocoque was my lightest yet at 50 lb (under 23 kg). I attribute this low weight to a combination of minimizing the number of members and using thin-gauge (20 swg) tubing - a fairly obvious recipe but one that works only if the designer really understands what happens to a frame in racing conditions. As before, the centre-section body panels were pop-riveted to the tubes for stiffness. Because the body shell had a lot of double-curvature, I sub-contracted its manufacture to Williams & Pritchard, a very competent North London firm who had already produced racing car bodies for a number of constructors including Lotus. As a one-off it didn't justify the cost of moulds, so 18 swg aluminium was used rather than GRP.

Front suspension was of orthodox double-wishbone layout, with a separate anti-roll bar, and modified Morris Minor rack-and-pinion steering was used. The front hubs were aluminium castings. For his first essay at independent rear suspension, Terry went for a strut layout in which the drive-shafts contributed to the lateral location of the wheels and so were of fixed length. Such a design was mechanically simple and robust, and not difficult to manufacture, while its geometry promised reasonably safe and predictable handling qualities.

Although this suspension had obvious affinities with the



Terry's strut-type independent rear suspension on the Gilby A Type and Terrier Mark 4 was an improvement on Colin Chapman's design (above) in that it eliminated side-loading on the struts

'Chapman strut' system, it had one major difference:

> **In Chapman's layout, cornering applies side loads to the struts, and the resultant 'stiction' tends to impair their response to road irregularities. This deficiency was minimized in my design by making each strut separate from its hub carrier and connecting it by a substantial yoke** (see accompanying sketch). **This yoke reacts some of the drive and braking loads but not the cornering loads which are taken directly by the transverse links – the broad-based wishbone and the drive-shaft above it. Hub carriers were steel fabrications, because this was the cheapest way of getting a light yet robust component, and the rear brakes were inboard to minimize unsprung weight and to relieve the suspension struts of the brake-torque loads.**

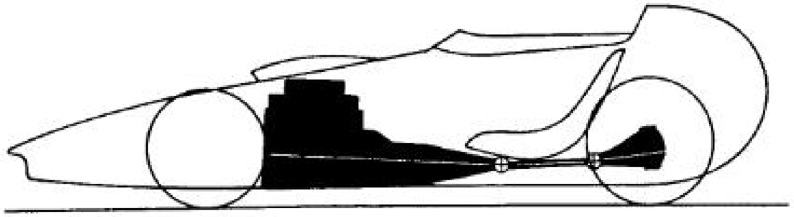
The Gilby gained a number of places during the 1960 season in Keith Greene's hands, never finishing lower than third in its class. Its greatest success, though, was when Peter Arundell drove it to victory in the very wet Archie Scott-Brown Trophy race for *Formule Libre* cars at Snetterton.

TERRIER MARK 4 (1960)

This Formula Junior car was another project for Brian Hart who again provided the finance. Unfortunately the budget was rather limited, so a front-engine configuration was adopted, since putting the engine behind the driver would have meant paying £200 for a Renault gearbox. Terry formed another small company to build the car, and in fact three Mark 4s were constructed.

This model was designed at the same time as the Gilby A Type, and the two cars had a number of common components, including most of the front and rear suspension items. The only significant difference between the cars here was that – for reasons of cost – the lighter Formula Junior car had Girling cast-iron drum brakes, as fitted to the Triumph TR2. The use of ordinary pressed-steel wheels was also dictated by price considerations.

As before, the wedge-shape space-frame had that Terry trade-mark, the integrated mid-section body panels. It was a straightforward structure which weighed about 55 lb (25 kg). All body panels were of single curvature except for the nose and tail portions, which once again were entrusted to Williams & Pritchard.



On Terrier Mark 4, the engine unit and final drive were given opposed inclinations to lower the propeller shaft and hence the seat

The Ford 105E engine was believed to be the first with the cylinder head modified to give the inlet ports a really steep down-draught angle (about 55 degrees). They emerged on the top of the head alongside the rocker cover. Since Len makes no claim to being an 'engine man', this work was entirely Brian Hart's responsibility although the idea was Terry's. It was certainly effective since the car was probably the fastest front-engined Formula Junior car ever built, and at one time held the Brands Hatch lap record for its class. However, the engine never gave its full potential on twisty circuits because the twin Solex carburettors (Webers were too costly!) suffered from float-chamber surge, causing spluttering on corners.

Terry overcame the difficulty of finding room for both the propeller shaft and a low-seated driver by means of some typical ingenuity:

I tilted the engine down at the rear and the final-drive unit down at the front, connecting them by a small-diameter thick-wall propshaft. Since this arrangement absorbed less power than the shaft-alongside-driver scheme then used by Eric Broadley on the Formula Junior Lolas, it probably contributed significantly to the Mark 4's good performance.

In spite of its disabilities on corners, the car was doing quite well until Brian crashed it at Oulton Park towards the end of the 1960 season. It was so extensively damaged that Terry and Hart decided to rebuild it completely as a Series 2 model during the ensuing winter. When it was almost finished, in early 1961, Brian decided to join the recently formed Cosworth organization. Since he wanted to take the existing engine, with its down-draught cylinder head, with him for analysis, it was replaced by one of Keith Duckworth's side-draught motors.

In its revised form the Mark 4 was still front-engined and had a similar but slightly shallower space-frame. Suspension was basically as before but the track at both ends was widened by 4 in (partly because of the change to magnesium wheels) and the geometry was modified to reduce the ground clearance a little. Another change was from cast iron to AlFin brake drums.

Although the engine gave less power than its predecessor, its Weber carburettors were devoid of temperament under lateral accelerations, so the Terrier's high cornering capacity could be exploited to the full. As a result the car was reasonably successful in 1961, again with Brian Hart driving, and the car was still running over ten years later though with a 1½ litre engine.

GILBY B TYPE (1961)

The second Terry project for Gilby Engineering – a Formula 1 car – was something of a milestone in Terry's career since it was his first essay at the mid-engine configuration. This car also was conceived as a monocoque structure; in fact it was to be much more of a true aircraft-type monocoque – 'all outer skin and stringers' – than anything that has yet appeared on the racing circuits. Once again, though, manufacturing complexity forced a reversion to the conventional space-frame.

In designing this frame I was very much aware of the weakness that results from the need of a driver; the cockpit bay has to be left virtually unbraced on top. I decided to compensate for this by taking tubular bracing round the *outside* of the cockpit. This made the frame wider than its competitors but appreciably stiffer for its weight of 62 lb (28 kg). Most of it was of ¾ in × 20 swg Truweld tubing; although this sounds rather thin, the frame gave no trouble at all in two seasons' racing.

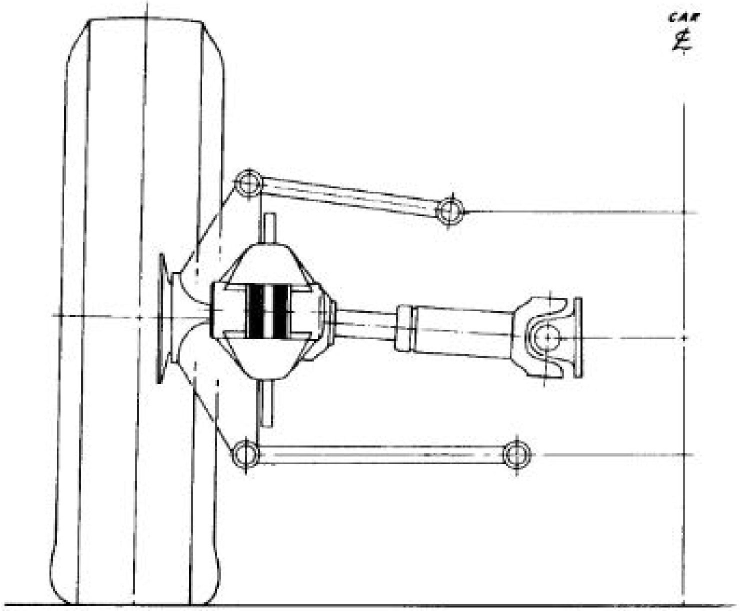
In an interesting contrast with the previous year's Formula Junior situation, it had become cheaper to build a mid-engined Formula 1 car than a front-engined one because of the ready availability of the appropriate hardware such as Colotti gearboxes.

Orthodox double-wishbone front suspension was adopted, embodying outboard-mounted coaxial coil-spring/damper units, and Morris Minor rack-and-pinion steering, but a major change was made in the rear suspension:

Using the drive-shafts as part of the linkage imposed limitations on the geometry because the desired low installation of the engine prevented the shafts from being at the optimum angle in relation to suspension articulation. In addition, I felt that the shafts would already have plenty to cope with in transmitting the driving torque, and a failure could have highly unpleasant consequences. I therefore separated the

driving and suspension functions by incorporating top links to complete the quadrilaterals; splined couplings were fitted on the shafts to accommodate 'plunge'.

Girling disc brakes were used, and although an inboard disposition of the rear discs was considered for the unsprung weight advantage it was rejected because of the cooling difficulty and the doubtful ability of the Colotti gearbox to withstand the additional loading and heat that the brakes would impose. As a compromise, the discs were situated inboard of the uprights, an arrangement also used by BRM at about that time. Since the discs were right in the airstream, they could be smaller than would have been practicable had they been within the wheels, so a small saving of unsprung weight was achieved.



In addition to having link-type rear suspension, the Gilby B Type featured semi-inboard rear disc brakes

The engine of the Gilby B Type was one of the familiar Coventry Climax 1½ litre four-cylinder twin-ohc units, and had been tuned by Willy Griffiths to give about 145 bhp with good reliability. The chassis was designed to take the 2.7 litre 'Intercontinental' Climax as an alternative, but the car was not tried in this form. It handled as well as any of its Formula 1 competitors but the more glamorous marques had - with due respect to Keith Greene - the better drivers, so the big win eluded it.

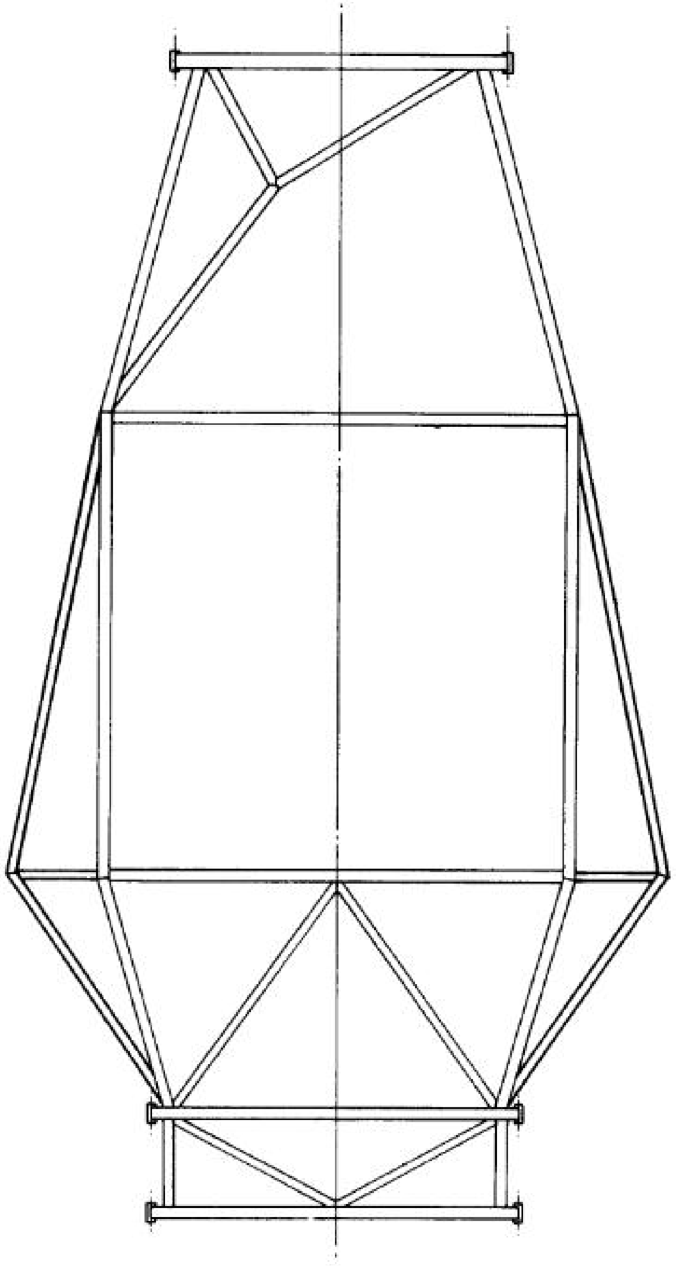
Early in 1962, after the Cope Allman takeover of Gilby Engineering, Terry was asked to design a Series 2 version as a freelance job for Greene who had decided to continue racing. The main modifications were to the frame, to take the BRM 1½ litre V8 carburettor engine, but unfortunately this unit never produced anything like the 170 bhp claimed for it in this form, and the car did not achieve any significant success.

TERRIER MARK 6 (1962)

The basic design of this small rear-engined open sports car was completed while Terry was in hospital recovering from his Oulton Park crash. He produced it for Geoff Miller, the owner of the Terrier Mark 2 he had written off, as a form of compensation! Consequently it involved as many as possible of the Mark 2's salvageable components.

Three cars were built, the first by Terry, after he had left hospital, and Miller, who footed the bill. The second was constructed by the small DRW company, which had been started by Dave Warwick, an engineer previously in charge of the Lotus development shop, and the third by Morris Mears with help from Brian Hart and under Terry's supervision.

A feature of the space-frame was that it extended well outboard of the cockpit area - in effect a development of the reinforcing method used on the Formula 1 Gilby. As



Stiffness in the cockpit area of a space-frame can be improved by taking bracing tubes round the outside of the opening. Terry first used the method on the Gilby B Type, and here is its application to Terrier Mark 6

would be expected, the mid-section panelling was riveted to the framework.

For the suspension I broke away completely from my previous practice by adopting the 'cross-over' system illustrated. The cross-connections at front and rear meant that the springing provided no roll stiffness whatever, this coming purely from the anti-roll bars. My purpose here, of course, was to separate the bump and roll control functions in the hope that each could be done better than in a combined system.

On the track the car proved to handle as well as the contemporary Lotus 23 and the rear-engined Elva (albeit with certain idiosyncracies), but its 'between-classes' Ford-based 1.2 litre engine, which was coupled to an inverted Renault Dauphine gearbox, was not powerful enough for it to be really competitive with 1½ litre cars. Had the suspension been fully 'sorted' by work on spring rates and bar strengths, some of this performance deficit might have been overcome by achieving still better handling, but time and finance did not permit. The other novel feature of this promising little car was the horizontal disposition of the radiator.

I adopted this in the search for low frontal area and it resulted in the body being 3 in lower than that of the Lotus 23. The air was taken in at the nose in the usual way, passed downwards through the matrix and out beneath the car. Although the arrangement worked well in this instance, it was less successful on my later Shelby CanAm car which had a ground clearance of only 3 in as against the Terrier's 5 in. Clearly the Shelby's underside was too near the road for the air to be extracted effectively.

TERRIER MARK 7 (1962)

Here was a dream car that never went beyond the sketch stage. Terry's intention was to give his wife an 'unbirthday' present of an Austin Seven-based car so that she, too, could go racing but, due to the lack of funds brought about by his accident, she had to take the thought for the deed.

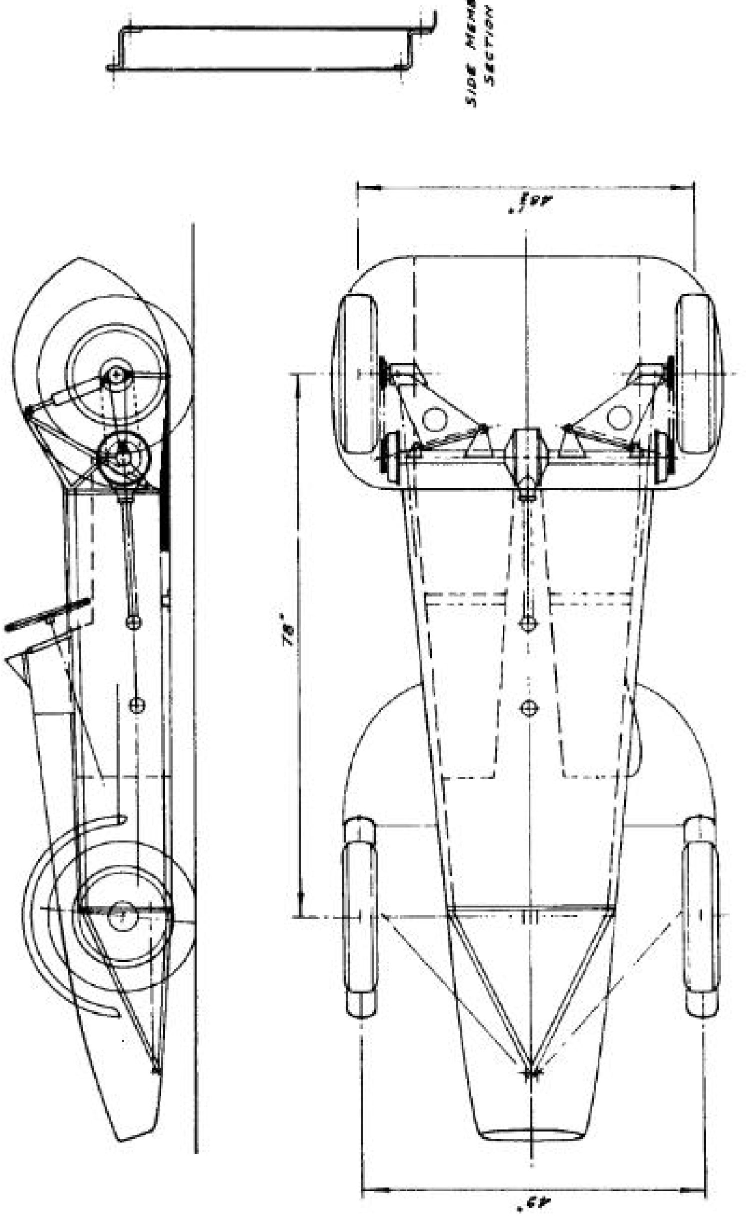
Under the 750 Club rules, the original Austin Seven channel-section side-members had to be used, serving their original function. However, the Terry brain had cooked up an ingenious modification which would certainly have caused the scrutineers something of a headache:

I proposed first to split each side-member longitudinally and then to join the resulting two angle-sections by aluminium sheet about 12 in deep. This would have given me a couple of deep-section side members to form the basis of a semi-monocoque structure.

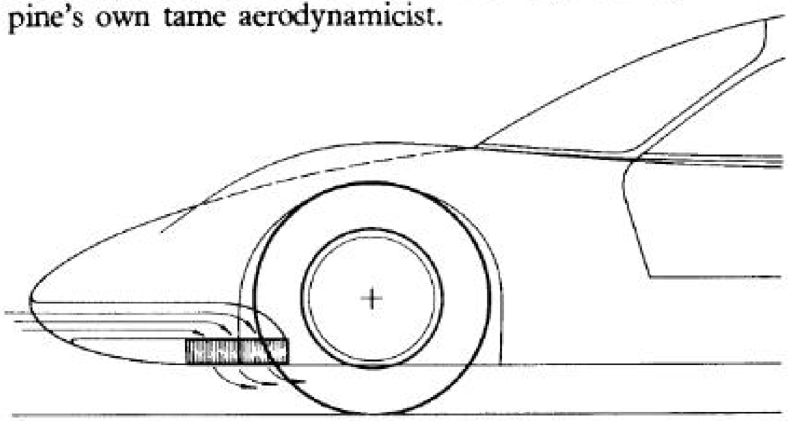
Another 750 Club regulation was that the original rear axle and quarter-elliptic springs had to be used. Terry's intended way round this was to mount the axle, complete with brakes, on the chassis and to have chain drives from the ends of the half-shafts to the independently sprung wheels. It seems a pity that this intriguing plot never took shape in metal.

TERRIER MARK 8 (1962)

This small rear-engined sports car, designed for the French Alpine company, was intended to compete at Le Mans. It was based largely on the Terrier Mark 6 and, as laid out, had a similar straightforward space-frame with outboard bracing around the cockpit. It incorporated numerous Renault components specified by Alpine, and metric dimensions were used wherever possible. As on the Mark 6, 'cross-over' suspension and a horizontal radiator



Terrier Mark 7, for 750 Club racing, was unfortunately never built; its chassis and final-drive layout were highly original were featured. Terry's design, however, did not include the bodywork, which was to be the responsibility of Alpine's own tame aerodynamicist.



A horizontal 'downflow' radiator was a feature of the Alpine sports car (Terrier Mark 8); it had already proved successful on the Mark 6 from which this vehicle was derived

In the event, the car was not built in its designed form. Bernard Boyer, the Alpine chief engineer, reworked it completely and, ironically, it proved unsuccessful in its first season. Although Terry was not involved at all in the development of the car, he ascertained that it was eventually brought back to somewhere near his intentions, whereupon it began to win the occasional race!

KINCRAFT (1964-5)

Shortly after Terry's return to Lotus, he was asked by Jack Pearce if he would design him a *Formule Libre* car. Terry explained that he could not because he was under exclusive contract to Colin Chapman. However, he agreed to act as a spare-time adviser if the job was given to Martin Waide, a Lotus draughtsman. Since Waide was on the ordinary weekly payroll, a 'moonlighting' task of this kind was perfectly ethical. Therefore an agreement was made between Pearce and Waide, and after Terry had set down the basic layout and geometry, Waide completed the detail design and the drawings, and supervised the building at Pearce's Midlands establishment.

This car, christened the Kincraft, is believed to be the first single-seat circuit racer designed specifically to take the Ford 4.7 litre V8 engine. In effect, therefore, it was the primeval Formula 5000 car, in which connection it is worth commenting that Martin Waide was later responsible for the Formula 5000 Lotus 70.

There was nothing fancy about the Kincraft, which was based to some extent on the Gilby B Type. Its space-frame was braced to withstand the extra engine weight and higher dynamic loadings, but it still weighed only about 80 lb (36 kg). The suspension was orthodox, with double wishbones at the front and reversed lower wishbone at the rear, and the spring/damper units were mounted outboard. We used Brabham uprights, hubs and wheels to save cost and production complications.

The car first ran in 1965 and was highly successful almost from the start, first in Jack Pearce's and later in Jim Moore's and Robin Darlington's hands. It was one of the most prolific lap-record gatherers of all time, its list including Lydden Hill, Castle Combe, Mallory Park, Snetterton, Rufforth, Llandow and Silverstone (Club circuit). Quite an achievement for one car with only one engine!

LOTUS 38 (1965)

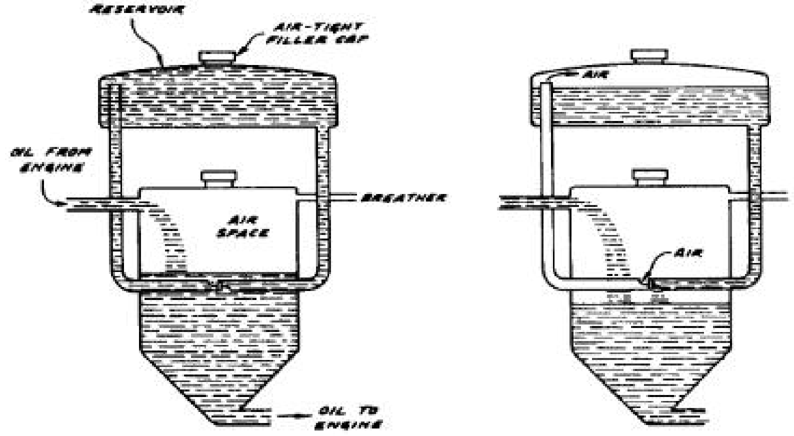
Terry returned to Lotus shortly after completing the Alpine design and was involved with the third Indianapolis car, the Lotus 38. He did not allocate it a Terrier number because, although he was responsible for the overall design, the running gear came 'off the Lotus shelf', as he puts it. However, the car is sufficiently interesting in several respects to warrant inclusion here.

It had the first *full* monocoque structure to be built by Lotus; previous so-called monocoques were in fact 'bathtubs' in that the body top panel was detachable to facilitate maintenance. The integral top skinning of the Lotus 38 increased torsional stiffness by something like 50 per cent – a very worthwhile improvement. It may be significant that, since then, I have never designed an open-top structure for a single-seater. This car was the first single-seat Lotus to have a 'droop-snoot' and a semi-wedge-shape body profile designed to give some aerodynamic downthrust at high speeds.

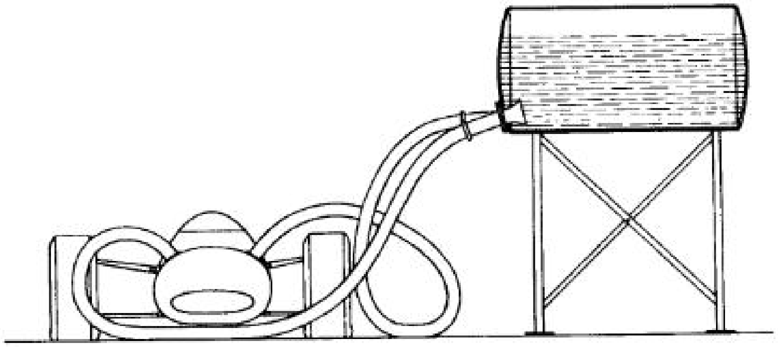
Because all the Indy turns are left-handers, it was decided to offset the chassis 3 in to the left, so the suspension transverse links were 6 in shorter on that side than on the other. Also, the geometry gave a relatively high roll centre at each end; with orthodox Formula 1 geometry many cars tend to run at too low a ride level on the banking, and Terry thought that a high roll axis would give rise to a 'jacking-up' effect (induced by centrifugal force) on the outside wheels, thus bringing the ride height back to somewhere near its straight-line condition.

An ingenious modification was made to the lubrication system to cater for the additional five gallons of oil needed for the Indianapolis race.

We carried the extra oil in a hermetically sealed reservoir above the driver's knees; this reservoir was connected to the vented main tank which was stowed in the nose behind the radiator, where it was cooled by part of the airflow coming in through the nose opening. When the oil level fell sufficiently in the main tank to uncover the connecting outlet, air could get up to the reservoir, allowing oil to flow down until the outlet was again covered – on the 'bird bath' principle.



This automatic replenishing device for the Lotus 38's lubrication system enabled an extra five gallons to be carried for Indianapolis



Double-sided refuelling arrangement invented by Len Terry for the Lotus 38, to reduce pit-stop times

Another novelty at that time was a gravity-fed fuel reservoir which ensured an air-free supply to the injection system. This was achieved very simply by utilizing the rearward surge of the fuel on acceleration as a means of opening a non-return valve; under deceleration the valve closed, thus preventing any reverse flow back from the reservoir.

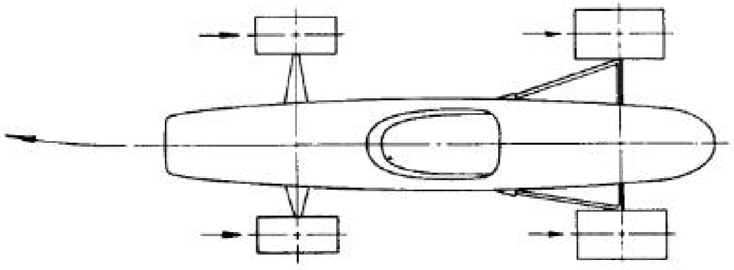
I think I made an important contribution to the effective performance of the Lotus 38 by designing a refuelling system that would give really quick replenishment from the gravity tanks which are obligatory in the pits at Indy. It was based on a venturi-shaped outlet designed to give good flow through the standard 3 in outlet of the refuelling tank; immediately after this outlet the pipe branched, in Y form, into two 3 in pipes which delivered to both sides of the car simultaneously.

This improved system enabled the Lotus to take on 45-50 US gallons of fuel in under 20 seconds, thus gaining about that much time on each of the three compulsory pit stops. However, as is so often the case in these situations, the company held the advantage for the 1965 race only, since everyone else had tanks similar to the Terry design the following year.

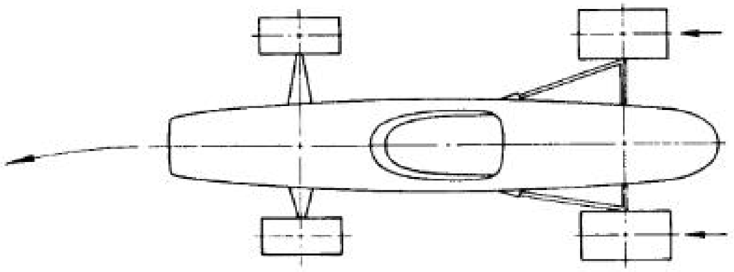
AAR EAGLE (1965–6)

The ninth in the Terry series was really two cars in one, the Formula 1 and Indianapolis versions of the Eagle. Dan Gurney's original plan was to have two different designs, one for each purpose, but he soon realized that both time and money would be too short for this. Since a win at Indianapolis was Gurney's primary objective, because of the enormous financial reward, Terry designed the car as an Indy model that could be adapted to Formula 1.

In two respects, however, it was necessary for practical



DECELERATION



ACCELERATION

If the body is offset towards one side (as on the Lotus 38 Indianapolis car), braking and acceleration cause a veering tendency because the forces at the wheels are asymmetrical reasons to depart from the optimum Indy specification. First, to keep the car as small as possible for Formula 1 use the tankage was reduced to the bare minimum, and one or two of the cars eventually raced with additional side tanks. The other compromise concerned the suspension. A high roll axis – with its attendant jacking effect already mentioned – would have been quite unsuitable for Formula 1 racing, so the roll centres were kept relatively low. Clearly, an asymmetrical suspension system would have been equally impracticable for Formula 1 work so the body was set in the middle.

In any case, I was no longer sold on asymmetry for Indy, because it caused the car to veer towards the outside of the track when braked for a bend. This, of course, is due to the different leverages exerted by the braked wheels about the centre of gravity of the car, and it meant that the brakes could not be slapped on so hard. Conversely, but for the same reason, the car would swing inwards when accelerated out of the bend.

As an overall concept the Eagle was not unlike the Lotus 38, though it had smoother and more elegant body styling. It had a 96 in (2438 mm) wheelbase and a 60 in (1524 mm) track – a little wider than the Lotus. The body section was slightly bigger than that of the 38 but the monocoque was also rather stiffer torsionally and its weight was almost identical at about 100 lb (45.5 kg). The skinning of the Indy version was in 16 swg aluminium, whereas 18 swg was used for the Formula 1 car to reduce weight. This and other lightening gave the quite significant weight-saving of about 50 lb (23 kg) but the Formula 1 Eagle was still heavier than its main competitors.

In designing the suspension and other tubular components, I went up in diameter and down in wall thickness wherever possible (in comparison with the Lotus 38) to gain strength without weight penalty. Front and rear suspension systems were similar to those of the Lotus but with anti-dive inclination of the wishbone pivots at the front. I used live stub-axles at the front for the first time, since these could be made lighter and more rigid than the dead type.

In fact the front and rear stub-axles were of almost identical design except that the rears were splined to take the drive-shafts. The magnesium wheels were designed specially for the Eagle in 1965 and it is worth mentioning that they were still thought good enough for Gurney's 1970 Indy car (see later).

For Formula 1 racing the Eagle was intended to have the Gurney-Weslake 3 litre V12 designed by Aubrey Woods, but because of development delays on this a Coventry Climax 2.7 litre four-cylinder 'Intercontinental' engine (giving about 260 bhp) was installed initially. The Indianapolis version was to have a Ford V8 four-cam power unit of around 480 bhp. Hewland gearboxes were used on both versions – the two-speed LG500 on the Indy car and the five-speed DG300 (instigated by Gurney) on the Formula 1 model.

Both had the gravity-feed extra fuel tank but the 'bird bath' oil reservoir was incorporated initially only on the Indy car. However, when the V12 was eventually run it proved to be something of an oil-burner, so the extra lubricant capacity was added to the Formula 1 vehicle. Both cars had the same size of radiator, the extra output of the Ford engine being offset by the use of alcohol-base fuel which, because of its high latent heat of evaporation, reduces engine temperatures significantly.

Among the modifications made to the Formula 1 Eagle as a result of track testing and racing was a reduction in the anti-dive effect to improve the handling. However, Terry left AAR almost as soon as the second Formula 1 car, with the V12 engine, was completed, so was not involved in any way with the subsequent development work. Both versions of the car achieved a measure of success. At Indianapolis in 1966 all five Eagle entries qualified and one of them, driven by Lloyd Ruby, led the race for a greater number of laps than any other competitor. In Formula 1, with the Climax engine, Gurney picked up World Championship points at Reims on the car's second outing, and the following year, with the V12 engine, he took the laurels in the Belgian Grand Prix at Spa.

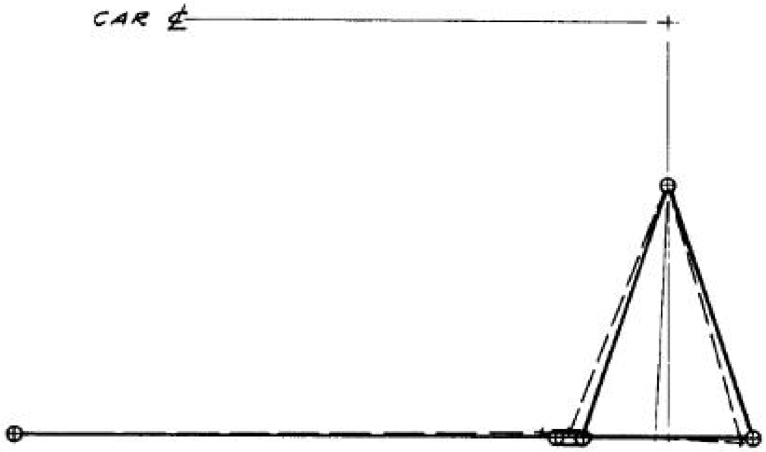
SHELBY CanAm (1967)

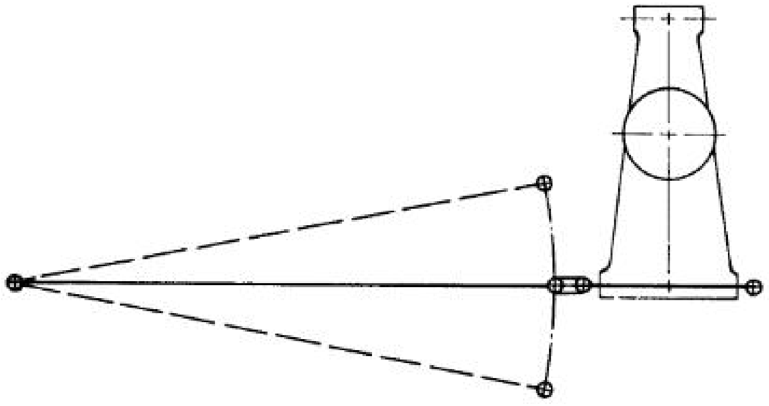
Transatlantic Automotive Consultants' first project, and Terry's tenth, was intended to be powered by a 5.7 litre Gurney-Weslake Ford-based engine, and on a 'waste not, want not' basis, the running gear was taken directly from the Eagle. There were no problems here, since the design was entirely Terry's and he had laid it out with an eye to a possible CanAm car in due course, while Shelby was involved with AAR anyway.

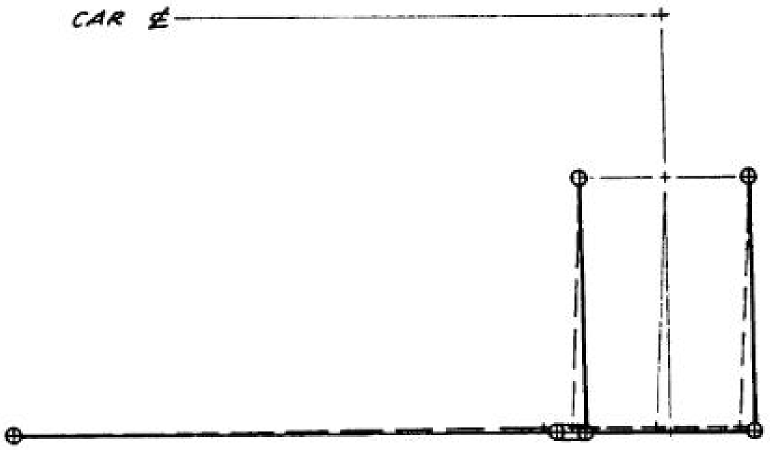
The basic monocoque was of orthodox construction, in 18 swg aluminium, and the car had a wedge profile though this was less angular than were most of the subsequent CanAm contenders. Its windscreen was blended into the bodywork since the screen height was no longer covered by the regulations - a fact of which Terry was probably the first to take advantage. Two features of the Terrier Mark 6 and Alpine (Mark 8) cars to be adopted were the horizontal radiator and cross-over interconnected suspension. The intention was to have American-made frictionless roller-spline couplings on the drive-shafts, as a means of obviating the normal splines' tendency to lock-up when transmitting high torques, thus 'solidifying' the suspension and adversely affecting the handling.

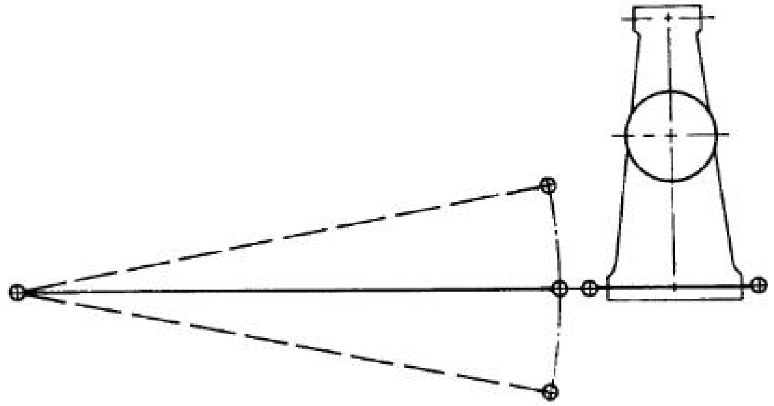
For the rear-suspension linkage, I used for the first time on one of my own cars a bottom link of the parallel-arm type. I did in fact incorporate this earlier on the Lotus 37, which was the Lotus Seven with independent rear suspension, but this car of course was basically a Chapman design. In my opinion the orthodox linkage (as shown in the sketch) **has a basic disadvantage in that, to minimize bump-steer, the designer has to juggle with radius arm lengths and give the rear uprights some castor inclination. By making the bottom wishbone into parallel arms, I not only reduced the bump-steer but facilitated setting-up the suspension by reducing the number of variables. This system has since been used on other racing cars, Jackie Stewart's 1969 Matra and the 1970-1 Tyrrells being notable examples.**

For the first time, too, Terry evolved his own rack-and-pinion steering gear, in effect a 'cut-and-shut' Alford & Alder unit of the type fitted to the Triumph Herald. Its aluminium pinion housing was bored and tapped on its right-hand side to take a screwed-in light-gauge steel tube, since the unit had of course to be almost central in the chassis. The existing left-hand tube was cut short and aluminium end caps containing plain bearings were fitted to the tubes. Mounting clamps at the extremities of this assembly virtually relieved it of any bending loads. Part of the untoothed end of the rack was cut off, threaded and then screwed into and welded to the other end, after which this component was lightened by drilling through at both ends. The drilled bore was then tapped to take the yoke-ends for the steering tie-rods. At 5½ lb the complete steering gear was exceptionally light, and its total cost of under £30 was significantly below that of making a complete new unit; it proved entirely trouble-free and has been used on most of the later Terry cars, some having an improved system with a very simple vernier adjustment on









Terry introduced parallel-arm bottom links on the rear suspension of the Shelby CanAm car to obviate the bump-steer effect given by a reversed wishbone. The drawings on this and the previous page show the essential difference: the wishbone swings longitudinally with suspension movement whereas the Terry layout deforms from a rectangle to a parallelogram the outer ball-joints as a means for minimizing bump-steer.

Since the Gurney-Weslake engine was not ready when the car was completed (so far as is known, the engine never was put into a car), a 5.7 litre Ford pushrod unit was installed by Shelby in the United States. The gearbox was a ZF five-speed unit which had the advantage of synchromesh on all gears, although the ratios could not be changed individually as on the Hewland.

I was present at the car's initial testing which began disastrously when two engines in succession ran their bearings; in my opinion this was because the oil was inadequately warmed-up before the car was driven hard. Also, the roller-spline couplings had not been obtained, so the car was run with the normal solid-spline type, and its handling difficulties proved very intractable. Although these could have been largely due to the splines locking-up under power or braking, rather than to any serious deficiency elsewhere, the cross-over suspension was condemned by Shelby's driver, the late Jerry Titus, and engineer Phil Remington, neither of whom appeared to like the idea from the start.

Distressed by this refusal to give his design a fair chance, Terry returned to England. Remington converted the car to conventional springing but it still had the solid-spline couplings and the handling remained troublesome. Shelby eventually disposed of the car to an American private owner, who installed a 5.7 litre Chevrolet engine and refitted the original springing arrangement, though still without the roller-spline couplings. Even so, the car was made to handle quite respectably and achieved a number of successes in club racing.

BRM P126 (1967)

This so-called Tasman car (the Terrier Mark 11) was TAC's second project, and to a great extent it represented what might have been the 1967 Eagle had Terry remained with Gurney. It came about after Louis Stanley had contacted Terry and explained that Jackie Stewart was disinclined to stay with BRM unless he had a more competitive Formula 1 car. Hence the P126 was designed basically as a Formula 1 machine, although BRM decided to build a 2½ litre version of their first 3 litre V12 engine to enable the car to participate in the Tasman races as a means of competitive 'sorting-out' before the 1968 European Formula 1 season.

The car was considerably smaller than the Eagle, since there was no longer any Indianapolis requirement and it could be designed around wee Scots Jackie rather than lanky Californian Dan; also, its fuel tankage was less. Since BRM's policy was to use as many 'shelf' items as possible, Terry was offered a choice of hubs, wheels, uprights, brakes and so on from previous Bourne cars; he chose to incorporate mostly those from the ill-fated 3 litre H16 Formula 1 car.

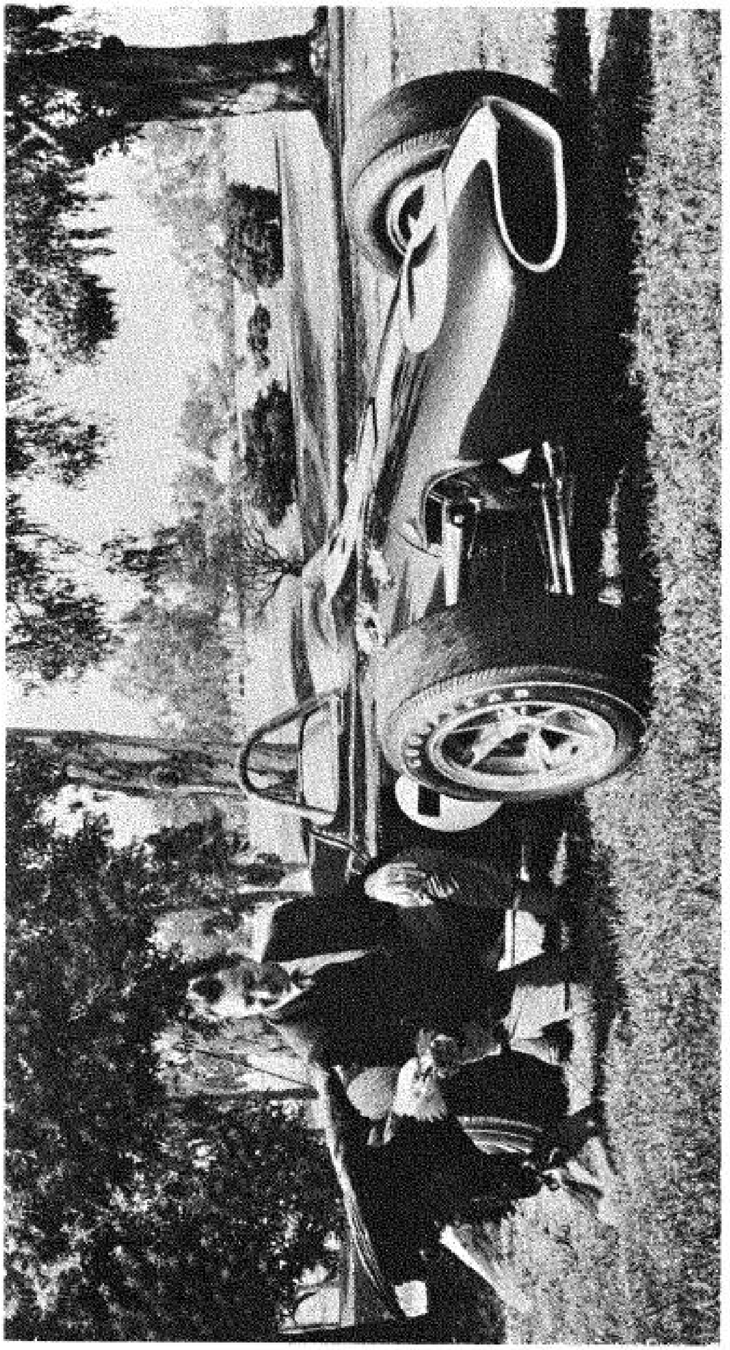
The basic structure of the P126 was my normal full monocoque. This time the front-suspension spring/damper units were mounted inside it and actuated by rocker-type fabricated top wishbones. The inboard mounting of the suspension units reduces air drag a little but takes the dampers out of the airstream, so we had to make additional provision for cooling them. Moreover, you get considerably higher bump loading of the wishbone pivot bearings which therefore have to be more substantial. In fact we used self-aligning single-ball bearings here with complete satisfaction.

As on the Eagle and Lotus 38, an acceleration-operated fuel reservoir was incorporated, and the oil tank had an internal de-aeration pot to reduce the risk of pump starvation. The rear suspension featured the parallel lower links described in the previous section, and threaded adjustment was incorporated for the rear ball-joints of the upper radius arms to facilitate setting-up the suspension to give the best handling.

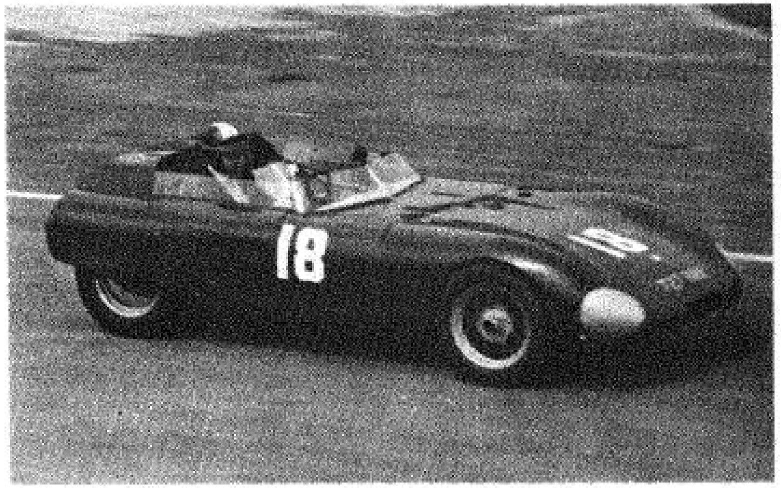
BRM reduced the swept volume of the engine by means of a shorter-stroke crankshaft. Also, since they felt the unit might have possibilities for Le Mans (with its emphasis on durability rather than sheer bhp), they retained the existing two-valve cylinder-head layout rather than experimenting with four valves. Initially a Hewland DG300 gearbox was installed but it was later replaced by one of BRM's own design.

On the circuits, the car proved to be down on power in comparison with its main competitors, Lotus and Ferrari, and it suffered from lubrication troubles. In compensation, its handling and braking were first-class although little testing had been done before it went 'down under'. The late Mike Spence, who drove the Formula 1 version initially, was impressed by these characteristics and felt that the car had plenty of promise though lacking about 20 hp.

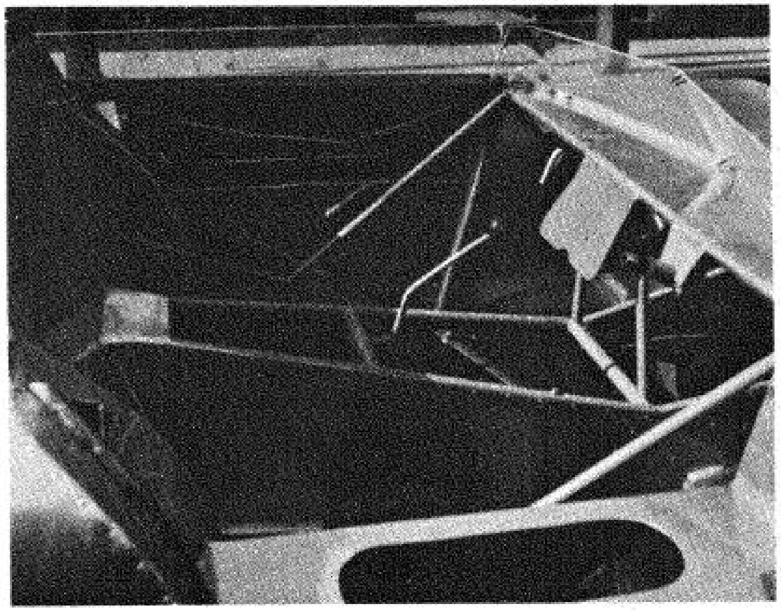
When poor Mike was killed at Indianapolis in 1968, BRM had no-one to replace him as a development driver. Also, there seemed to be some resistance at Bourne to the whole idea of going to an outside designer. Consequently, I was not consulted at all on the development of the design after Mike's death, and the car seemed to become progressively more and more BRM and less and less Terry. They tackled its lubrication difficulties from the wrong end by modifying the oil tank, rather than the engine itself, so little was achieved. The fuel system and the aerodynamics were altered also, but the car seemed to get worse rather than better.



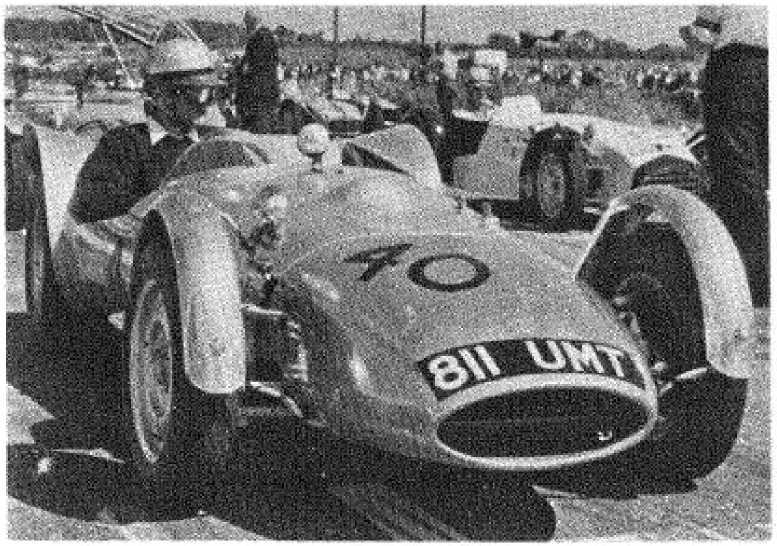
Eagle to right of him, Eagle to left of him . . . Len Terry with feathered and mechanical variants in sunny California



Terry does his stuff in the 'front-room special' – his Terrier Mark 1 with Ford 1172 cc side-valve engine; this stub-tailed racer/roadster was completed in 1958

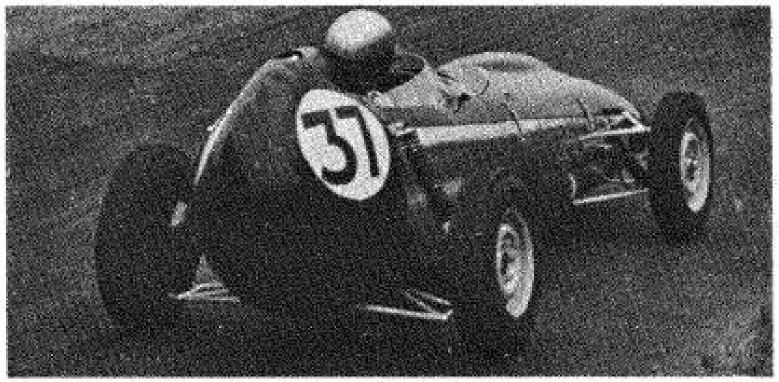


The space-frame of Terrier Mark 1 had riveted-on mid-section body panels

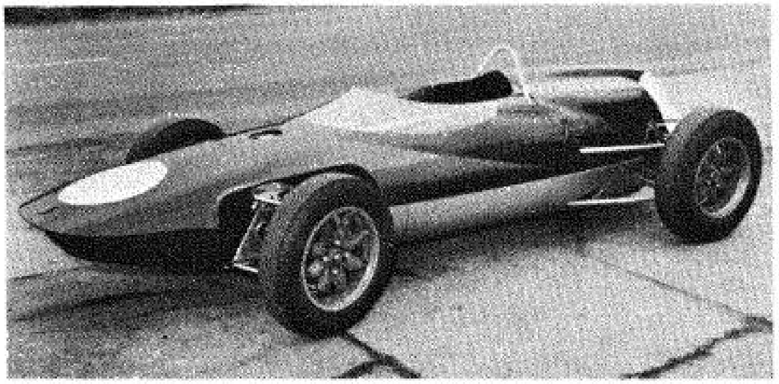


Terrier Mark 2 (here with Brian Hart at the wheel) was certainly a distinctive car, with its motorcycle front wings, low nose and flared rear wings

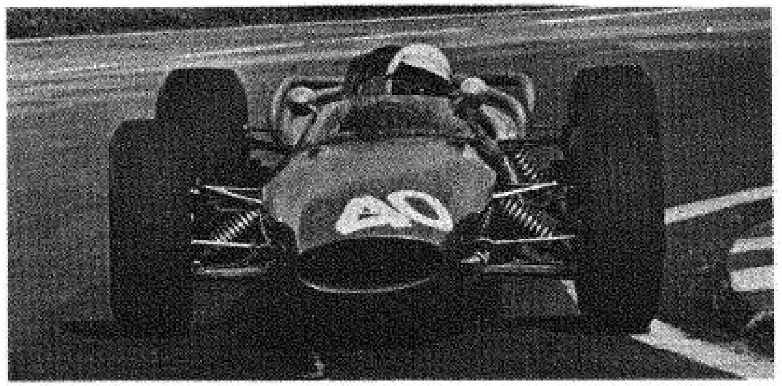
Williams & Pritchard built the aerodynamic bodywork of Terry's third design – the Gilby A Type, powered by a Coventry Climax 1100 cc engine



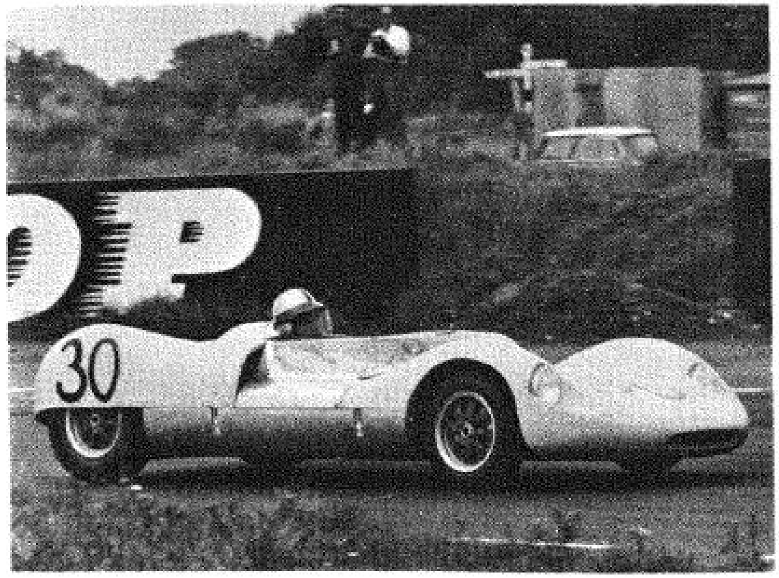
Strut-type rear suspension was a feature of the wedge-shape Terrier Mark 4, a Formula Junior car



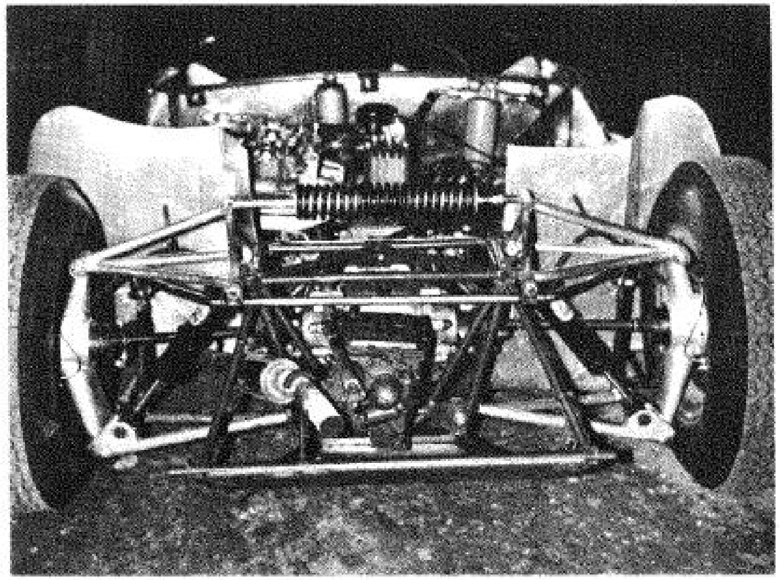
Terry's fifth project, the Gilby B Type, was also a 'double-first' for him: it was a Formula 1 car and had the engine behind the driver. Note the Minilite magnesium wheels



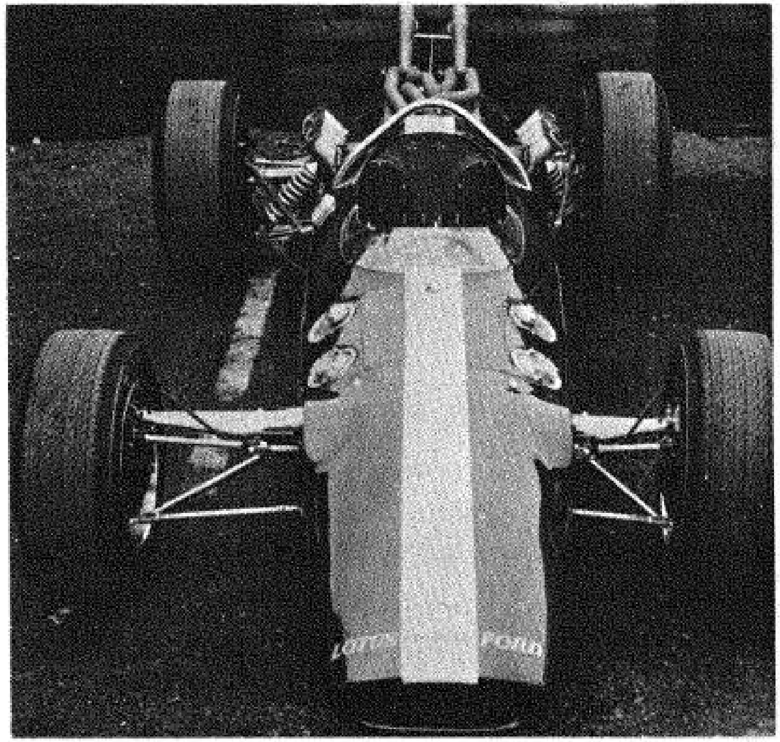
Only the basic layout of Jack Pearce's Kincraft was executed by Terry, the donkey-work being done by Martin Waide. The car, powered by a Ford 4.7 litre V8, had a very successful racing career in the middle 1960s



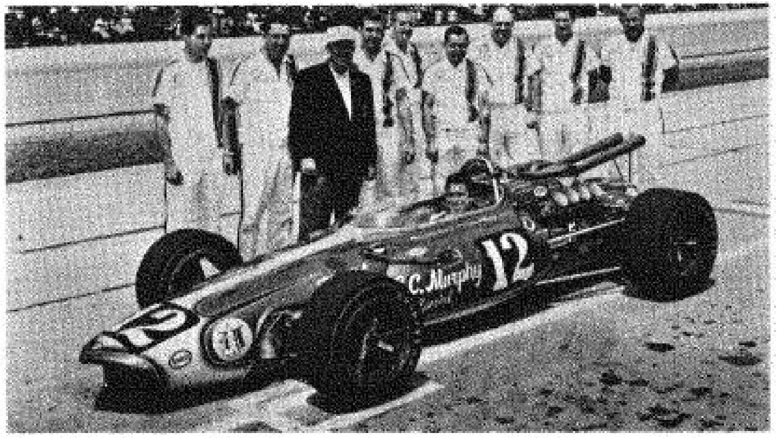
Bodywork of the Mark 6 was characterized by the low nose, achieved by the horizontal mounting of the radiator, and partial enclosure of the rear wheels



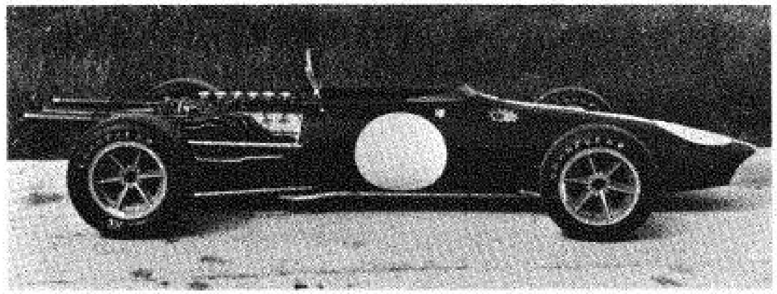
The outstanding feature of the Terrier Mark 6 mid-engined sports car was the laterally interconnected suspension layout. Roll stiffness was provided only by the anti-roll bars, while the springs coped with the bump loads



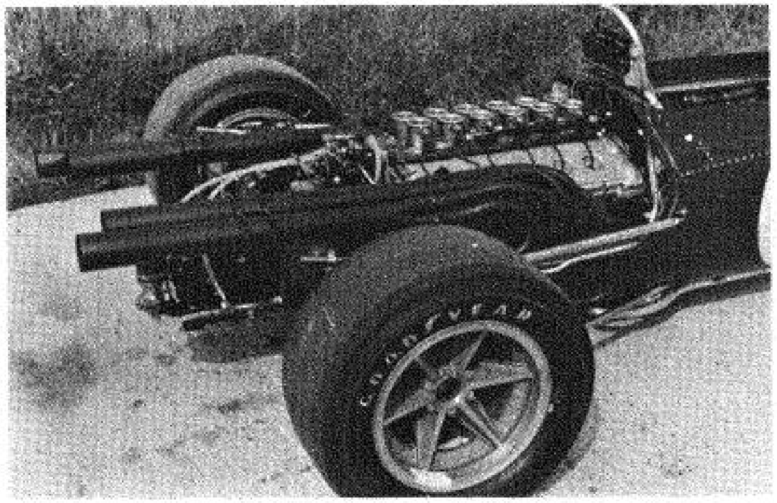
Asymmetry for Indianapolis: the Lotus 38, for which Terry had overall design responsibility, had its full monocoque body structure offset 3 in to the left



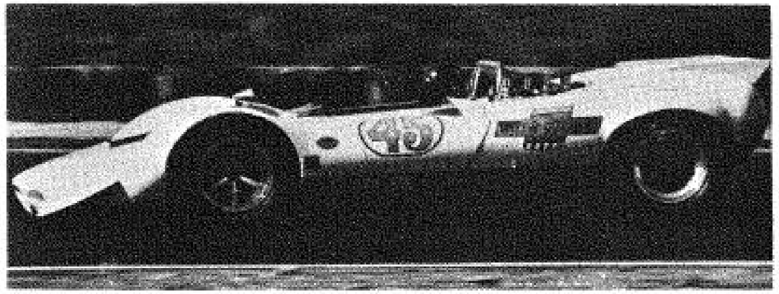
The AAR Eagle, which first went into action in 1966, was a dual-purpose Formula 1/Indianapolis car. Here it is in its second form before the 1967 Indy race, with Roger McCluskey aboard



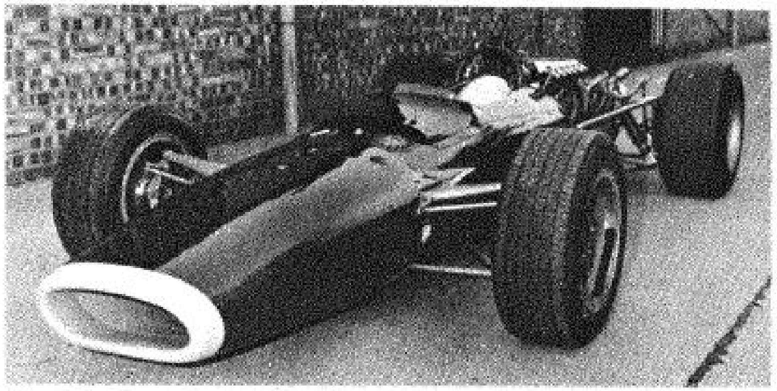
The first AAR Eagle was a relatively large car, to meet its Indianapolis requirements. In this view of the Formula 1 version, the low overall height of the Gurney-Weslake V12 engine is apparent



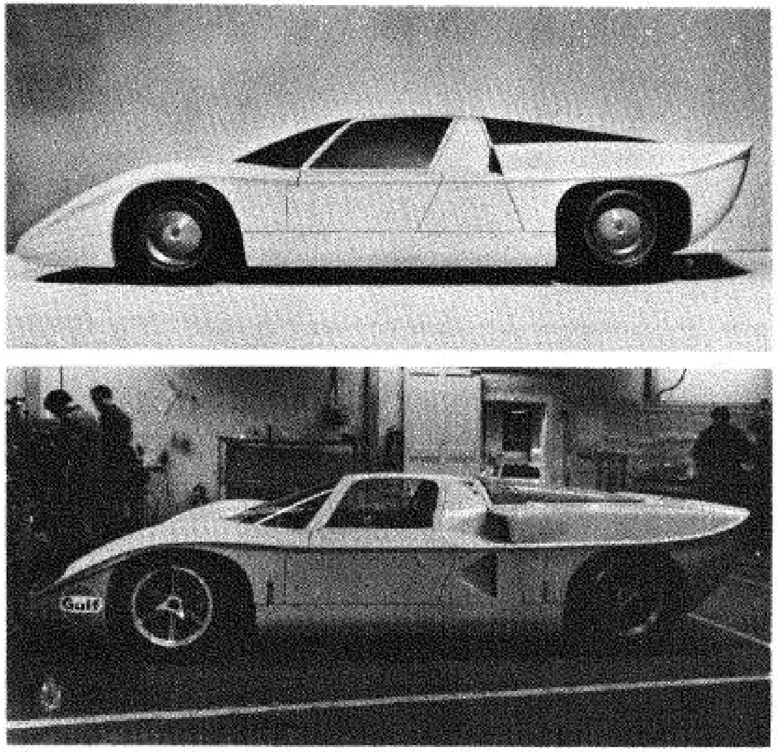
A feature of the Eagle was the specially designed cast-magnesium wheels which proved very satisfactory



TAC's CanAm car, designed in 1967 for Carroll Shelby, was noteworthy for its horizontal radiator and 'cross-over' suspension, as on the Mark 6, but it suffered serious development troubles



The sleek Terry-designed BRM P126 Tasman car incorporated a number of existing BRM components. Its front spring/damper units were inboard to reduce air resistance



In translation from a quarter-scale model to the real thing, the Gulf Mirage-BRM changed its shape very little. It had a nose-mounted spare wheel, and the radiators were immediately ahead of the rear wheels – the lower intake on the actual car is the oil cooler

Its only real success, in fact, was Dickie Attwood's well-deserved though unexpected second place at Monaco early in the 1968 season. A contributory factor to this was undoubtedly the power and durability of the brakes which, as mentioned earlier, were those evolved for the heavier H16; also, at that time the car was more or less in its original form.

GULF MIRAGE-BRM (1967–8)

The first Design Auto project was to design and build two 3 litre prototype sports cars, with BRM V12 engines and Hewland DG300 gearboxes, for JW Automotive. John Wyer originally considered fitting either the Gurney-Weslake or the Cosworth-Ford engine, but the first was inadequately developed at that stage and the second he considered to be too brittle for long-distance races. In practice the BRM unit was not a very good choice since it also revealed a lack of stamina.

I based the Mirage monocoque on that of the Shelby car. The GRP cockpit section was reinforced with steel tubes and bolted to the main structure to increase the stiffness, while a fabricated tubular extension carried the rear suspension and engine rear mountings. The wheelbase was 94.5 in (2400 mm), and front and rear tracks were relatively wide at 58 in (1473 mm), because the BRM engine was quite a bulky and heavy unit. To help compensate for the weight behind the driver, the compulsory spare wheel was mounted in the nose, in a nearly horizontal position. The smooth front-end shape resulted from having the water radiators on the sides of the body, forward of the rear wheel-arches; their ducting had forward-facing intakes and top outlets into a low-pressure region. For minimum drag, the oil-cooler matrix was buried in the side, ahead of one of the water radiators, and was

supplied with air through an NACA duct. The oil radiator subsequently was moved to the nose when a spare wheel ceased to be regulation equipment.

Front suspension had the usual unequal-length wishbones and a separate anti-roll bar, its geometry incorporating 4 degrees of anti-dive inclination on both the upper and lower wishbones. At the rear Terry used what was becoming his standard suspension layout - parallel-arm lower link, single top link and twin radius arms. The anti-squat inclination was adjustable from zero by having three anchorage positions for the leading ends of the radius arms.

To get round the sticking-spline difficulty with telescopic couplings on the drive-shafts, the latter were of fixed length, with a Hooke joint at each end to take the angularity variations and a rubber 'doughnut' inboard of the inner joint to look after the plunge. This arrangement, similar to that of the Formula 1 Brabham, worked well and proved very reliable, but was rather heavy. The ventilated disc brakes were by Girling, as used on the Ford GT40.

After the cars were built at Poole and handed over to John Wyer, I had very little say in their development. They handled reasonably well except for some instability under braking, this being due to their being run on wider tyres than those for which the suspension had been designed; the camber-angle change when the brakes were hard on meant that the tyres were running on their inside edges. Once this problem was pin-pointed it was quickly cured by modifying the linkage geometry to give less camber change on bump at the front and on droop at the rear.

Because of John Wyer's involvement in 1968 with the Ford GT40 for Le Mans, the Gulf-Mirage development work was largely neglected during that season. By the time JW Automotive really got down to it early in 1969 a second version was already being built, and this car was given the modified suspension arrangements as well.

Terry did not find the design stage of these two projects as satisfying as with most of his cars, for the reason that his course of action was so circumscribed by what he regarded as irrelevant regulations - height, door size, luggage space and so on.

HONDA FORMULA 1 REPLICA (1968)

Since designers are as superstitious as the next man, this car for John Surtees is listed as Terrier Mark 14, not 13.

It presented me with unusual problems since in effect I was endeavouring to re-create, almost entirely from photographs and five or six rough layout drawings, rather than designing from square one. In theory, Derrick White (who designed the original Honda while with Lola and left to join Surtees when the latter severed his connection with Eric Broadley) was available for discussion and the car for examination. However, both were nearly 100 miles away, which added at least four hours' travelling on to my day's work.

Some redesigning of the monocoque was necessary merely to allow for the different method of fabricating the steel components. Lola had made these by argon-arc welding but at that time the Design Auto finances did not run to the expensive equipment involved, so nickel-bronze welding had to be used instead. The suspension also came in for modification:

I decided that the front upper wishbone brackets were on the flimsy side, so these were stiffened. Also,

since I was going to incorporate my parallel lower links in the rear suspension, I thought it advisable at the same time to reinforce another possibly weak area, the upper anchorages for the rear spring/-damper units.

The monocoque, suspension and associated components were built at Poole and then handed over to John Surtees, who supervised the installation of the engine, transmission, radiators and so on, and looked after the development work. Partly because of its bulk - the inevitable consequence of the portly engine - the Honda replica never achieved any real success, its best race being the 1968 Mexican Grand Prix in which Jo Bonnier gained fifth place.

TERRIERS MARK 15, 16 and 17 (1968–9)

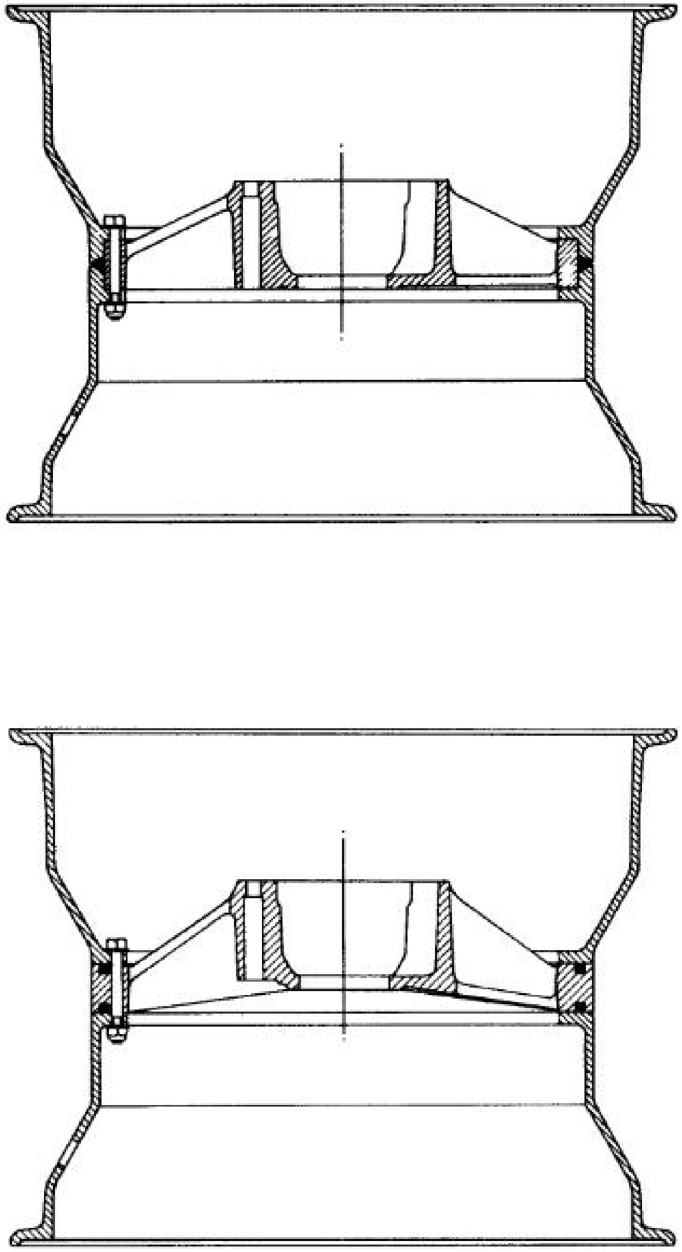
When Nathan Racing requested a Formula 5000 car, Terry agreed to design one and to build two prototypes, the plan being that the Nathan organization would then produce several replicas. When this arrangement fell through and John Surtees accepted the project, the design had already been completed and the two prototypes were almost constructed, but John increased the order to four complete cars plus three 'tubs' and various spares. The Mark 15 was the Nathan car as originally designed, the Mark 17 was the slightly modified Surtees version (the TS5 as it became known) and the Mark 16 was a designed but unbuilt Formula 2 version of the original car.

The full monocoque had an affinity with the Honda in having a single-curvature skin which enabled us to use the relatively high-tensile but low-ductility L72 aluminium alloy; because of the higher strength, 18 swg was sufficient, so the weight was kept down to a very reasonable 85 lb (39 kg). I'm still not sure that this was really the better compromise, since double-curvature panelling is inherently stiffer than single-curvature, but the basic structure certainly gave no trouble.

For standardization between the Mark 15 and the intended Formula 2 Mark 16 version, the nose half of the monocoque was smaller than usual for a Formula 5000 car, so the radiator needed quite a pronounced forward inclination to fit within it. The Mark 16 design, of course, had shorter rear booms for carrying the engine and suspension, as well as shorter wheel-carrying uprights and smaller wheels. Originally, all the uprights were steel fabrications, since this method of construction was significantly cheaper than cast light-alloy components for only two cars. The front uprights never gave any trouble but the rears showed signs of weakness and Surtees duly replaced them by castings. The front suspension incorporated rocking-lever upper wishbones and inboard spring/damper units, but the rear units were outboard, the suspension layout being similar to that of the Mirage-BRM. The original intention had been to fit Girling solid-disc brakes but Surtees opted for a Lockheed vented-disc system instead.

The Marks 15 and 17 were designed for the Chevrolet-based engine only, coupled to a Hewland LG600 five-speed gearbox. At the time, the makers were claiming 400–500 bhp for this engine but the performance gap between Formula 5000 and contemporary Formula 1 cars, even allowing for the greater weight and bulk, suggested a lower installed output. Had the Mark 16 been produced it would have been powered by a Cosworth Ford FVA engine driving a Hewland FT200 five-speed gearbox.

For use on all three variants I designed three-piece cast-magnesium wheels which comprised a spoked central portion and two half-rims; the three



The three-piece wheels designed by Terry for the Marks 15-17 (left) enabled rim width and offset to be varied relatively cheaply, since alternative outer portions could be bolted to the central spokes-and-hub member. For the first Lada 5000, he evolved a simplified and even cheaper form of three-piece wheel, with fewer bolts and only one sealing ring

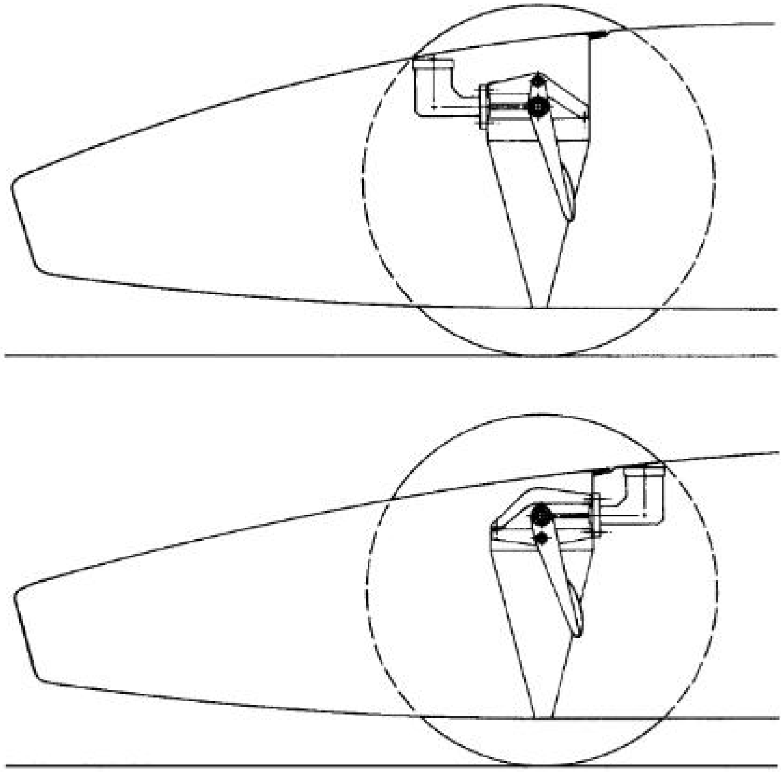
components were held together by means of 16 bolts, and sealing was effected by two large-diameter O-rings. Although these wheels were slightly heavier than one-piece types they had two advantages in that the overall width could be increased or decreased at will, and the offset could be varied as required without the expense of complete new wheels.

As indicated in the biographical chapter, the Terrier Mark 17 or Surtees TS5 was one of Terry's most successful designs. After the rear upright weakness had been cured, and the upper front wishbones strengthened, it proved highly competitive and was winning most of its races by the end of the 1969 season. It is worth recording in this context that Len was involved in all the earlier development work on the car.

BMW FORMULA 2 (1968–9)

When BMW approached Terry for a Formula 2 design, he offered them the Mark 16, but this was not acceptable since they wanted to incorporate a number of existing components, including suspension uprights, hubs and wheels. He therefore started again with a new layout (the Mark 18) based on these special items.

As designed, the car had an orthodox full-monocoque chassis structure. Dornier - the German aircraft company who were employed by BMW to build the car - made an important modification, however, by introducing a detachable top section from above the driver's knees to the engine bulkhead. Although this cover was bolted on, I am sure that the resulting cross between monocoque and bathtub must have been torsionally weaker than a full monocoque. I was given no reason for the alteration but assume that it was to improve accessibility to the interior of the mid-section.



To give the BMW Formula 2 car a lower nose than that of the Terriers Mark 15-17 (above), the clutch and brake master cylinders were resited as shown and the pedal linkage modified

One of the design objectives was to keep the body as shallow as possible. To minimize the depth of the nose section, the clutch and brake master cylinders were mounted behind instead of in front of the bulkhead, and the pedal pivots were also reversed to suit (see sketch). The Girling brakes had solid discs, and AR and NR front and rear calipers, respectively.

The suspension layout followed the established Terry practice, but with outboard-mounted spring/damper units. At the rear, the same method of adjusting wheel alignment was used as on the BRM P126. Some very interesting one-piece aluminium-alloy radius arms and steering tie-rods were used. Produced by the French aerospace industry, they were of relatively large-diameter thin-wall tubing with the ends formed in such a way as to reduce the outside diameter while increasing the wall thickness sufficiently to take the thread for the end fitting.

The BMW 1.6 litre four-cylinder single-ohc engine was the latest racing version of a successful line which had started in 1961; by that time its output was up to about 230 bhp. It drove through a Hewland FT200 gearbox, and the half-shafts incorporated rubber doughnut couplings to accommodate plunge.

In its first racing season (1969) the BMW scored no wins but did secure several places. Terry was not consulted on the earlier development and is convinced that the German engineers concentrated too much on aerodynamics and not enough on handling:

There *was* a handling problem and I was invited early in 1970 to help solve it. The criticism was instability under heavy braking at high speeds, and its cause was very simple. Because of the downthrust of the aerofoils which BMW had added, the car was running below its designed ride height at higher speeds. Hence, when the brakes were applied hard, the reduced bump travel of the front suspension

was not enough to cope with the weight transfer, so the car came down on to the bump stops, with consequent 'patter' if the surface was other than dead smooth. The solution was equally simple – I merely persuaded BMW to raise the static ride height ½ in, by adjusting the spring platforms.

When he tried the car at Vallelunga in February 1970, Belgian star Jacky Ickx was impressed and signed-up to drive it. During that season he notched-up two of BMW's five wins and might have won the July race on France's new Paul Ricard circuit had his engine proved more durable. Since Terry had no further approaches from BMW, he assumes that the handling continued to meet with Ickx's approval.

GULF MIRAGE-FORD (1968–9)

In effect this car (the Terrier Mark 19) was an adaptation of the earlier Gulf Mirage, to take the 3 litre Cosworth-Ford engine which was more powerful, shorter and lighter than the BRM unit, but also wider. As before, the car was built at Poole and then handed over to JW Automotive for development work.

To accommodate the greater engine width, the monocoque was shortened to finish in front of the rear wheels, and as before a space-frame section was built on the back of it; this longer space-frame incorporated the engine and rear-suspension anchorages. It raised the structure weight by a few pounds as the penalty for the improved accessibility. The greater engine output necessitated increased cooling capacity, so the water radiators were larger than in the BRM-powered version.

The original Gulf Mirage car had closed bodywork, designed by Terry and produced in GRP by Specialised Mouldings, but the Cosworth derivative was converted to open form which by that time was allowed by the regulations, and this change gave a substantial reduction in frontal area. In its closed form, incidentally, the body proved to generate virtually no lift at high speeds, even without the use of spoilers. Although the open bodywork had the additional advantage of lower weight, it probably also reduced the overall stiffness of the structure. Nevertheless, once the car was given the suspension modification mentioned earlier it proved competitive enough for Jacky Ickx to win the 1969 Imola sports-car race quite comfortably.

LEDA FORMULA 5000 (1969–70)

In designing this his first 'unsponsored' car since the early Terriers, Terry had to set his own standards. One of his basic concepts was that, for economy of manufacture, the front and rear suspension components should be interchangeable. The 18-gauge L72 alloy monocoque structure was straightforward, with deep-section booms projecting behind the rear bulkhead, under the exhaust system, to provide mountings for the suspension and the engine/transmission unit. Since the suspension anchorages were isolated from the mechanical units, the car could be wheeled about when minus its engine and gearbox. The skinning of the main section embodied no double curvatures (as with the Honda), so there was no sweep-up to the windscreen; instead a GRP surround was fitted.

The suspension systems were relatively straightforward and reminiscent of those for the Lotus turbine-powered Indy car. An upper and a lower wishbone were used at each corner, the upper one, of the rocking-lever type, actuating an inboard-mounted coil-spring/damper unit and an anti-roll bar. There was, of course, a third link in each assembly – at the front the tie-rods connecting with the steering-rack ends, and at the rear two similar rods anchored to the chassis structure.

The road wheels were similar in concept to those I designed for the Mark 15–17 (TS5), but having had further time to think I evolved a lighter and simpler design. This time only 12 bolts and one O-ring were needed per wheel and, as an additional advantage, the cost was reduced by around 25 per cent.

Initially five cars were laid down. One was the Malaya Garage works car, two were ordered by Dan Gurney, for sale in California, and the other two were bespoke by Broadspeed for their own use. The second car was delivered to Dan Gurney but for various reasons he could not accept it and Terry agreed to take it back; it duly reached Poole in the autumn of 1970 and was at once subjected to a bit of updating.

Because of the rumours and exaggerations at the time regarding the Broadspeed cars, it is only fair to Terry and his team to set out the whole matter in some detail. It is a fact, which is not offered as an evasion of responsibility, that Terry had to dash off to Indianapolis (as explained in the biographical chapter) at a critical stage in the design work, some of which therefore was completed by an assistant. Had he been able to do it all himself, as with previous designs, some of the subsequent problems might have been avoided.

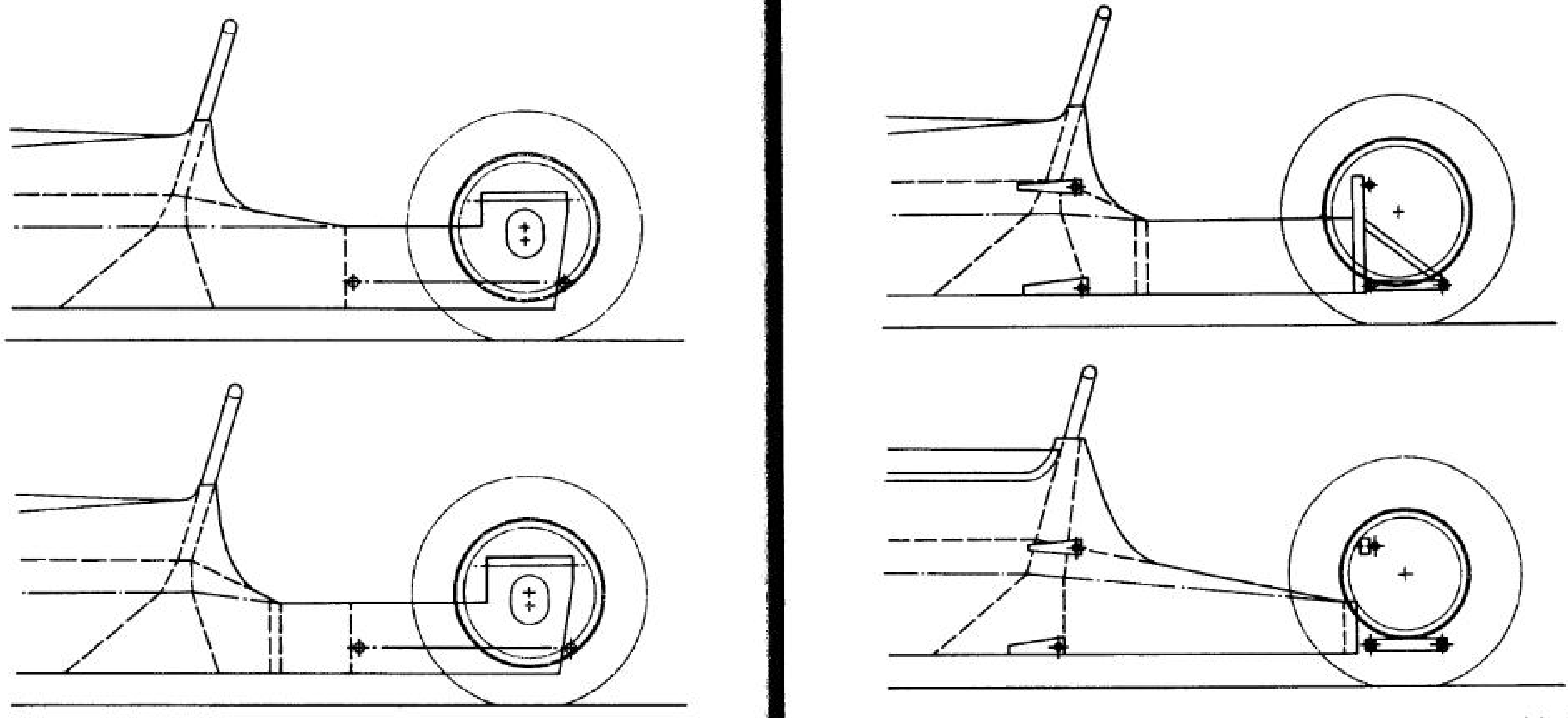
Our difficulties started from the necessity rapidly to modify the Broadspeed cars, which were numbers 3 and 4, to take Ford engines instead of the Chevrolet units for which the rear end had been laid out. The Chevvy front mountings were well forward of the kink-points of the booms (where these change from tapered to parallel form as viewed from the side) and quite close to the very stiff bulkhead. To install the Ford engine in the same position, however, the depth of the booms had to be decreased considerably and the kink-points moved forward so far (to clear the exhausts) that the engine front mounts now came behind them. The result, inevitably, was that we lost quite a lot of both beam and torsional stiffness of the rear end.

This was not all, though. Originally the forward arm of each rear-suspension lower wishbone had its anchorage at the kink-point, the boom being reinforced there by an internal diaphragm. When the kink-points were moved forward, as just explained, the wishbone anchorages were not, since this would have meant departing from the interchangeability concept.

Terry admits that he blundered here, because the resulting weakness, added to what had already been caused, made the cars handle so badly that Broadspeed rejected them without giving Leda Cars a chance to rectify them. It must be recorded in this context that car number 1, with the Chevrolet engine and the original boom design, showed promise during its early testing sessions, but was written off in practice for its first race at Oulton Park - unfortunately the first of several shunts during that unhappy 1970 season.

Anyway, drastic remedies had to be adopted before one of the ex-Broadspeed cars could be raced (with Chevvy engine) by Malaya Garage who agreed to take it over from Leda Cars. The reduced stiffness of the booms was countered by fitting a bracing frame between the cylinder heads and the top of the bulkhead, thus converting the rear assembly into a partial space-frame.

In addition, I improved the stress path from the rear suspension by modifying the lower wishbones to pick up at a stable point on the chassis. The combined effect of these changes was a considerable improvement in the handling qualities. Looking back, though, I feel that the idea of interchangeability was a bad one for a car of this type. Apart



Leda rear-boom story in four episodes: upper and lower left are the original design for the Chevrolet engine and the modified layout to take the Ford engine; shown above are the stiffer version for the Leda Mark 2 (LT 22) and the Mark 3 (LT 25) design with no kink-point. The various stages are explained in the text

from the restriction it imposed on modifications, the cost saving proved to be insignificant in relation to the overall sum involved, though such an economy might be valuable in the case of, say, a Formula Ford car.

In its original form the Leda was eye-catching because of the upswept rear bodywork with integral anti-lift surfaces. This was an interesting attempt to avoid the weight increase and parasitic drag of the separate aerofoil system. Although this large-area rear surface worked well enough, giving an average downthrust of 350 lb on the Goodwood circuit at racing speeds, it had the major disadvantage of non-adjustability.

Experience has shown us that some form of incidence adjustment is essential to suit different circuit conditions; for a given angle of incidence, the average downthrust on a high-speed circuit is clearly greater than on a slow one, so a fixed setting must be a compromise.

Terry therefore had to fall into line early in the season and fit an external aerofoil arrangement. Like most others, his wings subsequently became bigger and better, the majority of them being based on a high-lift/low-drag NACA aerofoil section. Clearly a good lift/drag ratio is the secret of success here, and he feels that some of the layouts used on other cars during 1970 and 1971 must have covered many miles in the inefficient stalled condition, with detriment to performance.

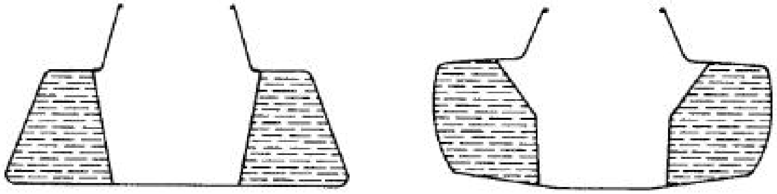
Since multi-foil systems appear to offer the best lift/drag potential for a given 'envelope' size, I have investigated several layouts of this type but have not yet reached any clear-cut conclusion. I would still like to revert to my original upswept-tail idea if I could evolve a satisfactory adjustment method, not least because it gave a much better airflow through the oil cooler and was generally 'cleaner' aerodynamically.

As indicated earlier, the disasters of the 1970 season did not finish with the handling problems. After getting close to the Silverstone lap record during testing of the modified car, Malaya's driver Roy Pike was going well at Mondello Park in June on dry tyres when the heavens opened . . ! A day-and-night effort by the team at Poole repaired the resulting considerable damage in time for the Silverstone meeting the following weekend. When Pike gained fourth place overall, followed by three 'thirds' in Europe, fortune seemed to be smiling at last, but he almost wrote the car off a few weeks later at Thruxton during an unofficial practice session, again without doing himself any harm. This in effect was the swansong of the Mark 1 version of the Leda 5000; more work would have been required to rebuild the bent car than to complete the improved version that was under construction.

AAR EAGLE INDIANAPOLIS (1969–70)

When Terry met Dan Gurney again during his information and finance seeking trip to Indianapolis in 1969, they discussed casually the possibility of a Terry design for the 1970 race. Then came the news that Tony Southgate, who had been designing for Dan at Santa Ana, was leaving to become BRM's Chief Designer, so Terry was not surprised when the Californian gave him a definite order for the design, stating that he would be building four cars.

Understandably, AAR wanted to use as many as possible of their existing components. Also they sent some rough drawings (prepared by Phil Remington, formerly with Carroll Shelby) which Terry used as a guide. These showed a foreshortened monocoque with a square-tube space-frame for the front bay. They also showed an almost flat underside, but this was designed-out at Poole because of the risk of excessive front-end lift when the nose came up on acceleration; a more rounded section would allow air to spill out sideways, thus preventing undue pressure build-up beneath the body.



Original and final monocoque sections of the Indianapolis Eagle; the flat-bottom form was shown on the rough drawings received by Terry from AAR, but was modified at Poole for aerodynamic reasons

Gurney insisted that the car should be as low as was practicable, with a low-slung fuel load and minimum drag. Therefore an almost 'delta' plan form was adopted – quite narrow forward of the front suspension but tapering outward immediately thereafter to a maximum width of about 48 in (1220 mm) just ahead of the rear wheels. A radiator layout similar to that of the Leda kept the nose profile down. At the front, the suspension spring/damper units were inboard for low drag, with the consequent rocker-type top wishbones. Unusually, the triangulating members of the lower wishbones were ahead of the transverse arms.

This arrangement means that under braking the triangulating tubes are in tension and so do not have to be as stiff as if they were in compression. On the other hand, the main stress-bearing structure of the car has to extend further forward to provide an anchorage.

When ordering, Gurney said that the rear end should be designed to take the Mayer-Drake Offenhauser engine only. However, after three weeks' work had been carried out on that basis, he telephoned to say that because additional cars were wanted Ford's turbocharged four-ohc engine or the three-valve pushrod unit also had to be accommodated. After giving vent to his feelings in the usual way, Terry set about the necessary redesign.

I completed the drawings for Mark 21 by February 1970, prints being sent piecemeal to AAR as the work proceeded. A few weeks later I went to California with the originals, ostensibly to supervise the first engine installation, and found that seven cars were already being built, and that Dan had parts for three more. After a fortnight, though, not one car was ready to have its engine installed, so testing clearly was still some way off.

Since the Leda work at home was pressing, Terry decided to leave Santa Ana, expecting to be asked to return when the first car was ready for test, but no such invitation materialized.

There were reports of handling difficulties during the development phase, and Terry reckons that these could have been caused by a buckling tendency of the upper gearbox-mounting bridge; this member was of 5/16in aluminium-alloy plate and could have had inadequate fore-and-aft stiffness since it was mounted 'on edge'. However, from the fact that Gurney finished third at Indianapolis it would seem that the problems were not serious or were easily rectified.

LEDA MARK 2 (1970)

Ahead of the seat bulkhead, the basic structure of this car was virtually unaltered from that of the Leda Mark 1, but aft of this point the chassis was extensively modified.

For a start, I made the rear booms considerably

stiffer, particularly in the region of the kink-point, which was given a heavier internal diaphragm. Also, the booms were shortened to terminate just forward of the rear-wheel axis instead of projecting rearward, the rear end being completed by a tubular steel hoop; this had detachable top and bottom transverse members for improved access during maintenance work.

As might be expected, Terry abandoned the idea of interchangeable suspensions at front and rear. The front layout remained unchanged but the rear was made very similar to that of the Gulf Mirage cars, comprising a normal upright with a single upper transverse link, parallel lower links and upper and lower trailing radius arms. One of the lower links was adjustable to facilitate setting the toe-in of the wheels. The rear brakes were moved inboard of the drive-shafts, in line with the current Formula 1 thinking.

Some inconclusive experimental work was carried out at this stage on an intriguing suspension development comprising the incorporation of anti-pitch torsion bars to control dive and squat. The thinking behind this development is discussed in some detail elsewhere in the book, but basically it was prompted by the thought that orthodox dive/squat control, by inclining the wishbone pivots, can have an adverse effect on the suspension and/or the steering, whereas anti-pitch bars should not.

On the Leda the bars were mounted along the outside of the monocoque and were connected to the suspension in the same way as an anti-roll bar. The effective stiffness of the first experimental bars was calculated approximately from weight-transfer and spring-rate data, and they certainly prevented nose scraping under heavy braking. However, it was clearly necessary to carry out a series of comparative tests with different bars and/or leverages, to

assess any improvement in handling and to ensure that there were no adverse side-effects.

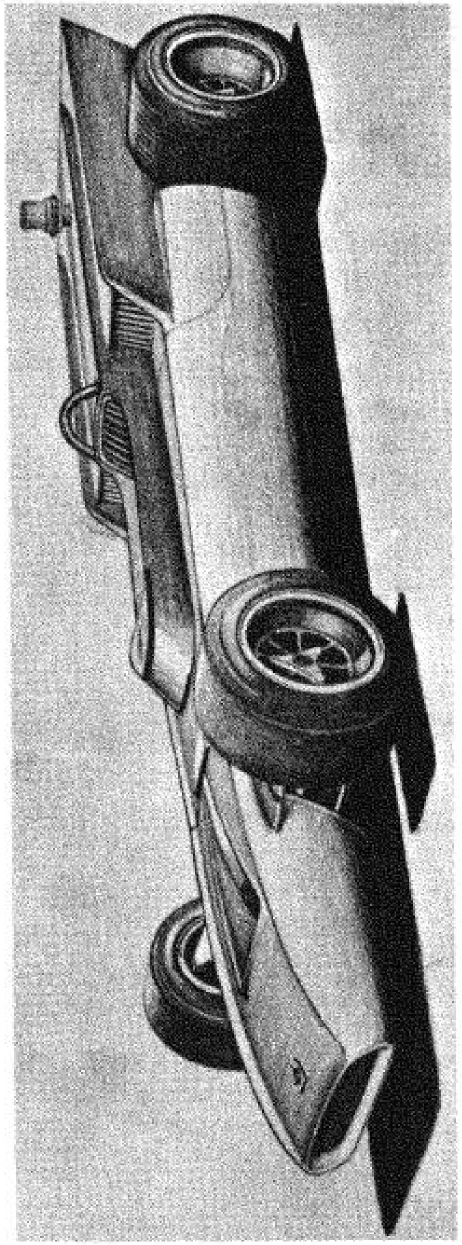
I decided, though, to concentrate first on getting the handling as good as possible without the anti-pitch bars, and asked Frank Gardner, at the end of a very successful Formula 5000 season, to try the car at Thruxton. His judgment was that the rear roll centre was too low, in comparison with that at the front, thus upsetting the balance of the car. On consideration this criticism seemed reasonable to me; because of changes of tyre profiles the front roll centre height had risen from 1 in to 2½ in (25 mm to 63.5 mm) and the rear one had dropped slightly from its designed 1¾–2 in (44–51 mm).

Following Gardner's appraisal Terry raised the inboard pivots of the upper links of the rear suspension. Because of the inboard brakes, the corresponding hoisting operation down below necessitated shortening the lower links in order that they would clear the discs on bump movement.

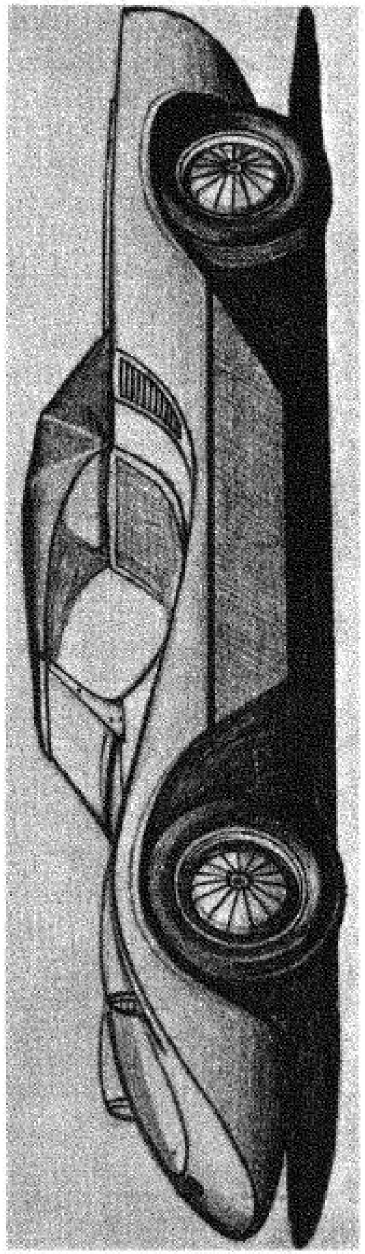
LT23 INDIANAPOLIS (1970–1)

The LT23 was conceived 'on spec' by Terry as a means of committing his latest ideas to paper. In the event, he failed to find anyone interested in sponsoring the car, so the design did not advance far beyond perspective sketches and a general-arrangement drawing. The outstanding feature of the basic shape was that, behind a nose of similar shape to that of the Leda Marks 1 and 2, the monocoque had a delta plan form, reaching a maximum width of approximately 55 in (1400 mm) at the rear wheels; it incorporated tankage of 70–75 US gallons. Its good aerodynamic shape can be seen from the accompanying illustration.

The nose, of course, was separate from the monocoque,



The handsome LT23 Indianapolis car – a design project only – had a monocoque of delta plan form and full-length 'fences' blending into fins behind the driver



Terry sketch of the LT24 mid-engine roadster which had a space-frame and incorporated numerous Ford components including the V6 power unit

as was the mandatory engine cover at the rear. To improve the airflow characteristics, each side of the body had a full-length boundary-layer 'fence' which swept upward behind the driver to form a pair of fins bridged by the engine cowling. The suspension layout resembled that of the Leda Mark 2.

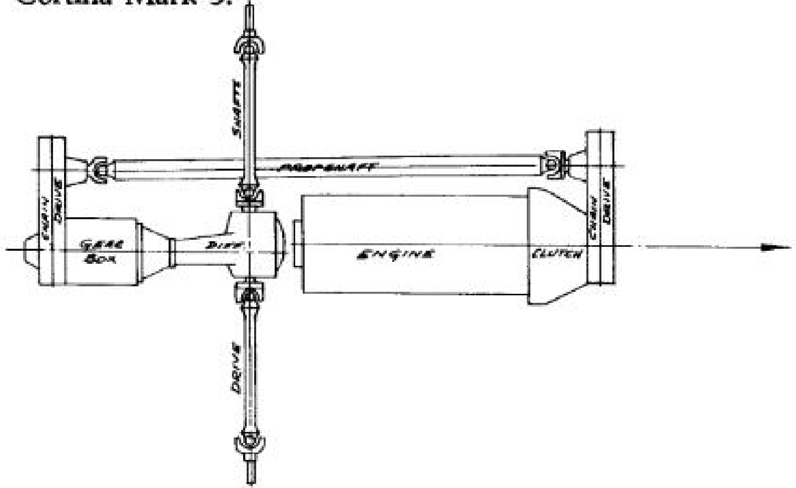
I intended that the car should be powered by an Offenhauser turbocharged engine running on methanol fuel. Because of the high latent heat of evaporation of this fuel, and the consequent cool-running of the engine, the radiator was the same size as in the Leda, in spite of the power surplus of over 250 bhp.

LT24 SPORTS CAR (1971)

This road car reached the first-prototype stage and covered over 2000 miles of strenuous testing, but unfortunately the project went into hibernation with the liquidation of Leda Cars in July 1972.

It was to be my first 'commercial' venture – a 'fun car' in the same vein as the Lotus Seven but much more modern in concept and with a considerably higher performance. It was a latter-day Cobra, really, since it was designed around the Ford 3 litre V6 engine, giving about 140 bhp and lots of torque at the bottom end.

A high standard of handling was essential, as were a striking appearance and a reasonably low price if the car, as a fairly stark piece of machinery, was to sell against existing sports cars of lower performance but more creature comforts. The styling (a combination of 'traditional' and modern full-width, with side-mounted radiators) can be judged from Terry's perspective sketch. Low cost was to come partly from simplicity and low weight - which would also help the performance - and partly from using as many standard Ford components as possible. This was one reason why Len opted for the Ford V6 engine in spite of its not inconsiderable weight, and he also chose the matching gearbox and final-drive unit, plus front-suspension components and the steering assembly from the Cortina Mark 3.



To avoid an excessively long wheelbase, the LT24's gearbox was behind the final drive; the engine was reversed and was connected to the box by two chain drives and a conventional propeller shaft

To achieve good handling, I decided that a mid-engine layout, in the modern racing-car idiom, was essential. However, a racing-type Hewland or ZF transaxle was out of the question for cost reasons, while a normal in-line disposition of engine, gearbox and final drive would push the occupants too far forward or mean an excessively long wheelbase. Therefore I departed from convention by reversing the engine and clutch and putting the gearbox behind the final drive. Transmission from the engine to the clutch was by means of an enclosed 7/16in triplex roller-chain drive, an exposed (standard Zodiac) longitudinal propeller shaft and a second, identical chain drive, as shown in the accompanying schematic layout. In this way I managed to save more than 12 in (305 mm) on the overall length of the installation, at the expense of a little complexity. Another plus, however, was that the engine reversal made the ancillaries such as the alternator and water pump more accessible for maintenance.

With the help of some useful advice from Renold on the chain drives, a surprisingly neat layout was evolved, even the gearchange linkage proving reasonably easy. Thanks to the proper enclosure and lubrication of the chains, the additional transmission noise was not significant in a car of this type. Also, there was little loss of mechanical efficiency, and the testing mentioned earlier caused no measurable chain wear.

Terry designed a straightforward and quite lightweight space-frame and, since the body was to have no doors, the structure was deep enough along the sides to ensure ample torsional and beam stiffnesses. The frame was fabricated from square- and round-section steel tube of 16 and 18 swg (0.064 and 0.048 in or 1.6 and 1.2 mm wall thickness); in its bare state it weighed approximately 110 lb (50 kg). As on his previous space-frames, the undertray ahead of the engine was pop-riveted to the bottom side-tubes, to enhance the stiffness.

The Cortina front-suspension uprights, stub axles and hubs were mated to Terry-designed upper and lower wishbones, with Metalastik rubber bushings. At the rear, the racing-type independent suspension was of Len's own design, as were the cast-aluminium uprights for carrying the stub axles. Drive-shafts, though, were standard Ford items from the Zephyr/Zodiac Mark 4 range.

It was intended that the two-seat body would be a one-piece GRP moulding and would have above-average luggage-carrying capacity for its type - about 7 cubic feet in all. To get the car running with the minimum delay, however, it was fitted with a rather primitive but quickly made aluminium covering. Most of the test running was carried out at the Military Vehicles Experimental Establishment's proving ground near Chertsey, Surrey.

Even in its 'lash-up' form the LT24 showed a lot of promise. It out-dragged a Porsche 911E and was able to stay comfortably ahead of it during some high-speed lapping of the Castle Combe circuit in Wiltshire. Consequently, both John Lambert and I were really sorry not to have been able to continue with the car. For the record, here are some of our acceleration figures: 0–60 mph in well under 7 seconds, 0–100 mph in 18.5 seconds and 0–100–0 mph in 23.5 seconds. All of these figures were obtained with a completely standard engine from Ford's Industrial Division and standard cogs in the Zodiac gearbox. However, my double chain-drive arrangement enabled us to get a 14 per cent step-up in the overall ratios, and this, too, could easily be varied by swapping sprockets. I felt that, with a tuned V6 engine, of the sort that later became available, plus wide wheels, we could have had a performance to match almost anything on the road, probably at less than a third of the price. Our original aim was to offer the car in basic form for well under £2000, including purchase tax, so it should certainly have been a marketable proposition.

LT25 OR LEDA MARK 3 (1971)

The LT25 was so different from its 1970 predecessors that it could be regarded as a new car rather than a development of the Mark 2. It was, of course, still a Formula 5000 machine, designed to take only the Chevvy engine. In laying it out Terry determined to make-good the deficiencies of the earlier cars. The new monocoque

structure was noteworthy for the way in which the torsional stiffness was maintained at the rear end.

The booms, which terminated just ahead of the rear-wheel centres, had no kink-points like those of the Marks 1 and 2; instead the section depth reduced progressively rearward from that of the side sponsons at the rear bulkhead, and I enhanced the structural stability of the sponsons by incorporating three internal diaphragms in each.

To simplify the rear structure, the engine/transmission group reacted more of the static and dynamic loading than before, though it still served no more than a semi-structural function. Since the rear suspension was in effect hung on the gearbox, it and the mechanical group could be removed as a unit if desired. To minimize lateral movement of the engine, which had been lowered by 0.75 in (19 mm), it was attached to the bulkhead through a horizontally disposed Warren girder of tubular steel construction. The rear mounting was to the ends of the booms, through 0.25 in (6.35 mm) Duralumin plates which picked up on the clutch bell-housing.

Bolted across the top and bottom of the gearbox were box-section mild-steel fabricated bridge members which carried the pivots for the transverse links of the rear suspension. A light tubular subframe was attached to the lower bridge and to the top of the gearbox. Both the upper and lower radius arms of the suspension were attached to the engine bulkhead.

For the rear uprights I broke nel ground by adopting fabrication in 14-gauge aluminium alloy; the material used was HS30, with an ultimate tensile strength of 22–25 tons/sq in (34.7–39.4 kg/sq mm), and I adopted double-box construction for maximum stiffness. Each upright proved to be al-

most 1.5 lb (0.72 kg) lighter than the corresponding magnesium casting without loss of strength or stiffness.

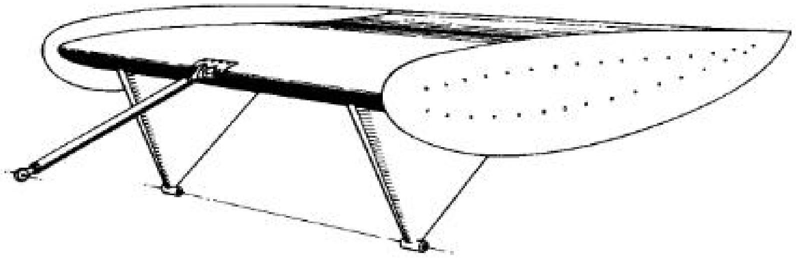
The front suspension, with inboard spring/damper units, underwent minor geometry modifications to bring the pivots of the upper wishbones closer to the body sides. Here, too, the uprights were new, being very neat steel fabrications of double-conical form. Ahead of the front bulkhead, the tubular nose structure was quickly detachable, and the cowling could be swung up for access to the radiator, battery (moved from the rear to increase the front-wheel loading) and master cylinders for brake and clutch systems. Though the radiator had Terry's usual considerable forward rake, its intake was unusual in being underneath the nose, in shark's mouth style.

By switching from pendant to rampant pedals, Terry was able to reduce the depth of the front bulkhead and thus lower the nose. Brabham front wheels were used and, since they were of 13 in (330 mm) diameter, the latest 10½ in (267 mm) discs had to be adopted. As before, the front brakes were outboard and the rears inboard, the calipers being the same at both ends.

The aerofoil system was entirely new and embodied some interesting thinking.

In my search for 'clean' air, I moved the rear wing quite a lot further aft. Since more downthrust was then necessary at the front to counter the rearward overturning moment, the front wing was mounted well forward above the nose, so all its span was effective. Both aerofoils had a section evolved by the British Aircraft Corporation and recommended to me by them.

An ingenious low-drag mounting system, with rapid incidence adjustment, was designed for the wings. Riveted to the underside of the rear aerofoil were two streamline-section supports of inverted delta profile; these were pivoted at the bottom on the rear subframe already mentioned, and drag loads were reacted by the upper rear crossmember through a tension strut to the leading edge of the wing. This strut was length-adjustable to vary the incidence. The first car had multiple anchorage points on the subframe to enable the best longitudinal position of the wing to be established.



Rear-aerofoil mounting arrangement for the LT25; the tension-strut was adjustable to vary the incidence of the wing

At the front the arrangement was similar in that two supports (again of streamlined inverted-delta shape) were used but in conjunction with two drag struts in compression, with slotted ends for incidence adjustment. Both wings had large end-plates and their chords were 11.5 in (292 mm) at the front and 22.5 in (572 mm) at the rear. For evaluation, Terry had intended to build a rear wing with two aerofoils of 15 in (381 mm) chord, disposed as indicated in the 'Aerodynamics' chapter and with the second one independently adjustable for incidence between the end-plates; however, time did not permit this scheme to be tried during 1971.

Initial trials of the LT25, in the hands of Trevor Taylor, were reasonably promising. Although it had a

1970 engine, it proved significantly faster than its predecessor but its handling was not to Trevor's liking. At that time the 1971 'small-crank' engine was still awaited; because of its smaller-diameter main bearings (hence the name) this unit could run up to 8000 rpm, as against the 7600 rpm of the earlier one, so could be expected to give the car a significantly higher performance.

The trials indicated a need to improve front-brake cooling, so small ducts were added in time for the car's first race - the European Championship event at Mallory Park in March. Unfortunately, the newly installed 'small-crank' power unit met with clutch trouble in practice and this could not be remedied in time, so the car was a non-starter.

Further experience with the LT25 indicated that the handling difficulties resulted mainly from a persistent oversteer, and consequent difficulty in controlling the rear end. This symptom pointed to the rear roll stiffness being too high relative to that at the front. The rear suspension was therefore softened slightly (to have softened it further would have led to excessive roll) and the front system was progressively stiffened until the optimum benefit was achieved. Here are the initial and revised settings:

	Front		Rear	
	Spring rate	Roll-bar dia.	Spring rate	Roll-bar dia.
Original	240 lb/in	$\frac{1}{2}$ in	330 lb/in	$\frac{5}{8}$ in
Modified	360lb/in	$\frac{11}{16}$ in	320 lb/in	$\frac{5}{8}$ in

Increases of 50 per cent in spring rate and over 300 per cent in roll-bar stiffness may seem very high, particularly since the front springs now had an appreciably higher rate than the rear ones. Nevertheless, these changes and an uprating of the dampers effected quite a transformation in the handling; the car understeered slightly until the driver 'gave it the boot'. On his first subsequent test session at Silverstone, Trevor was lapping faster than either Frank Gardner or Graham McRae! Contrary to my expectations, the ride also was better than before.

It might be thought that a more basic approach to the problem would have been to lower the rear roll centre and to raise that at the front, keeping the spring rates at a conventional level. Terry considered this course of action but decided against it because of the time involved in making a series of suspension-geometry modifications: each change at each end of the car would have meant repositioning at least four mounting brackets, whereas springs and anti-roll bars could be swapped in a matter of minutes.

Although the handling presented these problems, the wing system worked well from the start:

The combination of an efficient aerofoil section and good installation gave us the required downthrust at a considerably smaller angle of incidence (and therefore drag) of the rear wing than any of the car's competitors. In comparison with the LT25's 13–14 degrees of incidence, some of the 'opposition' wings had as much as 25 degrees and so must have been fully stalled even at moderate speeds.

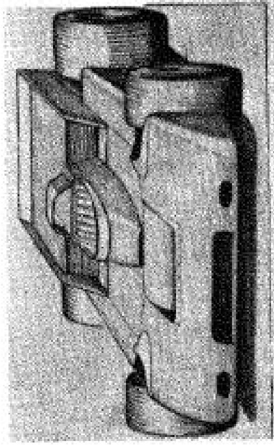
After some miles at racing speeds, the new light-alloy rear uprights showed signs of weld cracks because of the relatively low ductility of the HS30 material. They were therefore redesigned with machined-from-solid hub barrels, the modified layout permitting the use of a more ductile material (NS6) for the box portions. The new uprights weighed virtually the same as their predecessors.

By the middle of the 1971 season the car seemed to be becoming really competitive. However, the Leda jinx was still there because in the early stages of the Rothmans Gold Cup race at Oulton Park in August, Trevor Taylor crashed at Knicker Brook when lying fifth, injuring a leg and virtually writing-off the monocoque. The reason for the accident is explained in the section on safety, but as already mentioned the LT25 was not to blame. After this misfortune, Terry and his team made a second car race-ready but Malaya Racing could not find a replacement driver of the right calibre, so the season ended on a low note.

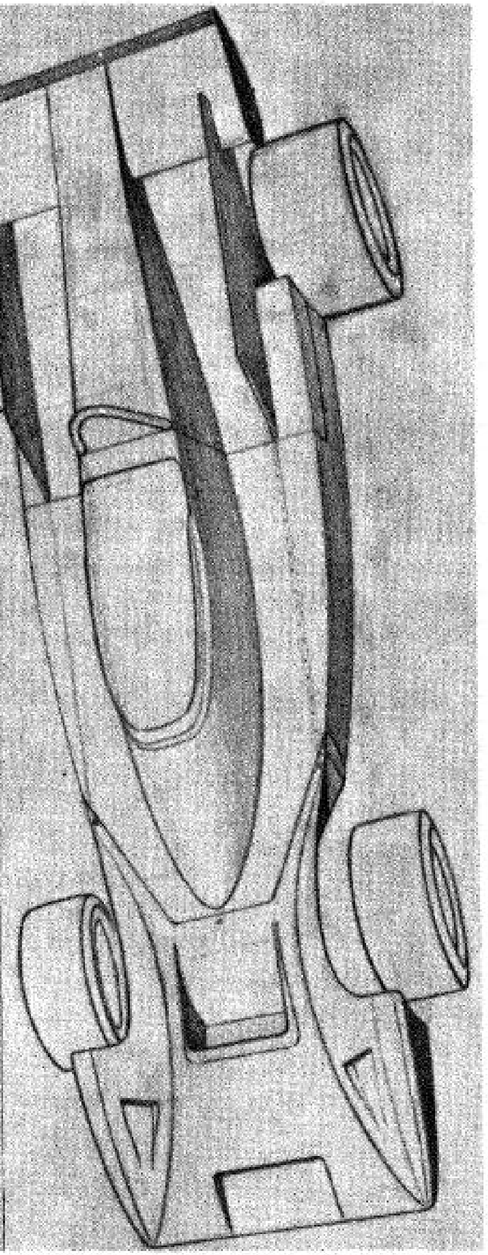
LT26 and LT27 or McRAE LEDA (1971–2)

On this project, to a greater extent than any since my early Lotus days, I was the interpreter rather than the creator. When Malaya Garage approached Graham McRae in September 1971 to see if he would drive for Leda, he agreed to do so on the primary condition that the car was designed and built to his own requirements. Malaya agreed to this, so Graham came to Poole the following month and explained to me what he had in mind. He gave me a set of ideas which basically were very sound, some of them parallel to the way my own thoughts were running at the time. In other respects I saw things rather differently but these were largely on matters of opinion rather than fact. Anyway, we agreed the overall specification and I started work. In fairness to myself, I should make it clear that at no time did Graham put pencil to paper on the drawing board, the actual designing being entirely my own task, with his agreement wherever necessary.

The first car, the LT26, was to be for McRae to tackle



A 1971 Terry doodle – an Indianapolis-type car developed from the LT23 but with a wide nose to improve airflow over the suspension and front wheels



Another doodle, drawn about a year later, this time for a proposed Indianapolis/Formula 5000 car. Features are the 'hammer-head' plan form and fin-mounted aerofoil into which the engine cowling is blended the Tasman series, and it had to be designed around the various items salvaged from his McLaren M10B; these included the suspension uprights, hubs and wheels, wishbones, pedals, rack-and-pinion unit and steering column. For them, McRae specified a very curvaceous monocoque, with a laterally bulged mid-portion of the then-fashionable form. The main objective here is to ensure high torsional stiffness, but the shape gives the secondary advantage of keeping the fuel weight low and central. An unusual feature of the LT26 structure was that, to save the weight of the overlapping portions of riveted joints, the skin panels (except the floor) were welded together to form a unit. This one-piece construction was a typical case where McRae and Terry had different opinions. The former wanted the weight-saving and smoother shape, whereas the latter was concerned also with the more precise manufacture necessary to align adjacent panels, and with the higher cost of repair in the event of damage.

This costly tub terminated at the engine bulkhead to which was bolted a tubular space-frame with ample lateral bracing. The engine/transmission group was supported at the front on a magnesium plate attached to the bulkhead, and at the rear by the space-frame. Rear-suspension geometry was as on McRae's M10B, the links being pivoted on the space-frame and the radius arms on the bulkhead. The front suspension, too, was virtually identical with that of McRae's McLaren, and the aerofoil layout and most other details were orthodox. As a matter of interest, both the front and rear suspension geometries, when plotted on the drawing board, were remarkably similar to those of the LT25.

Happily the car went well right from the start. Its Chevrolet engine, supplied by Morand of Switzerland, seemed to have more steam than the opposition, and the combination of this, good handling and a first-class driver was sufficient to give McRae a well-deserved victory in the Tasman races. In fact he won four out of the

eight events in the series and had remarkably little trouble with the car. It is interesting to speculate on the effect of his having his own car rather than driving one that was designed and built elsewhere. The fact seemed to give him an enhanced sense of responsibility and tempered his previous exuberance; as a result he spent more time on the track and less exploring the scenery than had previously been the case.

While McRae was 'down under', Terry busied himself with the LT27. This was to have the same basic tub as the LT26 but with the McLaren components replaced by Leda items which were to be lighter wherever possible.

The only other stipulation made by McRae before he left was that the suspension geometry should not be altered unless he advised accordingly, which he did not. Because of this relative freedom of action, I decided to move the rear brakes inboard, in a manner very similar to that of the LT25, and to incorporate my parallel-link rear suspension. In addition, of course, I designed the new uprights, wishbones and other components mentioned earlier.

So far as Terry was concerned, the project came to an abrupt halt in July 1972 when, as mentioned in the biographical chapter, Malaya Garage pulled out of racing and sold the Leda set-up to McRae.

4

A blank sheet of paper

Len Terry explains his procedure for advancing a new design from the sketch pad to the race track

DESIGNING A RACING CAR from scratch is basically a matter of solving a problem, or rather a whole series of problems which are all interlinked. Therefore one's best starting point is to make a list *defining* the major requirements, it being difficult to win a fight if you cannot see your opponent!

Having defined the problems, one must then compile another list proposing the solutions. This is the more difficult task because unfortunately the answer to one difficulty may very easily create a new problem or be in conflict with the solutions to others. In essence, the 'solutions list' is a basic specification for the car and constitutes a design brief from which the designer can conjure up a picture of what the finished car should look like.

My next step is to draw one or two perspective views together with rough small-scale (about one-sixteenth) side, plan and end views. From these sketches I start full- and quarter-scale general-arrangement drawings. First a quarter-scale side view is drawn, starting with a ground line, an undertray line and the rear-axle vertical centre-line. I choose quarter-scale as, while it keeps the drawing to manageable proportions, it is sufficiently large to ensure a reasonable degree of accuracy. Having laid in the main datum lines, one can then plot in the appropriate positions of the engine, transmission, driver and finally the front-wheel vertical centre-line. And if one's initial calculations were correct the

Basic design requirements

Primary objective	*Qualifying objectives*
a. Maximum acceleration	Maximum torque Maximum tyre adhesion Minimum weight *Minimum drag
b. Maximum deceleration	Largest practicable brakes Maximum tyre adhesion *Maximum drag Minimum weight
c. Maximum cornering speed	Maximum tyre adhesion Minimum unsprung weight Minimum overall weight Minimum C of G height
d. Maximum terminal velocity	Maximum power *Minimum drag

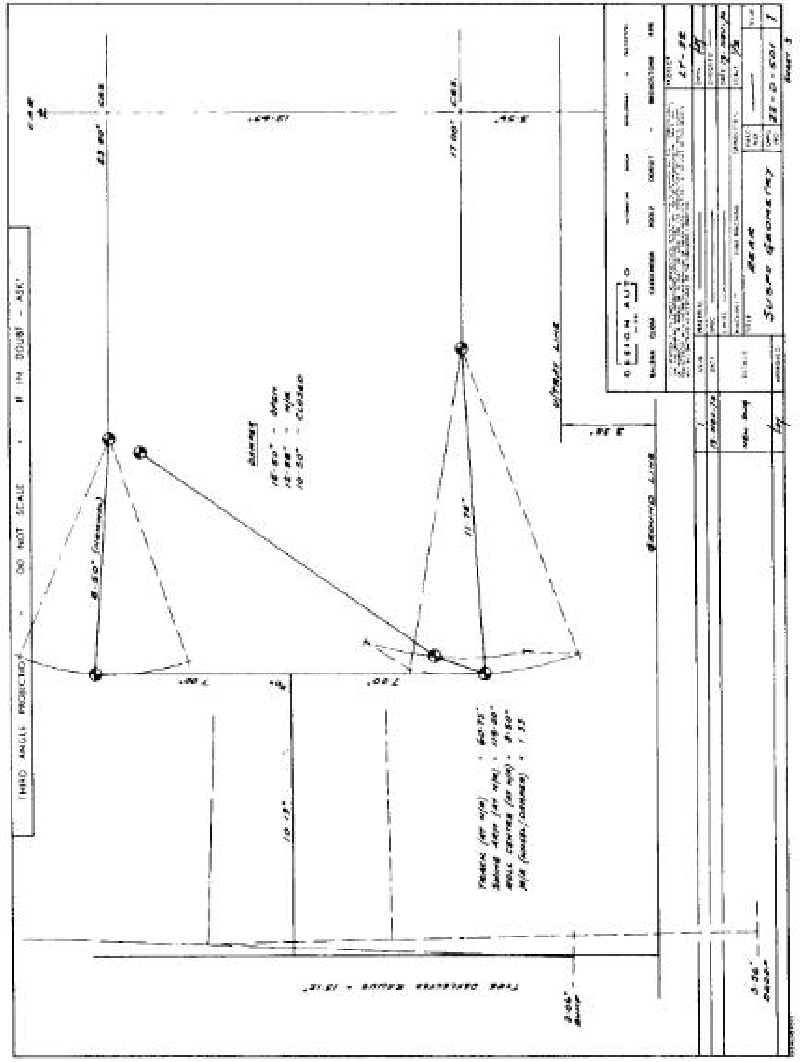
*Note conflict between b and a/d; this item includes both aerodynamic drag and rolling resistance.

wheelbase should correspond to that laid down in the original specification.

At this point I find it useful to lay in (normally in ink) a 10-inch grid with the front-wheel vertical centre-line as the zero datum. In the plan and end views the longitudinal and vertical centre-lines respectively are used as a datum, and in the side and end views either the undertray or the ground line may be used for the horizontal datum. This grid system (2½ inches on a quarter-scale drawing, of course) is widely used in both the aircraft and automotive industries and has many uses. It is most helpful when plotting body lines and can be used on working drawings to indicate the exact locations of various brackets etc, rather in the same way as grid references are used in map reading.

My next task is to make a start on large-scale suspension drawings, which normally I produce full-size in the interest of accuracy. To assist in this matter of accuracy, plastic film is used rather than ordinary drawing or tracing paper, since it is far more stable in conditions of changing temperature and humidity. In passing, it is worth mentioning that I also use plastic film as working templates for much of the sheet-metal work. This method can save considerable time and effort both in the drawing office and in the workshop, and can also help to minimize mistakes in both departments. A really accurate drawing with no dimensions given will have no *wrong* dimensions and is unlikely to be misread by workshop personnel.

In conjunction with the full-size suspension drawings I also lay out the front and rear geometries in order to determine the link lengths and pivot points necessary to give the characteristics decided upon – *i.e.* static roll-centre, virtual swing-arm length, camber-change curve, pitch centre etc. In the

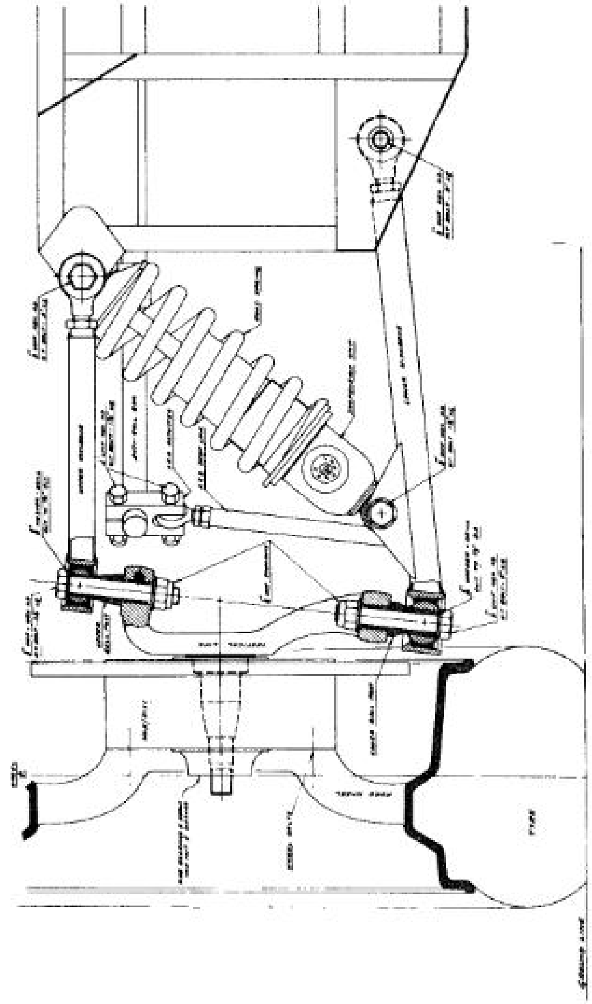


Typical Terry drawing of rear-suspension geometry – in fact that for the Leda Mark 2 (LT22). The centres of the links and spring/damper unit are shown, together with the main dimensions, angles and relative positions case of the front end, the geometry drawing enables one to plot in very precisely the location and lengths of the steering components, and, at the rear, the amount of plunge required on the half-shafts.

The suspension drawings are started in much the same way as the quarter-scale general-arrangement. Usual practice for me is to draw one side only, starting with the front end, since most racing cars are completely symmetrical so far as suspension layout is concerned. The vertical centre-line, ground line, undertray line and vertical centre-lines of the wheels are the main datum lines to be laid in initially. These are followed by the hub centre-line, the height of this from the ground being determined by the deflected radius of the tyres to be used. One can then plot in the king-post angle and offset, typical figures for these being 10 degrees and 2 in (50.8 mm).

At this stage I like to start a basic parts-list which also makes provision for the allocation of drawing numbers; it is very necessary to be methodical about such things, especially if a series of cars is to be built. The numbering system I use is quite simple, each item being allocated a three-part number which itself is quite informative. A typical example would be the front hub spindle which, in the case of the LT25, was 25-C-003, 25 being the project, C indicating a front-suspension component and 003 indicating a hub spindle. The rear hub spindle for the same car was given the number 25-D-003, D indicating rear-suspension components. Where basically similar left- and right-hand parts are used, odd numbers indicate the former and even numbers the latter.

The project number is always that for which the part was originally designed. For assemblies the last number is always in the 500 series, 25-C-501 in-

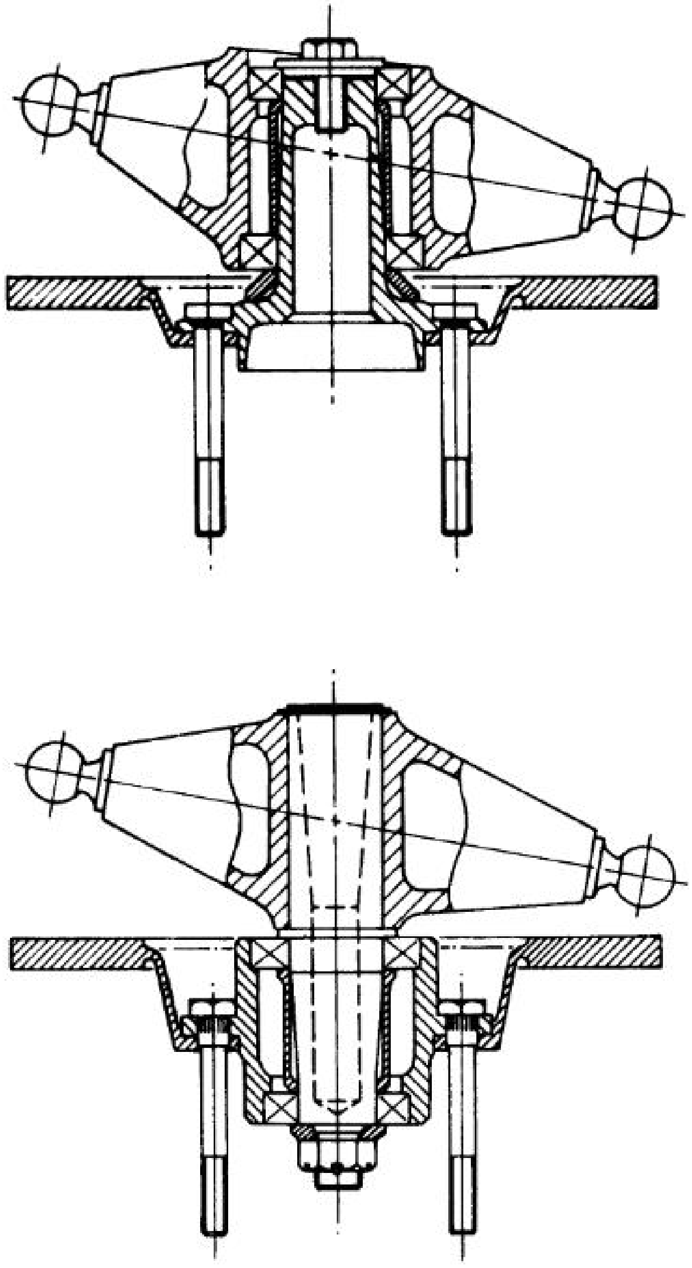


Complete front-suspension assembly drawing, derived from a geometry drawing of the kind shown in the previous illustration dicating the complete left-hand front-suspension assembly. Generally speaking the drawing number corresponds to the part number, although where more than one item is shown on a drawing the lowest of the part numbers shown is utilized.

So far it has all been plain sailing, but we are rapidly approaching the tricky stages where one needs an eraser at the ready to help make the compromises that are so necessary. The next item to draw in is the wheel rim since this, to a great extent, will determine the 'spread' between the king-post upper and lower pivots. In positioning these it is essential to ensure that, in all conditions, no fouling occurs between the wishbones and the rim. However, at the same time it is desirable that the lower pivot be a reasonable distance below the hub centre-line, to achieve a good loading distribution. It will be found that on most racing cars the distance between pivots is in the 8-10 in (203-254 mm) bracket.

The next item to be plotted, assuming outboard brakes, is the disc or drum. If this is buried too deeply in the wheel, cooling problems may arise, so it must be positioned as close as is practicable to the king-post; the limiting factor here is usually the ball-joint of the lower pivot point. Again, care must be taken to eliminate any possible fouling, bearing in mind that under extreme cornering loads a certain amount of flexing will take place in the various components. It may appear that a simple answer to the potential brake-cooling problem would be to move the king-post inboard further from the centre-plane of the wheel. However, this increases the king-post offset, which usually results in heavy steering – a classic example of the compromises that have to be effected throughout almost the whole design process.

Having reached a decision regarding these



Front stub-axles can be of either the fixed (left) or live type; the former carries bearings for the wheel hub, while the latter revolves in bearings within the suspension upright. Terry considers that the second scheme gives the better stiffness/weight compromise conflicting factors one can progress to the detailing of the king-post/hub-spindle assembly. Here we have the choice of a live stub rotating in the king-post, or a fixed stub-axle and a rotating hub. My own preference is for the former as I feel that, overall, it can be lighter and/or stiffer than the latter. A further possibility, once quite popular, is to fix the stub-axle and install the hub bearings directly in the wheels, so eliminating the need for a separate hub. Although this can provide a very light assembly it does pose problems of wheel removal when disc brakes are used.

A point that requires consideration when designing the hub assembly is the need to combine a very high degree of rigidity with the minimum possible weight, because all the latter is unsprung and is subject to high stress. Stiffness is helped by having a good spread between the inner and outer bearings, and here one is faced with the choice of taper-roller, needle-roller, deep-groove ball and angular-contact ball bearings, or a combination of different types. A great degree of variety is also available when it comes to methods of sealing the bearings. At various times I have used all the bearing types mentioned and, if I have a preference, it is for the deep-groove journal type with built-in seals. This choice in my opinion has the advantage of simplicity, lightness and low friction losses. It is well worth stressing here that throughout the whole design process simplicity is one of the factors uppermost in my mind, and I rarely use two or more components if a single one can be designed to serve a multiple purpose.

Once the front view is well under way one can move on to the full-size plan and side elevations. Quite frequently it will be found that, as these views take shape, modifications will be necessary to the primary view, unless one is gifted with the ability to

see all the problems well in advance. Naturally, experience is of great help in this respect because many of the problems will have been encountered and overcome on previous projects. The side and plan views, of course, will have their own major datum lines; some of these will be transferred from the front view but others will be peculiar to the particular view that is being tackled.

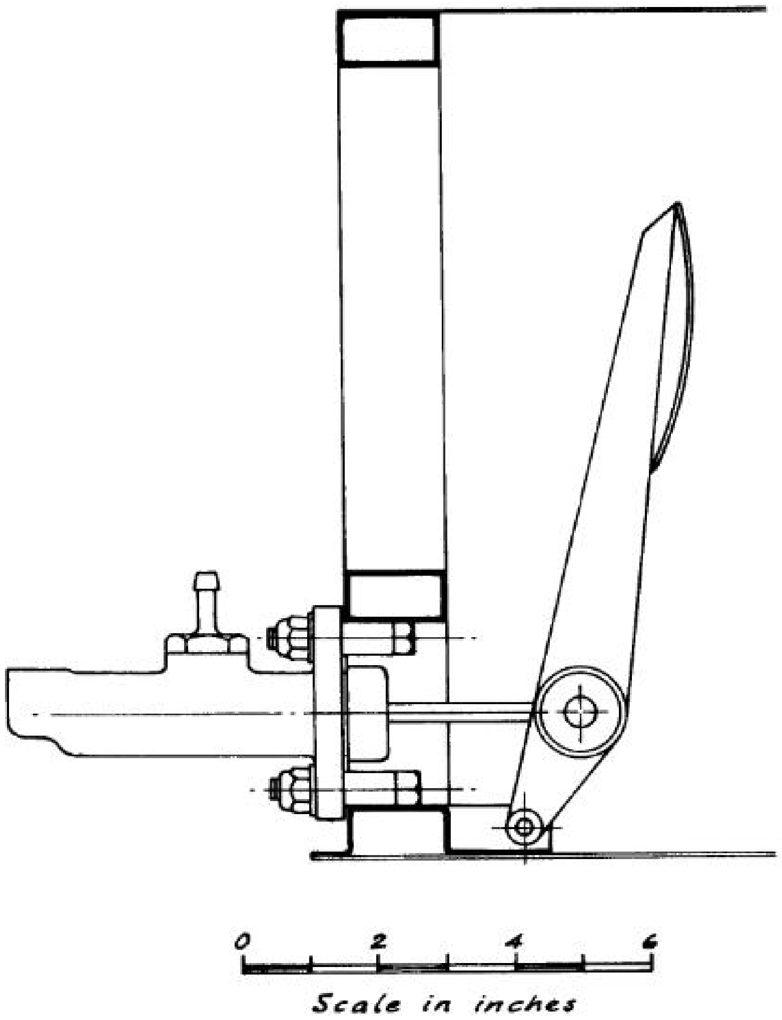
When the suspension components are drawn in on all three views it becomes possible to finalize the wheel details. A reasonable clearance should be allowed between the brake caliper and the inside face of the wheel for, apart from the previously mentioned flexing, one must also bear in mind the thermal expansion that occurs under hard running conditions. Take into account, too, that the wheel spokes are in effect cantilever beams supported at the hub, at which point therefore they should have the greatest section. Loadings here, at maximum cornering speeds, can be of a very high order indeed, as will be clear if a diagram of forces is drawn.

With all the front-suspension components plotted in and detailed it is now possible to lay in the steering components such as steering arms, track rods, rack-and-pinion assembly and so on. Usually I like to position the steering arm, or its equivalent, as near to hub height as possible in order to minimize the torsional loading in the king-post, and thus to keep down its weight. If anything, my final preference is to have the steering arm slightly below hub height as this means a lower centre of gravity for the whole steering assembly. Other things being equal, the lower the overall C of G the better-handling the car will be owing to the reduction of weight transfer under cornering, acceleration and braking. One should bear this fact in mind throughout the design process, while remembering that the best compromise is the main target. For example, the whole car could be lowered to give just one inch of ground clearance but then the springing would need to be so hard that on anything other than a 'billiard-table' surface it would be impossible to keep the wheels in continuous contact with the road.

Having dealt with the front suspension, I draw in all the major details on the quarter-scale general-arrangement, then move on to tackle the rear suspension. This is handled in virtually the same way as the front, and there will be similar snags and pitfalls to be overcome. If anything, the rear-suspension components need to be even more rigid than those at the front, because any flexing here will create rear-end steering or instability which just cannot be tolerated if the car is to be a race-winner. Once all the rear-suspension drawings are completed, the major details can also be transferred to the general-arrangement.

Next I turn to the chassis details and such points as the radiator location and mounting, engine mounting, pedals and master cylinder mountings, the cockpit end of the gearshift mechanism and the myriad other minor components essential in a modern racing car. Very often it is in this sphere of detail design that quite a promising basic car can become merely an also-ran or even a complete failure. For example, an insufficiently sturdy pedal/master cylinder mounting can reduce very considerably the efficiency of the brakes. Here it is as well to ponder on the fact that this particular bracket may be called upon to withstand loads approaching half a ton. Another example is that a difficult or badly placed gear lever can cause driver fatigue, frustration or eventually even a wrecked engine or gearbox.

After the majority of the mechanical components



Brake-pedal/master-cylinder mounting providing the necessary high strength and stiffness are finalized and drawn in it should be possible to lay in the body outlines and, with a little luck, they may even bear some resemblance to those shown in the original perspective sketches! Of course, there are two basic approaches in this matter. One can either do the 'styling' first and try to fit the mechanical components inside the proposed envelope or, conversely, design the body shape around the hardware. Obviously it is a great help if one can think three-dimensionally, and when this is the case the original perspective and small-scale drawings will not be far removed from the final vehicle.

Having drawn in the outlines in all the views shown on the quarter-scale general arrangement one can then transfer to full-size section drawings using the 10-inch grid. Normally I draw the sections to quarter-scale first and then scale-up from there to full-size on plastic film. These drawings can then be used as templates for making a wooden body jig around which either metal panels or a GRP mould can be made. It is very often worthwhile making a plywood mock-up of the cockpit, too, since this will be found invaluable in positioning the controls for maximum comfort and efficiency.

Generally speaking I like to finalize the complete design as far as possible before beginning the actual working drawings, as it has been my experience that almost every component affects others to some degree. Quite often this becomes a chain-reaction that can force one back almost to 'square one' and goes a long way to explain why racing-car design tends to be a matter of evolution rather than revolution. Again it becomes a case of compromise because there is normally a deadline to meet and many items, such as those requiring complex pattern equipment, have long delivery times. Unless these parts are under way fairly early in the programme

a car may become obsolete before it is ever built!

Certain details, such as the linkage between the gear lever and the gearbox, may be left until the car is almost built, because in many instances it will be quicker and more convenient to sort them out 'in the metal' rather than on the drawing board. Nevertheless, they should still be drawn at some stage in order that replacements or replicas can be manufactured. In all probability, as the car takes shape in the workshop, one will see better ways of doing certain things, but this can be a pitfall and it is best to 'freeze' the design at the earliest possible stage and concentrate on getting the car on to the circuit. Unless one is sure that a modification is going to make a really worthwhile improvement, such changes should be executed at a later date. Finally, do not be too disappointed if practice at first does not bear out all your theories, for in each race there can be only one winner, and no-one can expect to win them all!

5

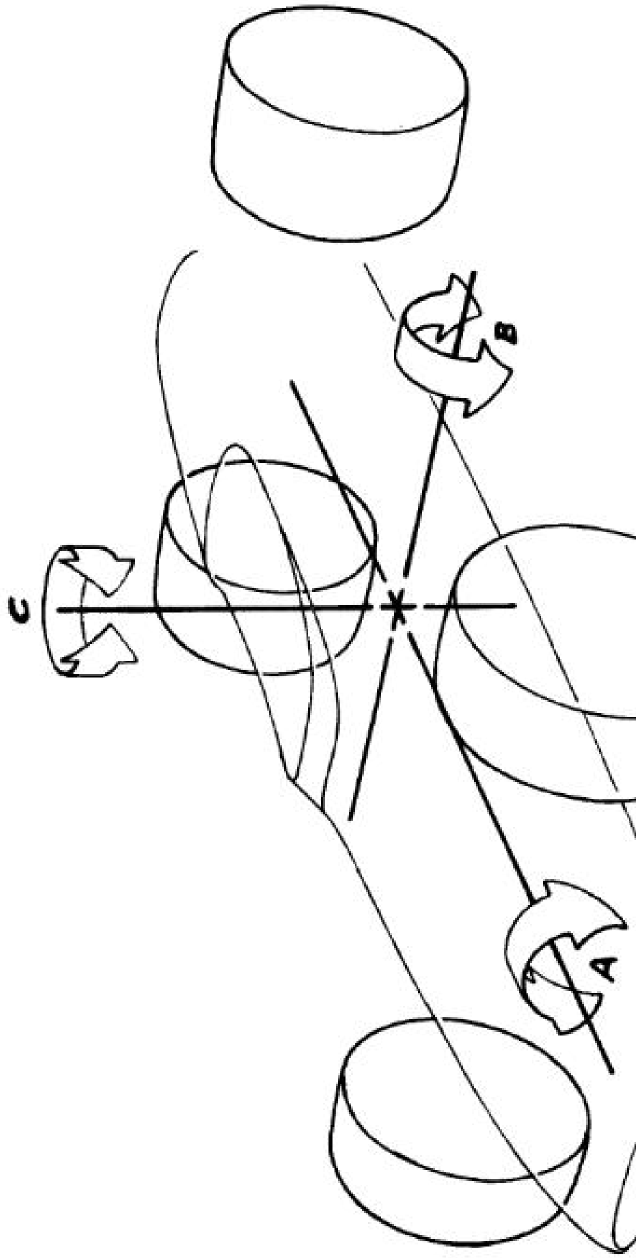
Handling characteristics

THE THEORETICAL ASPECTS

The handling of a racing car is influenced by an unpleasantly large number of factors. These include the weight distribution, centre of gravity height, suspension design (in the broadest sense), tyres, wheelbase and track dimensions, polar moments of inertia about the three axes of the vehicle, and even the amount of power being applied to the driving wheels.

By his work in the 1930s, Maurice Olley, an Englishman who became a naturalized American, laid the foundation of our present-day comprehension of handling phenomena, incomplete though this still is. His mantle has since fallen on a handful of scientifically minded engineers who have endeavoured to evolve valid mathematical analytical methods involving the computer. The most significant was probably the Cornell University aeronautical stability group under Bill Milliken. Such methods are outside the scope of this book (apart from being beyond Terry and Baker!) so I shall consider briefly here some of the more generally comprehensible and significant aspects as they apply to racing cars.

Technological advances have so narrowed down the



Diagrammatic representation of the axes of roll (A), pitch (B) and yaw (C) of a car; all three pass through the centre of gravity design scope that, for any given type of car, the weight distribution is really predetermined to quite tight limits. This is equally true of the C of G height; though lowest is best, in principle, the bottoms of engine, car and driver should not be allowed to 'ground' in any normal racing circumstances. The lower the C of G, of course, the smaller are the weight-transfer effects during acceleration, braking and cornering, thus reducing the problems of suspension design. Although in theory wide variations are possible in tyre handling characteristics, the essentially practical consideration of maximum road adhesion imposes severe limitations on this parameter as well.

Polar moments of inertia sound rather frightening, but all they signify is the readiness with which the car can be deflected from its path. There are three such moments, about the yawing, rolling and pitching axes, but only the first is of real significance in the racing-car context. In general terms, a car with the main masses situated towards the ends has a high polar moment in yaw, which means it will not readily change direction. If, on the other hand, the masses are concentrated near the C of G, the moment will be low and the car will respond quickly to the steering. The high-moment car will be reluctant to spin, but once spinning it will take more stopping than a low-moment vehicle which requires less inducement to start its antics.

Here we have yet another case where compromise is necessary, and the best compromise will vary to some extent with the driver. When Robin Herd designed the March 721X to have the lowest possible polar moment, he had very much in mind that it would be driven by Ronnie Peterson, a 'dashing' type of driver with the lightning reflexes necessary to cope with a car having quick response characteristics. A less youthful driver, who relies on experience rather than flair and verve, would probably prefer a car with a rather higher polar moment in yaw.

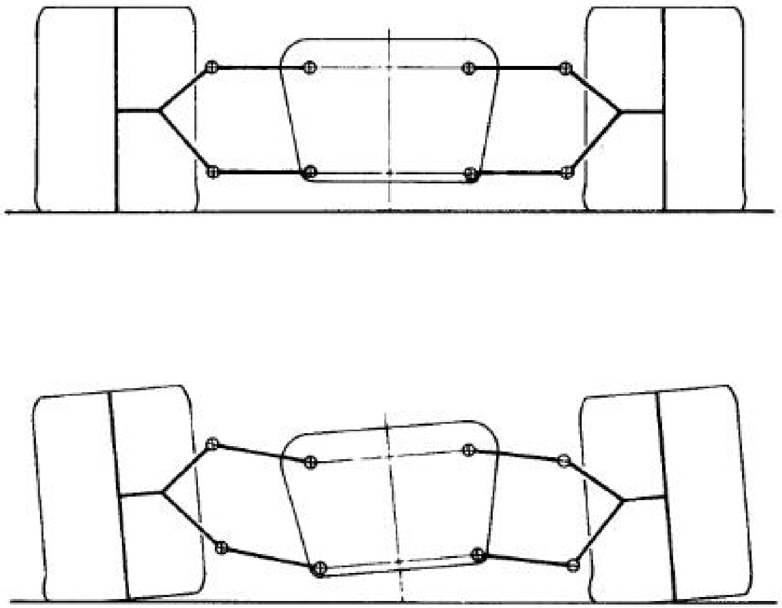
Not much can be done with the main chassis/body structure to affect the polar moment, other than to get the

fuel load as near the C of G as possible; this was one of the reasons for the 1971-2 tendency to have the tankage amidships in bulged sides. The driver is of course already in that position, but the wheelbase (because of the heavy wheel/tyre assemblies), engine and transmission group, aerofoils, radiators and oil tank can all play a significant part in determining the overall polar moment. In practice, though, other considerations probably limit the difference between low and high polar moments to something like 20 per cent.

The suspension gives the designer plenty of scope in respect of handling characteristics. Although technology has again led us to a relatively small number of practicable configurations, many degrees of freedom exist within the basic framework. In fact, it is here that the design and development team has its greatest opportunity of producing a better racing car than the opposition.

Most cars today have suspension layouts which, in effect, are variations on the double-wishbone theme. Other types exist but to bring them into this general review would only complicate matters, so comment on them will be reserved until later. What, then, are the variables of the orthodox suspension and what effect do they have on the behaviour of the car? First we have the geometry, which covers the length and disposition of the links, and hence the paths followed by the wheels when they move under the influence of the dynamic loads. How far the wheels move is controlled by the spring/damper assemblies and the anti-roll bars.

If the wishbones were parallel and of equal length, roll of the body due to the centrifugal force of cornering would clearly cause the wheels to lean outward at exactly the same angle *(see sketch)*. The cornering power of the tyres would be reduced not only by this positive camber of the outside wheels but also by the fact that all the tyres would then be riding on their edges. In the case of front wheels, the steering too would be adversely affected by



Where the suspension linkage comprises parallel wishbones of equal length, the wheels lean as much as the body rolls in cornering; this is particularly undesirable where very wide tyres are used

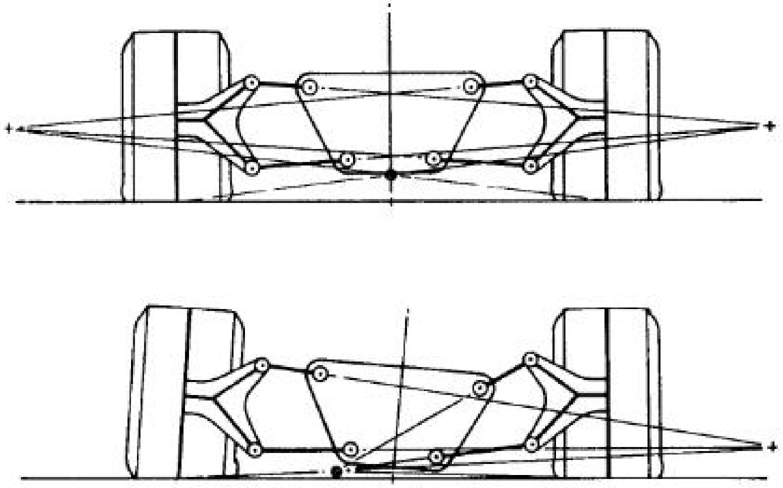
this phenomenon. Since the adoption of a negative camber angle of the outside wheels on roll would also result in edge-riding (although it would increase the basic cornering power of the tyres), the linkage must be based on unequal-length, non-parallel wishbones which are disposed so that the wheels remain as nearly as possible vertical to the road during cornering, as illustrated in Chapter 7. Of necessity they therefore adopt some camber angle when the wheel is deflected over bumps or hollows, but these are more transient conditions. It is worth pointing out here that suspension geometry was a lot less critical in this respect in the days when tyre aspect ratios, – i.e. (section depth ÷ width) × 100 per cent – were only a little under

100 per cent; as a corollary, further reductions in aspect ratios seem unlikely, purely for suspension reasons.

Linkage geometry has two other associated areas of influence. First, it affects the roll stiffness – the resistance to body roll under centrifugal force. Secondly, the relationship between the front and rear geometries determines how the outward weight transfer in cornering is distributed between the front and rear ends. The second point is very important since, at either end, the combined cornering power of the inner and outer tyres (under a given total load) falls off with increase in the difference between the two individual loads. This is because of the non-linear load/cornering-force characteristics of a racing tyre; the cornering power of the inner tyre falls off more rapidly with unloading than that of the outer tyre rises with increasing load.

It is worth dwelling on this question of lateral weight transfer because it has previously been incorrectly explained by more than one author who ought to have known better. The vital point here is that the overall weight transfer is dictated by the track and the height of the centre of gravity and *not* by the suspension characteristics, any more than the latter can affect the forward transfer under braking. To alter handling characteristics by attention to suspension geometry, all that can be done, as indicated in the previous paragraph, is to proportion the transfer more on to one outside wheel than the other. A higher roll stiffness at, say, the front means that proportionately more of the total transfer goes on to the outside front tyre, and correspondingly less on to the outside rear.

Standard practice until recently was to define this aspect of handling in terms of roll centres and the roll axis. The roll centre of a suspension system (front or rear) was defined as the instantaneous centre about which the relevant end of the body would try to roll under the influence of centrifugal force, and the roll axis was the imaginary line through the front and rear roll centres. This

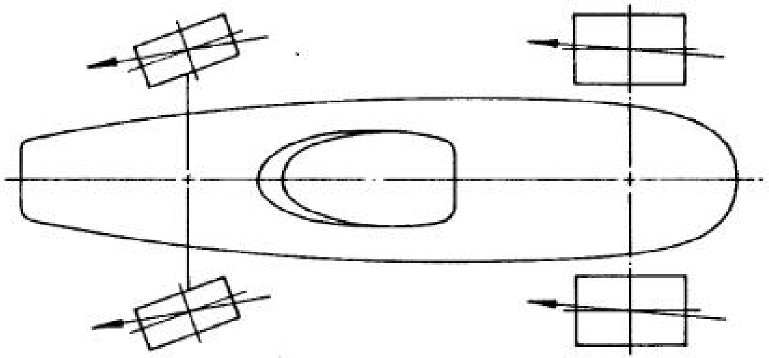


The roll centre of a suspension system can move considerably, both vertically and sideways, with wheel travel. These drawings show how the roll centre is found – by extending the centre-lines of the wishbones and joining each point of convergence to the middle of the tyre/ground contact line. The upper drawing shows the roll centre's normal-ride position on the centre-line of the car, while the lower one indicates how far it could move under combined bump and roll

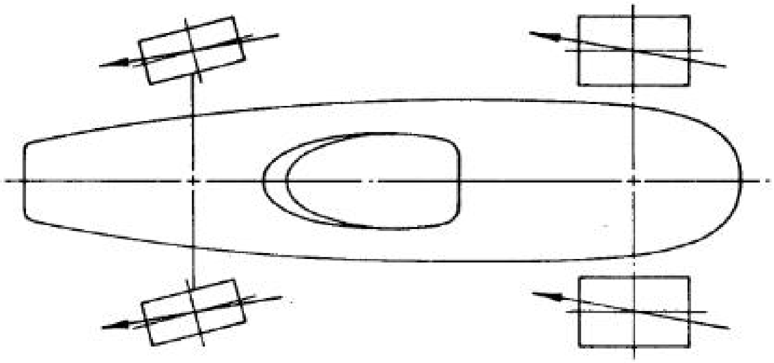
concept has the fundamental disadvantage that, in the case of virtually all practicable types of springing, the notional centres and axes are not static but are continuously moving with suspension activity, both vertically and laterally. Although some authorities are therefore abandoning this interpretation in favour of something more viable mathematically, I shall make limited use of it here because at least it enables certain things to be explained without undue difficulty.

OVERSTEER AND UNDERSTEER

It seems appropriate at this stage to introduce that world-renowned double-act of vehicle handling, oversteer and understeer. In essence they are a simple pair, though they manage in their knockabout way to lead some designers a pretty dance. A tyre has to have a slip angle (that is, to be at an angle to its actual direction of travel) in order to develop a cornering force. If the rear tyres have a larger slip angle than the fronts, the car will be in a state of oversteer; should the front slip angle be the greater, then understeer will be the result. Too much of the latter and you go straight on at the corner, but too much oversteer and you spin.



UNDERSTEER CONDITION
(FRONT SLIP ANGLE GREATER THAN REAR)



Basic explanation of understeer (above) and oversteer: in the former, the slip angles – those between the rotational planes of the wheels and their actual directions of travel – are greater at the front than at the rear; in oversteer, the rear slip angles are the greater

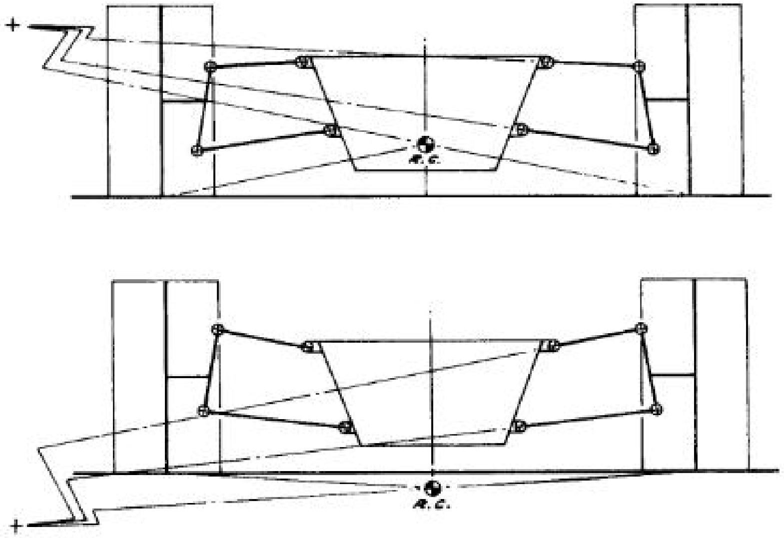
Most racing drivers today seem to prefer the car to be set up with marginal understeer in the steady-speed state. They can then convert to oversteer if they wish by applying more power. A racing car with its engine behind the driver will have around 65 per cent of its weight on the rear wheels and so will be basically an oversteerer. This trait has to be corrected, partly in the design and setting-up of the suspension and partly by fitting wider tyres (which have a higher cornering power) on the rear wheels than on the front; these wider tyres are necessary in any case to obtain adequate traction.

There are two aspects to the suspension side of the corrective process - the geometry and the combination of the springs and anti-roll bars. An anti-roll bar is a transverse steel torsion spring (of rod, tube or bar) with cranked ends; these are linked to the suspension, at or near the wheels, and the straight mid-portion is held (but not clamped) to the chassis. On two-wheel bumps or hollows the bar merely rotates in its mountings, but in cornering roll or single-wheel deflections of the suspension it is twisted *(see sketch)* and so resists the deflection. Its effect can be changed by altering either its length or its diameter - and therefore stiffness, which varies inversely with the length but as the fourth power of the diameter - or the leverage it exerts. This last depends on the attachment position of the connecting links in relation both to the bar ends and to the suspension links. Anti-roll bars form an essential part of today's racing-car suspension systems because they not only limit body roll, and hence suspension deflection and camber change during cornering, but also provide a quick and easy means of adjusting the roll stiffness; as already explained, this affects the weight-transfer distribution on corners and therefore the combined cornering power of the tyres at the two ends.

If excessively stiff anti-roll bars are employed, the phenomenon known as 'roll-rock' can arise; it is due to the bars oscillating at their natural frequencies, as any undamped spring is liable to do. Roll-rock can be decidedly unpleasant on sinuous stretches of track, where frequent changes of steering lock are necessary; so far, though,

no-one seems to have seriously investigated the possibilities of overcoming it by means of supplementary damping, on the anti-roll bars only.

Reverting to geometry variations, I must now make my threatened reference to roll centres. For a double-wishbone suspension, the position of the instantaneous roll centre is determined on the drawing board by extending the axes of each pair of wishbones, as viewed from the front or rear, until they intersect, and then drawing a straight line between each point of intersection and the mid-point of the appropriate tyre/ground contact. The roll centre is where these two straight lines intersect, as illustrated earlier. By varying the angles of the links, both to each other and to the ground line, one can in theory get any height of roll centre from below ground level to way up in the air. High and low centres are illustrated on the adjacent drawings.



Roll-centre height depends on where the wishbone centre-lines converge. High and low roll centres are illustrated here, that on the lower drawing being below ground level

Low roll centres mean low roll stiffness and, conversely, if the roll axis passed through the C of G there would be no rolling moment at all under centrifugal force. Just the thing, you might think, but such a layout would be impracticable. A high roll centre results from a high intersection point of the wishbone axes, and this point can be regarded as the instantaneous centre about which the wheel is articulating on an imaginary swing-axle. The higher this centre, the greater is the tendency during hard cornering for the body to be lifted and the outside wheel therefore to tuck-under, with consequent further (and severe) reduction of cornering power. This phenomenon, known as the 'jacking' effect, is responsible for the well-known violent oversteer of swing-axle cars such as the Volkswagen and Triumph Herald, particularly if the driver lifts off in a corner and the weight transfer off the rear wheels raises the roll centre further. The higher the roll centres, too, the less warning the driver would have that he is approaching the cornering limit. However, as was mentioned in the earlier description of the Lotus 38, use can be made of the jacking effect to maintain ride height of the chassis on a banked track.

It follows that normally the roll axis should be relatively low, but if one lowered it too far the increased body roll would be disadvantageous, as mentioned earlier. True, one could then stiffen the springs or the anti-roll bar but either of these actions could adversely affect the road-holding and ride, so the last state might be worse than the first.

This is perhaps the place to give some sort of a guide to the roll-centre heights currently favoured for high-powered racing cars with the engine behind the driver. At the front they are usually in the 0-3 in (0-75 mm) bracket, whereas at the rear they are usually rather higher, say 2-5 in (50-125 mm). The front roll centre is the lower because the very wide rear tyres (necessary for traction, as explained earlier) have more than enough cornering power to offset the basic oversteer. The range of heights given is quite wide, but different design/development teams find different compromises between geometry, spring rates, anti-roll bars and damper settings, while different types of car have differing basic requirements.

PRACTICAL IMPLICATIONS

We have spent quite a time on the theoretical aspects of handling, and the variables that affect it, so let us finish with a look at the practical implications. Supposing we have a car which understeers too much, what can be done to correct it? First we have to decide whether to tackle the front suspension, the rear suspension or both. In general, designers prefer the front-end approach initially, in case any geometry changes prove necessary, because of the complicating factor of the drive-shafts at the rear. Let us assume, therefore, that the understeer is only a little more than would be acceptable, and so can probably be cured merely by alterations to the front suspension.

In basic terms our task is to increase the cornering power of the front wheels. Assuming that we cannot get front tyres with more favourable slip-angle/cornering-force characteristics, we do this by reducing the front roll stiffness and hence (as already explained) the proportion of the total weight transfer that goes on to the outside front wheel. For a start we would try the effect of fitting a less stiff anti-roll bar (or increasing the lever-arm length of the existing one, to reduce the amount it twists), because this is the simplest course of action. It is usually not worthwhile trying the alternative approach of fitting softer springs in the front suspension units. We might then suffer from grounding under braking, and the roadholding and ride might suffer through a less favourable balance between the

front and rear spring rates (and therefore bouncing frequencies).

Should we still prove unsuccessful, even with various combinations of softer anti-roll bars and damper settings (which can be critical), we are faced with lowering the front roll centre. This means repositioning the inboard or outboard pivots of upper and/or lower wishbones, and perhaps altering their lengths to keep the track and steering geometry as before. Having done this, we can now ring the changes on the springs, bars and damper settings to get the best result, and of course further 'tuning' is possible by varying the rear components as well. Here, though, we should make sure not to alter more than one thing at a time - the first lesson for the aspiring development engineer! The driver, of course, is the key man in all this testing and retesting, so his full co-operation is essential for the success of the exercise.

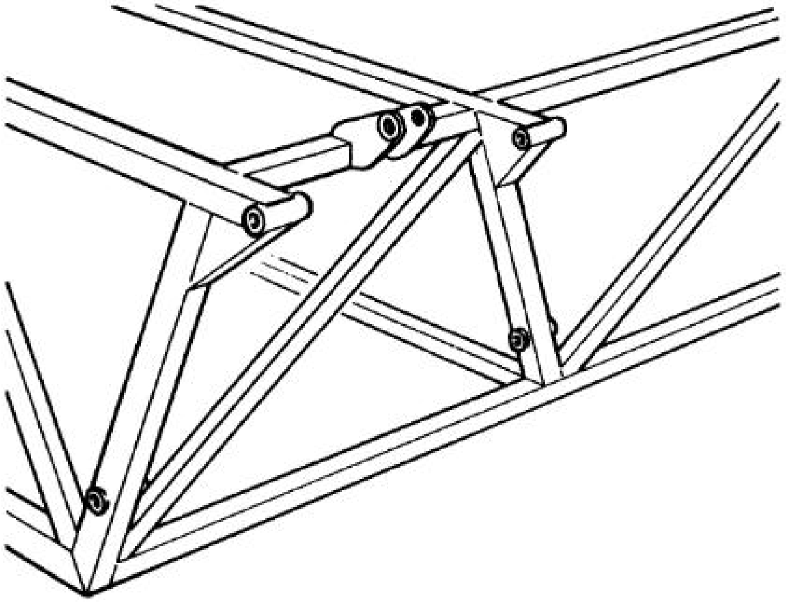
6

Structural considerations

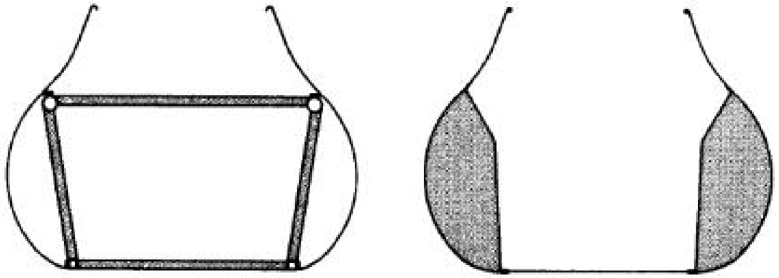
SPACE-FRAMES AND MONOCOQUES

With the evidence of the early Leda troubles to back me up, I am more convinced than ever that unless a designer starts with a really stiff chassis he will never achieve first-class handling. To obtain adequate stiffness in practice, though, it is not sufficient merely to have a basically well-designed monocoque or space-frame. One must also consider how the dynamic loads are fed into the structure, since local lack of rigidity can cause undesirable flexing. Trouble could arise, for example, if an engine mounting is insufficiently rigid, or if a suspension pivot is carried at the middle of an unsupported tube. Conversely, a properly mounted engine can contribute significantly to the overall stiffness; in the case of the 1½ litre Formula 1 Lotus, the torsional figure rose almost 50 per cent when the engine was installed.

On the space-frame *versus* monocoque issue, there are numerous aspects to consider. Although the basic space-frame is a comparatively light structure, it requires a



Mounting a heavily loaded bracket mid-way along an unsupported tube will detract from the effective stiffness of an otherwise well-designed structure



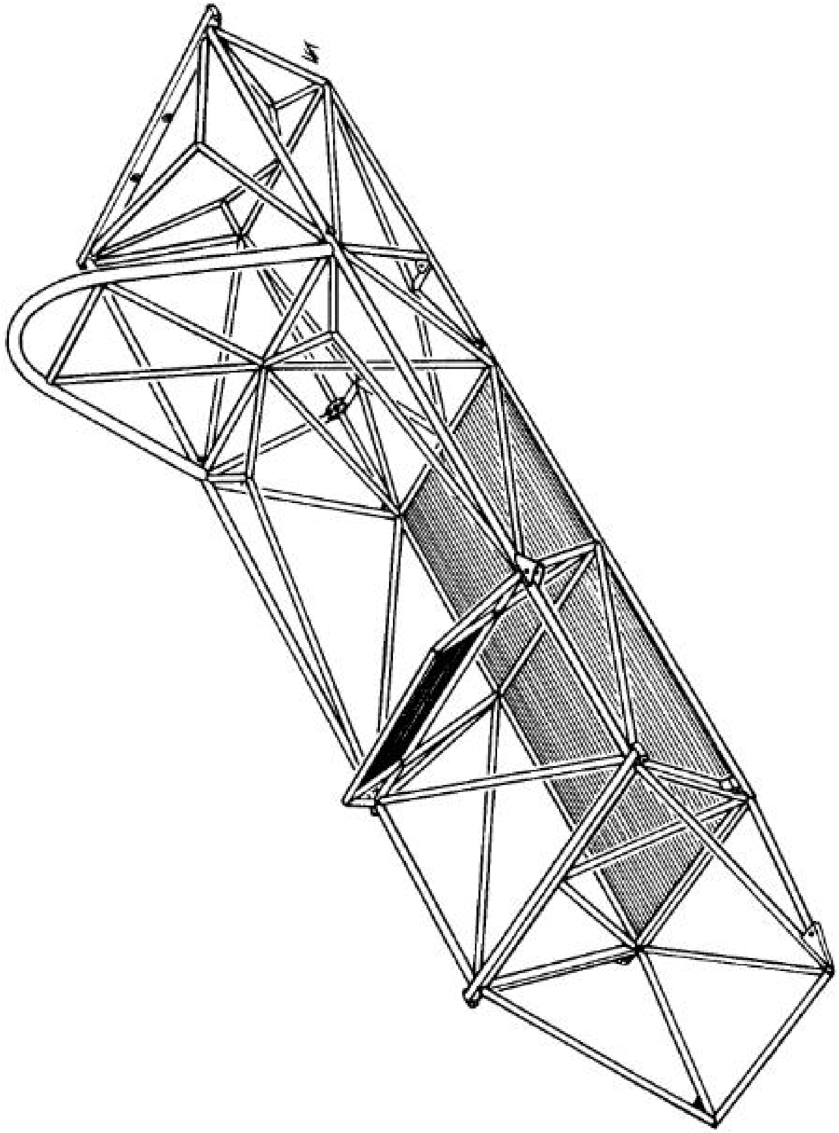
A monocoque (right) is inherently stiffer in torsion than a space-frame because of the wider spacing of the (shaded) main load-carrying members

separate body and fuel containers, all of which are integral parts of a monocoque, so this tends to nullify any hoped-for weight advantage. Also, for the same weight and overall dimensions, the monocoque is fundamentally the stiffer of the two in torsion. This is because its main load-carrying members or sponsons are at the outside of the section, where they exert a greater resistance to twisting than do the corresponding space-frame members, which are situated nearer the middle of the structure *(see accompanying drawing)*. As the dynamicists put it, the monocoque has a 'higher section modulus' than the space-frame.

But all design is a compromise, and torsional stiffness is not the only criterion, nor necessarily the prime one; cost and ease of production are among the other considerations.

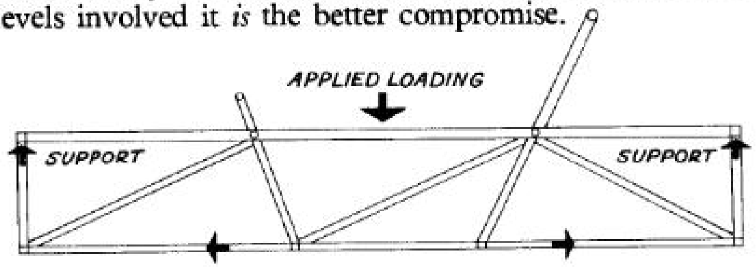
The space-frame clearly scores in both respects, so is more suitable for the lowlier, less expensive formulae. Typical costs might be about £150 for a space-frame and £450 for a monocoque; this is a serious difference in a Formula 3 car costing around £2000 but much less so at the £8-9000 level of a Formula 5000 machine. In any case the Formula 3 car, because of its lower weight and performance, probably does not need even as much as half of the 3000 lb ft/deg (414 m kg/deg) torsional stiffness desirable for Formula 1 or Formula 5000 racing. If I were to design a 'commercial' Formula 3 car today, I would almost certainly give it a space-frame basis but would make the structure composite by riveting-on the main body panels, as with the early Terriers.

The space-frame scores, too, in respect of maintenance accessibility of the various systems, because the body shell can be removed altogether. It is also quicker and cheaper to repair after an accident. Damage tends to be localized,



Typical Terry space-frame for a single-seater. The structure is fully triangulated for maximum stiffness, the bottom being stabilized by the riveted-on floor-panels

so the appropriate section can be cut out and replaced, whereas in a well-stressed monocoque the distortion will probably extend well beyond the actual impact region. Yet again, the space-frame lends itself better to modifications such as the repositioning of suspension pivots. All this appears to boil down to the fact that designers of the more exalted racing cars have adopted monocoques really because they have had to, since at the performance/cost levels involved it *is* the better compromise.



Under normal loading, the bottom tubes of a space-frame are in tension and the top ones in compression. Since compressive loading tends to cause buckling, the top tubes can with advantage have a stronger section than the others

When one is laying out a space-frame, it is structurally correct to make the top rails of larger section (or thicker gauge) than the bottom tubes, because in the normal direction of loading the former are in compression and so must be given adequate resistance to buckling. Although square-section tubes have an inferior strength/weight ratio to the round type, they are preferable for bottom rails and cross-members because the undertray can be riveted-on more easily. As a purist, too, I deplore the use of gussets to reinforce space-frame joints; in effect they convert a triangle into a quadrilateral and therefore serve as stress raisers.

Reverting to monocoque structures, it is noteworthy that several of the 1971 Formula 1 cars (BRM, McLaren and Tyrrell among them) had bodies which bulged laterally in the cockpit area. This 'pregnant' form enabled the fuel load to be concentrated around the car's centre of gravity, so that the weight distribution – and hence the handling – altered relatively little from full to empty. In addition, the cornering abilities could have been improved slightly by the reduced polar moment of inertia in the yawing mode. Any higher aerodynamic drag of the bulged shape is offset by the increased stiffness resulting from the larger 'radius of gyration' of the body section and from the greater use of compound curvatures. Weight, on the other hand, was not significantly affected.

By 1972, though, the influence of the Lotus 72 wedge shape was making itself felt in the single-seater exposed-wheel categories. This form, of course, makes a raised cockpit surround, or 'conning tower', necessary. At first glance, one might think that wedges would be inherently less stiff than more curvaceous shapes, but a closer look at the Lotus, for example, shows that in fact it has few straight lines or flat panels; the double curvature is subtle but it is there, and the effective depth of the monocoque remains much the same as before.

THE COCKPIT AREA

With any racing car, but particularly the open-wheel type, the cockpit area is structurally the weakest, whatever form of chassis is used. The ideal would be a body of circular section, built round the driver and with merely a hole in the top for his head (or perhaps even internal closed-circuit TV!), but this layout would meet nobody's regulations and I doubt if even the most dedicated driver would tolerate it. We therefore have to accept that the driver must have room to get in and out, without the need to remove the steering wheel as on the pre-war Mercedes-Benz GP cars. However, the cockpit opening area of 500 sq in (0.32 sq m) specified by the Indianapolis regulations is unnecessarily generous and inevitably detracts from the body stiffness.

A point of interest here is that there still seems to be divided opinion as to the relative desirability of the 'bathtub' structure with detachable top (as used for example on the Lotus 72) and the full monocoque, favoured by McLaren and Tyrrell amongst others.

I have a marked preference for the latter design, because the integral bridging at the top must impart greater stiffness for a given weight. A removable top does of course give better accessibility of the pedals etc, but I think this is inadequate compensation for a less satisfactory structure. For minimal loss of structural integrity in a full monocoque I believe in having the smallest practicable windscreen, so that the sheet metal can be taken right up to the opening and its edge wired. It is also worth referring back to my earlier space-frame technique of taking bracing members round the outside of the opening.

THE 'STRUCTURAL' ENGINE

The use of the engine as a structural member, to absorb some of the rear-suspension loads, has technical justification in terms of weight reduction. However, it also has its more dubious aspects. The pioneer here was, of course, the Cosworth-Ford Formula 1 power unit and it was stressed to withstand the torsional and bending load levels obtained at that time, no doubt with a margin for expected increases.

When aerofoils arrived, though, these load levels rose substantially, all in one go; by 1973, values were around 1.5g for cornering and 1.8g for braking, whereas when the Cosworth engine was designed they were perhaps 0.3g lower. It follows that the engine casings were being stressed much more highly, and the deflections were proportionally increased, resulting in higher internal friction.

Although Cosworth deny any subsequent modification, this fact may have accounted for the significantly reduced reliability of these power units during the 1970 season. Certainly Mike Hewland found it necessary to stiffen-up the casings of his transaxle units to cope with the higher loadings.

If deflectional troubles can occur in an engine designed as a structural member, they are clearly more likely in one intended to be carried on a chassis. For this reason there are objections to the cantilever mounting of Formula 5000 engines; their thin-wall iron castings are unlikely to be stiff enough. A V12 engine is fundamentally less suitable than a V8 for structural integration. Being appreciably longer and thinner, it must be less resistant to torsional stresses unless the castings are so massive as to incur a serious weight penalty. Any such extra overhung weight, too, would bring a further difficulty in that the loads fed into the mounting bulkhead would be increased.

Even with a compact V8 engine it is none too easy to feed the loads in satisfactorily through a four-point mounting. If I were to design another Formula 1 car, I would seriously consider the apparently reactionary step of incorporating a tubular 'fail-safe' reinforcing structure at the rear. This would have the secondary advantage of enabling the car to be built-up and wheeled around without its power unit.

PROGRESS AND LEGISLATION

Although the structural ultimate has not yet been reached, the way ahead looks like a refining process rather than the discovery of any startling new concept. In addition to their higher costs, exotic materials do not appear able to increase structural efficiency by a really significant amount.

All-American Racers tried replacing aluminium by magnesium, and steel by titanium, in one of their monocoques. They claimed a weight reduction from 80-90 lb (38-43 kg) to about 50 lb (24 kg) but this seems over-optimistic when the relative tensile strengths are taken into account – 30 ton/sq in (47.3 kg/sq m) for L72 aluminium alloy as against 22 (34.6) for a comparable magnesium alloy. The characteristics of any possible replacement materials must also be considered. For example, magnesium is more flammable than aluminium – though the danger here may have been overstated – and its fatigue characteristics might not be adequate; if work hardening were to occur under cyclic stress, a panel might tear along a line of rivets, for example.

Increasing safety-consciousness caused the F1A to stipulate that, for 1972, the outer skins of all Formula 1 monocoques had to have a minimum thickness of 16 swg (0.064 in or 1.6 mm). Since most constructors had been using 18 swg (0.048 in or 1.2 mm) aluminium alloy for this purpose – though some adopted the thicker material for their 1971 cars – weights tended to rise slightly in 1972, in spite of the efforts made to effect savings elsewhere.

The 1973 Formula 1 regulations affected design more fundamentally since they required a double-skinned 'deformable structure' enclosing the fuel tanks. This structure had to have a fire-resistant foam filling between the skins, and had to be at least 10 cm clear of the tanks at the widest part. To allow for the change, body maximum width was increased from 110 to 140 cm.

Although the deformable structure adds to the weight and frontal area of the cars, the more imaginative designers have been able to take advantage of the new regulations by increasing the structural stiffness of their monocoques and utilizing the extra width to improve the aerodynamics.

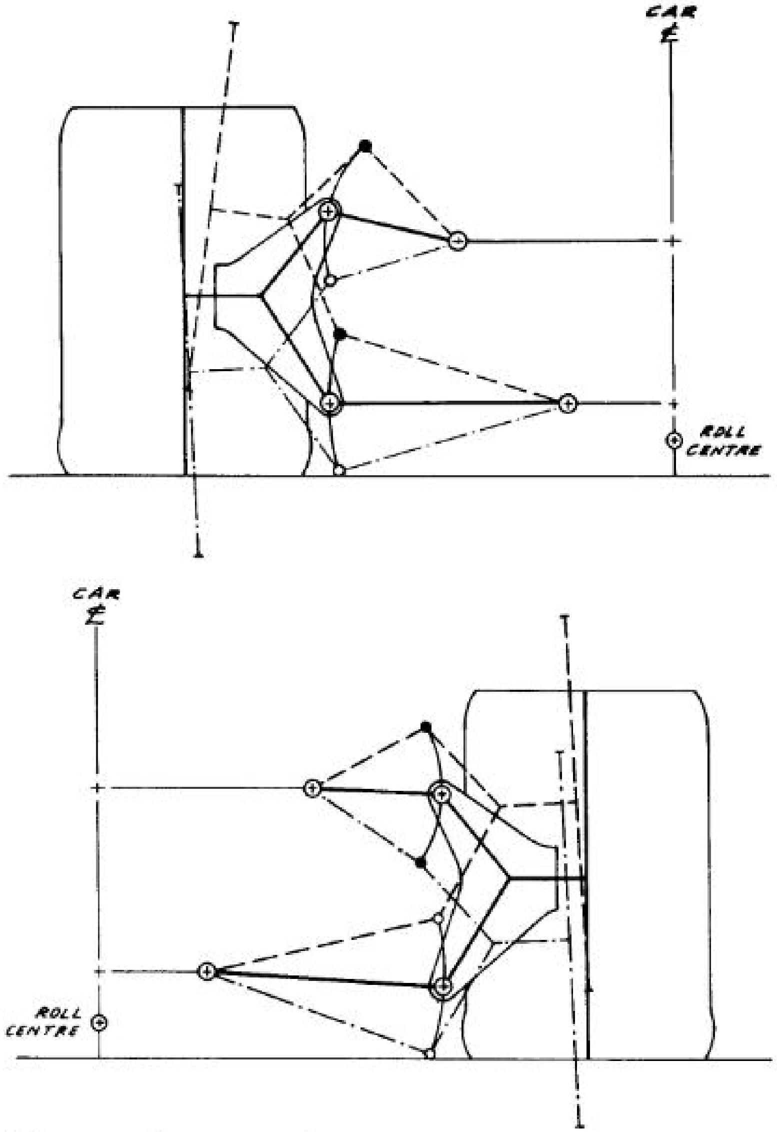
7

Suspension

CHANGING NEEDS AND LAYOUTS

The Formula 1 car of the 1970s is considerably more difficult to suspend than were, for example, the first of the 3 litre vehicles produced in 1966. There are two reasons for this, each with ramifications and interrelations. First we have the enormous increases in wheel and tyre widths. Current wheel/tyre assemblies are at least half as heavy again as those of seven years ago, yet chassis weights have tended to reduce slightly; the result is a substantial worsening of the sprung/unsprung mass ratio, the prime parameter of suspension effectiveness. The very wide tyres raise the secondary problem of keeping their treads reasonably flat on the road at all times, to ensure that all the rubber is doing its work and that the car handles properly.

By juggling with link lengths and angles, the designer of a conventional racing-car rear suspension – which in terms of camber change is in effect a double-wishbone layout – can keep the tyres almost square with the road, but only over a limited wheel travel. He also has to contend with the second



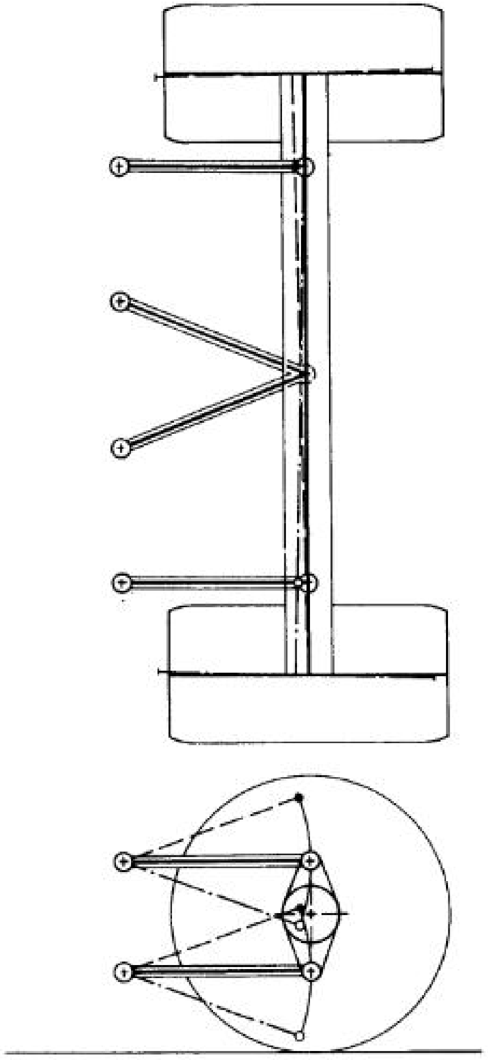
Where very wide tyres are used, the suspension geometry must give the minimum camber change with wheel travel. The upper layout has highly convergent links, and hence a short 'equivalent swing-arm' length and considerable camber change; in contrast the more nearly parallel links of the other geometry provide relatively small changes of camber

major suspension difficulty – that of coping with the considerable variations of downthrust with speed resulting from the use of body-mounted aerofoils. As a result he has to fit springs of significantly higher rate than were necessary a few years ago. Admittedly these prevent today's low-clearance cars from grounding after bumps or on heavy braking, but they also raise the natural frequency of the suspension; a higher frequency means not only a less good ride but – more important in the racing context – inferior road-holding characteristics.

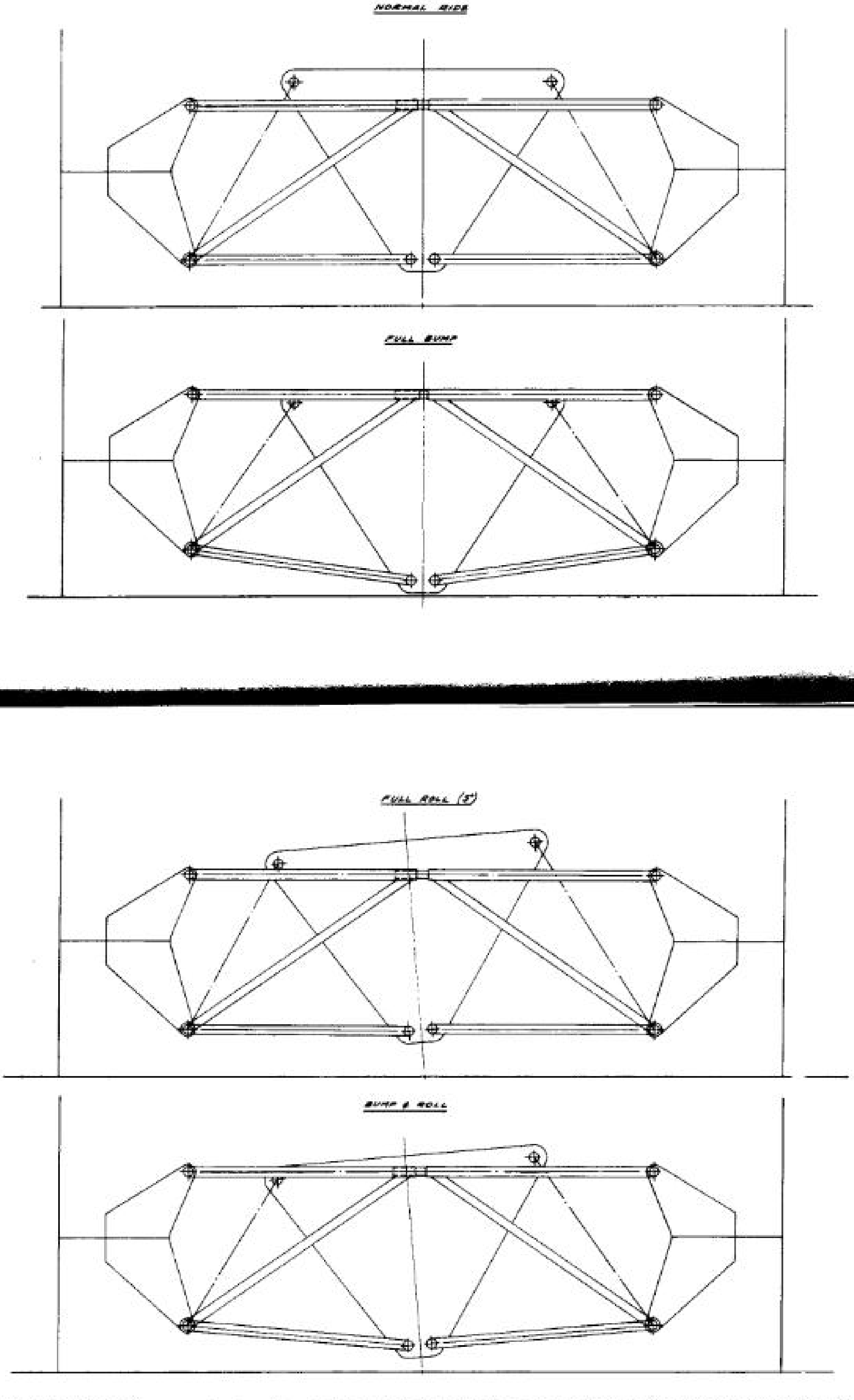
In view of this 'cleft stick' in which the designer now finds himself, it is valid to consider whether any alternative suspension layouts offer the prospects of a better compromise. Lotus are among those who have tried a reversion to the de Dion scheme at the rear because, like any beam-axle system, it keeps the tyres square to the effective line of the road surface at all times. Their experiment on a Formula 2 car was short-lived, however.

The most likely source of handling troubles deriving from a de Dion layout would be steering effects resulting from skewing of the axle on one-wheel bumps, though there could also be problems in matching a de Dion rear system to a double-wishbone front layout, because of conflict between the fixed camber angle at the rear and the variable angle at the front.

A de Dion rear suspension was reintroduced, of course, as a competition option on the Lotus Seven. In this layout, longitudinal location is by means of radius arms, which give the steering effect just mentioned. Clearly, the longer the arms the smaller the skewing effect, but long arms are less easy to install and require a higher section modulus to maintain stiffness. Replacing the arms by twin Watt



De Dion rear suspension with link location has a self-steering tendency over one-wheel bumps due to skewing of the axle, which moves forward on deflection either up or down



Len Terry's proposed design for a suspension layout that keeps the wheels square to the road under bump and/or roll conditions. Details are given in the adjacent text linkages keeps the axle square but necessitates a longer chassis frame to provide anchorages for the rearward links.

Because of the desirability of keeping the wheels upright, I began to think some time ago about possible variations on the de Dion theme. The Rover scheme of introducing a degree of freedom into the beam inspired me to spend a session on the drawing board, and I eventually came up with the layout illustrated. It comprises two simple frames, each forming a triangle with its 'upright', connected by a sliding central joint. Each frame is located by a parallel-arm lower link, as shown, and by the usual top and bottom longitudinal radius arms which are not seen in this view. In the drawings the body is depicted purely diagrammatically to indicate the attachment points.

This system keeps the wheels perpendicular to the road under any combination of bump, rebound and roll, and the lateral sliding travel at the central joint is less than half an inch. Unsprung weight is clearly rather higher than for a conventional rear suspension, but the advantage of no camber change could well outweigh this, and the structure does fit surprisingly well into the layout of a normal open-wheel racing car.

There would seem to be prospects of getting better suspension characteristics from systems that separate the bump and roll functions in some way. Apart from Terry's own efforts with the Terrier Mark 6 and the Shelby car, the Trebron and Torix Bennett designs are of this type. So far, though, the Terry layout is the simplest and therefore probably the lightest. However, there is still a lot to be learned about such layouts, and the learning promises to consume more time and money than are readily available to most racing-car constructors.

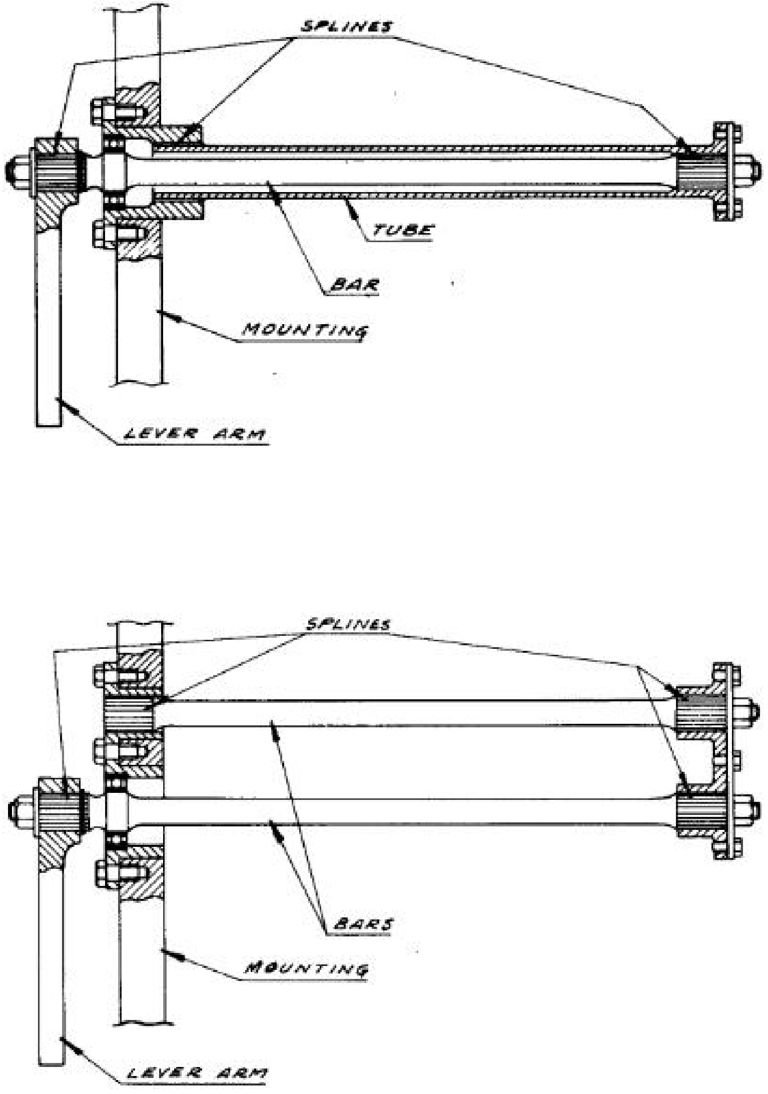
THE TORSION BAR

As a method of effecting a minor reduction in the sprung/unsprung mass ratio, torsion-bar springs deserve closer study than they have received so far. Until the advent of the Lotus 72 at the beginning of the 1970 season, the coaxial coil-spring/damper unit held universal sway, primarily because it is compact, self-contained and easy to install and adjust. A torsion bar has higher energy-storage capacity for a given weight than a coil spring, but its main advantage for vehicle suspension is that its mass is fully sprung, whereas half of a coil spring's mass is unsprung.

The main objection to the torsion bar is its length, which many have regarded as making it difficult to install. Colin Chapman and Maurice Phillippe surmounted this difficulty on the Lotus 72 by using a compound system at front and rear. In this arrangement, a torsion rod lies within a torsion tube, the two being splined together at one end; at the other, the tube is clamped rigidly to the chassis and the rod projects from it to carry an arm connected to the suspension linkage, each assembly being mounted longitudinally.

This compound torsion-bar arrangement is far from new; there were even examples in the 1930s. Although the resulting spring is significantly shorter than a simple bar, it has undoubted disadvantages. First comes the additional weight introduced by the splined coupling between the two portions. Then there is the extra complication and cost. Finally, if a spring assembly of different torsional stiffness is needed, it is not desirable to replace only the inner or the outer member because this would unbalance the stress distribution between them.

In my view, too much has been made of the installation difficulties imposed by the simple torsion bar. There is no valid reason why bars of this type should not be mounted longitudinally outside the



On the Lotus 72, compound torsion-bar springs are used instead of coils; each comprises a bar within a tube, as in the upper drawing. An alternative layout is to have two bars in parallel

bodywork. Their extra drag would be insignificant and they would be very accessible for adjustment. The fixed end of each bar could have a rotatable anchorage (as on the Rover 3 Litre and 3.5 Litre models) for varying the ride height. At the 'working' end a lever of adjustable length would enable the basic rate to be varied as well. As with a double-wishbone layout, the geometry of the linkage to the wishbone could be laid out to give a variable-rate effect which also could be adjustable if required.

As a further means of reducing unsprung mass, I am in favour of a return to the lever-arm or semi-rotary damper. If the body of such a damper is chassis-mounted, only half of the lever itself is unsprung, whereas half the total mass of a telescopic unit is in that situation. The simplest and lightest layout is in fact that used by BMC on some of their earlier cars and by BLMC on the Morris Marina; the damper body and spindle are of massive construction, and the actuating lever forms the upper transverse link of the suspension system.

SELF-LEVELLING SYSTEMS

The effect of aerodynamic downthrust on ride height has already been mentioned. Fuel load, of course, has a similar variable effect. The present-day Formula 1 car weighs about 1200 lb (570 kg) dry and carries a maximum fuel load of around 350 lb (167 kg) so the full/empty weight variation is appreciably over 20 per cent.

In the case of an Indianapolis car, dry and fuel weights are increased by about 200 and 100 lb (95 and 47.5 kg) respectively, so the variation may approach 25 per cent. For a CanAm car, weighing about 1650 lb (785 kg) and carrying over 500 lb (240 kg) of fuel, the full-to-empty change would be somewhere between the two percentages already quoted. A variation of this order would result in the ride height increasing by perhaps 1 in (25 mm) as the fuel was used up, and the roll centres rising by about twice that figure - sufficient to make a significant difference to the handling characteristics.

Some form of self-levelling device incorporated in the suspension systems would therefore seem to be a logical and worthwhile development. In fact, I would have incorporated this in my last Indy car design if suitable units had been available. Although I cannot find any precedent for self-levelling on racing cars, Ferrari did try an experimental Koni system on certain road cars a few years ago, but did not persevere with it.

This Dutch design may well be ripe for further development, but in any case there are two other self-levelling devices that might be used. One is the Armstrong, which has been around for several years and was standardized on the Austin 3 Litre. The other is the Boge, already fitted to the rear suspension of both the Range Rover and the big BMWs. Of a more fundamental nature is the Automotive Products roll-free suspension which, since its announcement early in 1972, has attracted considerable interest in the racing world. At the expense of weight and complexity, this hydropneumatic system keeps the ride height constant and should improve cornering power by keeping all four wheels continuously in their optimum attitude relative to the road; also it obviates dive and squat.

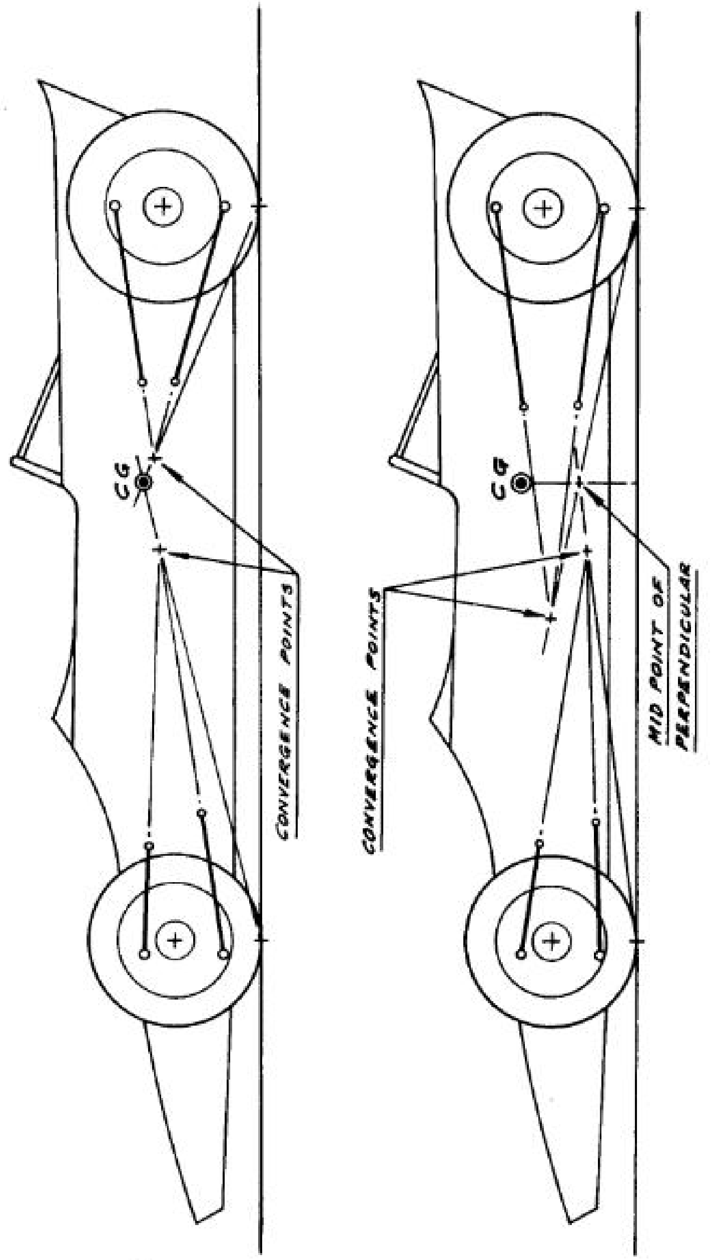
ANTI-DIVE AND ANTI-SQUAT

Modifying the suspension geometry to reduce braking-dive or acceleration-squat, due to weight transfer, is no new idea. Anti-dive, for instance, dates back to pre-war days and was adopted on a number of typically softly sprung American post-war cars to prevent them from standing on their heads when their over-servoed and under-sized drum brakes grabbed-on hard at low speeds - which was difficult to avoid even with a featherweight touch on the pedal.

Owing to brake and tyre improvements, softer suspension and considerably higher engine outputs, the Formula 1 and sports-type racing cars of the mid- and late-1960s revealed substantially greater changes of attitude when slowing or accelerating than did their predecessors, in spite of their favourable ratio of wheelbase to centre-of-gravity height - the basic factor in the tendency to such attitude changes. Most of the present generation of designers therefore have experimented at some time with means of controlling this phenomenon. However, opinion is still very much divided on the degree, and even the basic desirability, of such control.

As mentioned earlier, the designed-in anti-dive of the Eagle was reduced to improve the handling. In addition, the Lotus 72 started life with a lot of both anti-dive and anti-squat geometry, but this was soon deleted. On the other hand, the Lotus 38 began with a front-suspension layout giving 20-25 per cent of anti-dive (100 per cent being the complete cancellation of dive), and this was never changed.

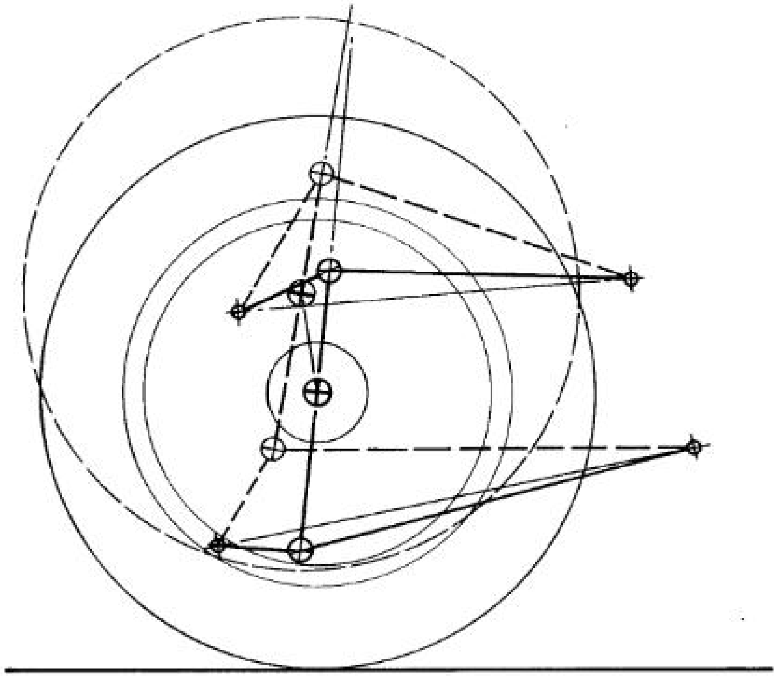
There are two basic methods of obtaining anti-dive and anti-squat (which is the same thing in reverse). The first is to converge the axes of each pair of wishbones, as viewed from the side. This convergence is towards the rear for the front wishbones and *vice versa.* In theory, if the convergence points coincided on the transverse axis through the centre of gravity, no diving or squatting moment would be created. Such a layout would be impracticable, but the same result can be achieved by having the convergence points (which are the instantaneous centres of the 'equivalent' leading and trailing arms) on the lines joining the tyre contact points to the



Anti-dive and anti-squat can be obtained by converging the pivot axes of the front and rear wishbones respectively. The upper sketch shows a layout giving 100 per cent resistance to both dive and squat, while the lower one reduces them by half

transverse axis through the centre of gravity *(see accompanying drawing)*. With this geometry, the diving moment under braking is exactly balanced by brake torque-reaction forces acting at the points of convergence. On a conventional two-wheel-drive car, squat is resisted only by the torque reaction upthrust at the rear.

Any displacement of a convergence point from the tyre-contact/C of G line will of course alter the anti-dive effect. For example, if one wanted 50 per cent anti-dive, the line through the tyre-contact and convergence points should cut the perpendicular through the C of G half-way up from the ground, as illustrated. Another point is that, if full anti-dive is applied to one end of the car only, the 'untreated' other end would still undergo vertical movement under braking or acceleration. Hence the car



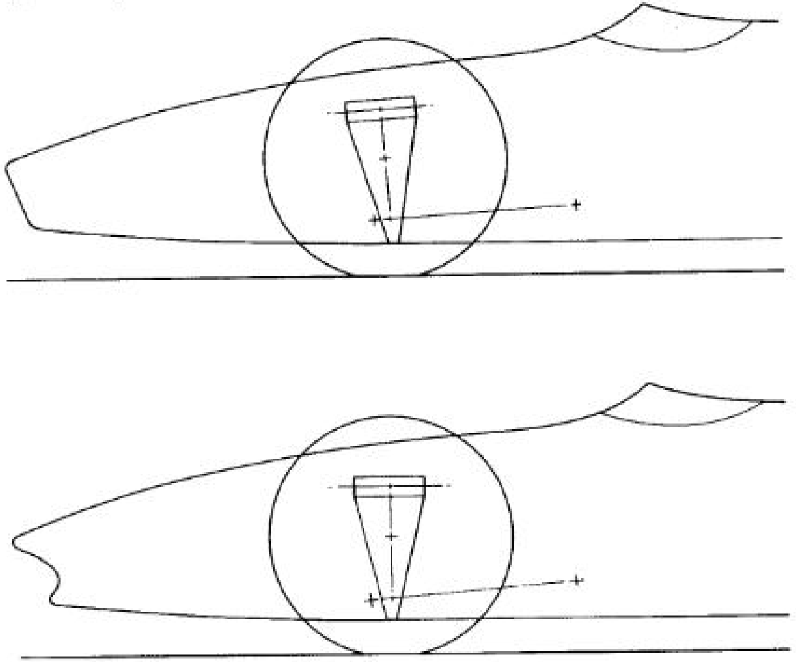
A disadvantage of convergent wishbone axes is that the steering castor angle varies as the wheel moves up or down from its static-load position would still change attitude, but to a lesser extent than without the modification. It should be remembered, too, that the whole principle depends on having outboard brakes, that is, on the unsprung portion of the vehicle. With inboard brakes, the convergent geometry is ineffective, since the brake-torque reaction then tries to rotate the vehicle bodily about the brakes - in one direction at the front and in the other at the rear.

Two other aspects also require comment. One is that the instantaneous centres, like their transverse equivalents, shift their positions with suspension deflection; hence the degree of anti-dive could vary as, for instance, the fuel load diminishes. The other point is that the opposing inclinations of the front wishbone axes cause that of the king-post, and hence the castor angle of the steering, to alter with suspension travel, as shown. This inconstancy of angle can undoubtedly have an adverse effect on the overall handling characteristics.

The alternative method of reducing dive or squat is to use the inertia of the sprung mass to generate the opposing force. To resist dive by this means, the pivot axes of the front wishbones are both inclined downward at the front, *(see drawing).* When the brakes are applied, and the body tries to get ahead of the wheels because of its inertia, the wishbones tend to move towards the 'droop' position and so to lift the front of the car. A corresponding down-at-heel inclination of the rear wishbone axes gives the anti-squat effect. For complete cancellation of attitude change, the inclination, should be parallel to the tyre-contact/C of G line mentioned earlier.

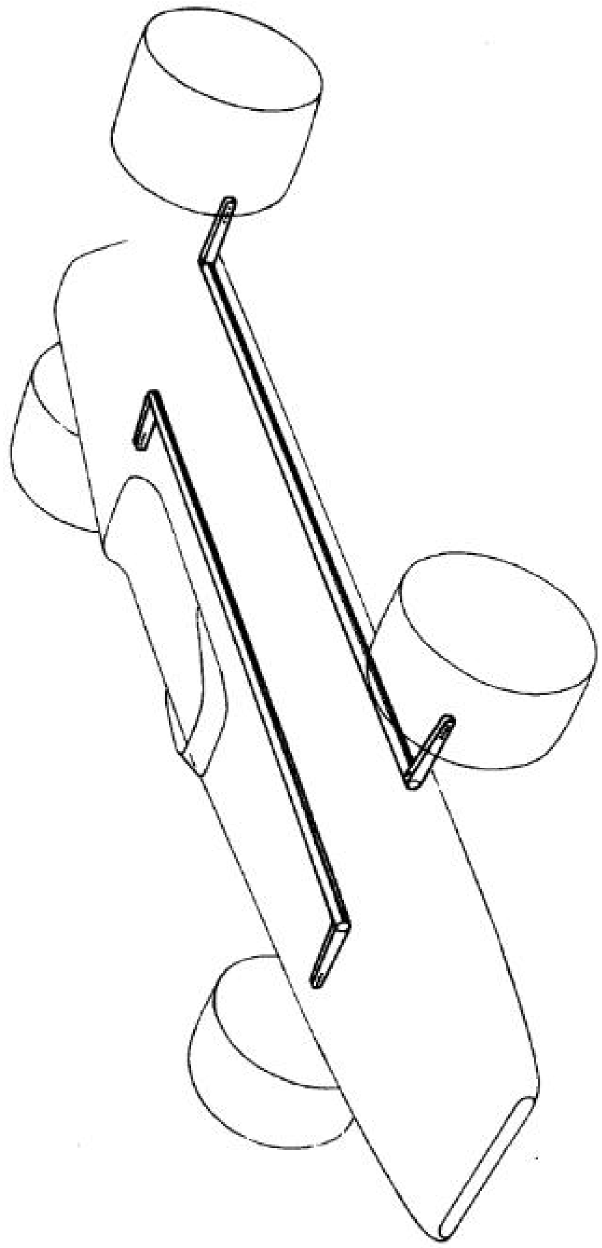
As in the case of the convergent-axes geometry, this parallel inclination has a serious disadvantage if it is more than a few degrees. The front wheels have to move appreciably *forward* as well as upward in response to road bumps; since the latter exert a *rearward* as well as an upward force on the wheels, the latter therefore have to travel in an 'unnatural' direction, so the suspension is less

sensitive than with vertical travel. Under braking, the rearward forces on the wheels increase; the suspension in effect then becomes still stiffer, so wheel patter and loss of adhesion can occur. At the rear, though, the wheel travel with anti-squat is 'natural' - upward and backward - so the suspension response is rather better than with normal geometry.



Another method of obtaining anti-dive is to incline the axes of both front wishbones downward at the front, as on the Lotus 38 shown above. The reverse inclination of the rear axes resists squat. On the Eagle (lower drawing), Terry inclined the axes of the lower front wishbones only, thus obtaining a convergence and hence variations of castor angle, as mentioned previously

On the Eagle, for example, I tried to compromise on this forward movement of the front wheels by inclining only the lower pivots. However, this at once introduced a castor angle variation with wheel travel and so did not help matters. Looking back, I suppose



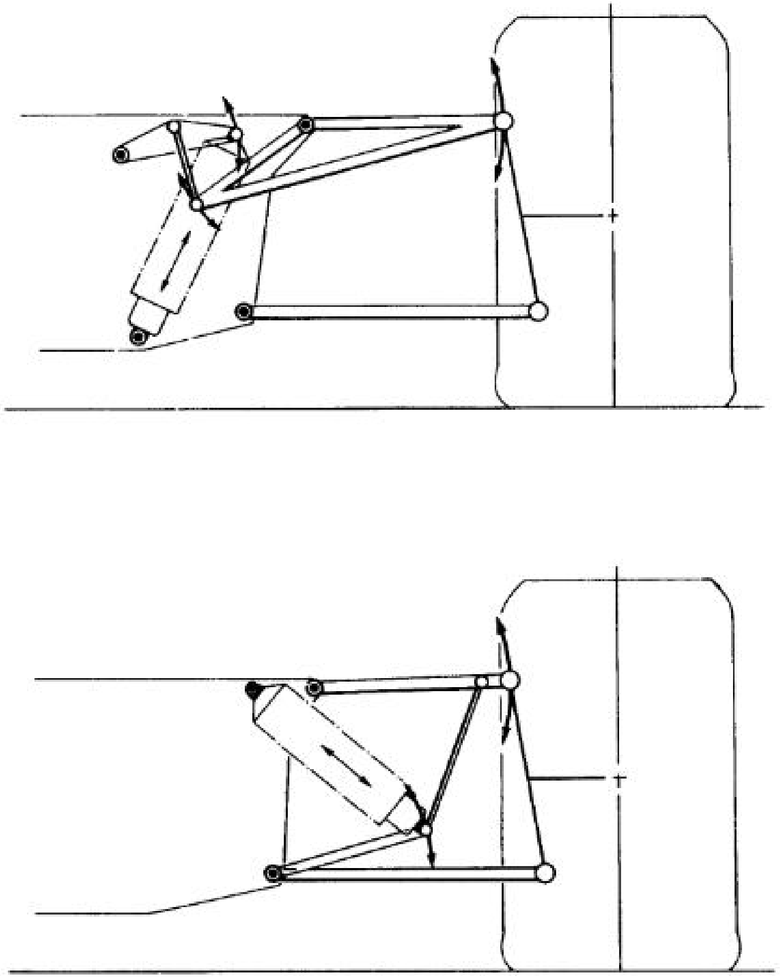
Terry experimented with this anti-pitch torsion-bar arrangement on the Leda Mark 2, but time did not permit any valid assessment to be made

it would have been better merely to have given a smaller inclination to all four pivots. It looks as though 3-4° (as on the Lotus 38) is about the practicable maximum here without any compliance in the linkage. This means about 20 per cent of anti-dive, but I am still not convinced that it can make more than a marginal difference to a car's handling. Although Alan is quite right regarding the absence of suspension stiffening with the 'down-at-heel' anti-squat geometry, one must be careful here not to introduce any rear-end steering effects, through the backward movement of the wheels, since any such effects could upset the handling. My own parallel-link design, of course, keeps the wheels correctly aligned.

Because of the problems posed by other methods of controlling attitude changes, I have every intention of looking further into the possibilities of my anti-pitch-bar system (to which reference was made in the Leda Mark 2 description). In effect these bars are like anti-roll bars moved through 90 degrees, and each serves to connect the front and rear suspensions on its side of the car. When the body tries to dive or squat, one suspension starts to compress and the other to extend; relative movement between them winds-up the bar in torsion and so is resisted. Although this arrangement would increase the sprung mass a little it does obviate the problems of the conventional approach. However, because in some circumstances the bars would be augmenting the main springs, quite a lot of experimental work would undoubtedly be necessary to establish the best combination of spring rates and bar stiffness.

PROGRESSIVE-RATE SPRINGING

At the beginning of the 1971 season, the McLaren organization – previously notable more for sound engineer-

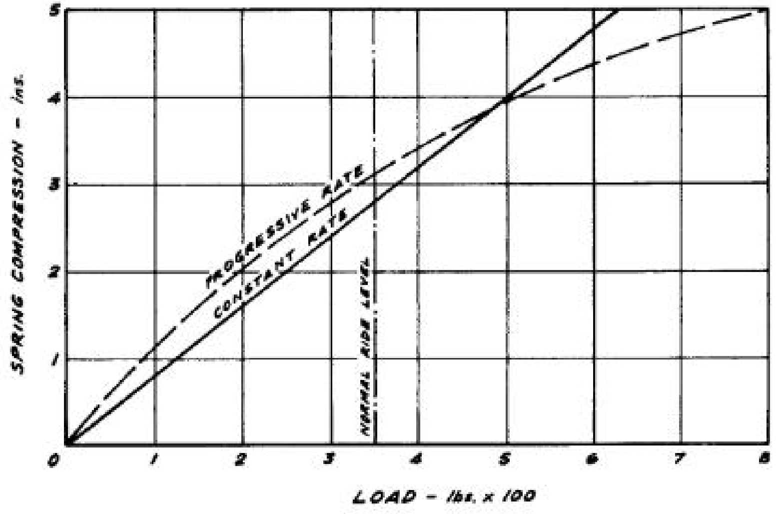


The 1971 McLaren M19 had Bellamy-designed suspension linkages (top) giving a progressive spring rate, increasing with the deflection of the wheel; the lower drawing shows an alternative simpler progressive system designed by Terry

ing than for innovation – revealed that their new M19 Formula 1 car had progressive-rate springing at front and rear. This interesting departure from orthodoxy was the work of Ralph Bellamy (an Australian who had worked for Jack Brabham under Ron Tauranac). With this system, progressive rate is obtained by linkages which cause the angle of attack on the springs to vary considerably with wheel movement *(see sketches).* Initial bump travel of the wheel from the static-load position causes relatively little compression of the spring, giving a low rate, but, as the wheel moves further, the spring is attacked more directly, so the effective rate increases.

The primary advantage of a progressive rate is that it enables the total bump travel to be reduced for a given energy-absorbing capacity. One result of this diminished travel is that the ride height of the car can be lowered, thus in effect reducing the frontal area (the gap between body and road is already so small that there is virtually no airflow through it, so it can be regarded as 'solid' and therefore part of the frontal area). Reducing the bump travel is also beneficial in terms of suspension geometry, since it means smaller camber changes, both over road irregularities and on cornering roll. Hence the tyres can be kept more nearly upright to the road at all times, which should mean slight improvements to the cornering, braking and acceleration. A secondary advantage here comes from the reduced ride height; this, of course, is accompanied by lowering of the centre of gravity, so the car's attitude changes less in roll, dive or squat conditions.

Because the spring used with such a system is stiffer than its counterpart in a non-progressive layout, and is compressed less on bump, it can be used more effectively



Comparative characteristics of constant-rate and progressive-rate springs. Since the latter are more compressed at the normal load, the ride height is slightly reduced

on droop. Wherease most springs are completely unloaded on full droop, those in a progressive system could still be pre-loaded in this situation, by the dampers having reached full extension. As a result, there would be some initial cushioning when the car hits the ground again after being airborne. In recent years, some designers have tried to meet this requirement by using longer and softer springs, pre-loaded on full droop, in conjunction with supplementary springs (such as the Aeon hollow-rubber units) which come into action for the final inch or so of bump travel of the wheels. Though better than nothing in theory, such composite systems are not fully progressive and tend to give a positive 'step' in the frequency.

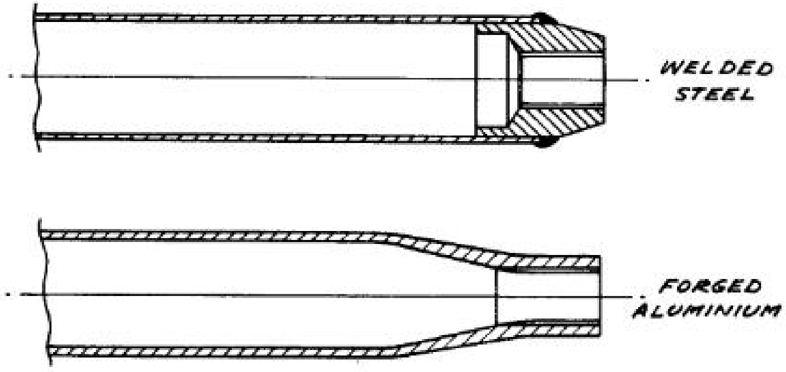
Whereas the Bellamy linkages were obviously more complicated and heavier than conventional ones, and had a number of additional wearing points, they did give a stepless change of rate, with a maximum-to-minimum range of about 1½ to 1. The possible alternative of progressive-rate springs (in which the pitch of the coils increases from top to bottom) has the major disadvantage that the springs are very costly to produce. Dual-rate springs have been tried – though more frequently on motorcycles than on cars; however, the substantial change in both rate and frequency when the softer spring becomes coil-bound has obvious adverse effects on ride and handling.

Although Bellamy's system proved to have various operational snags, and did not last long on the Formula 1 McLarens, I still approve of the thinking behind it. Ideally, though, the rate should be proportional to the load on the spring, so that the frequency remains constant throughout the operating range. This is difficult to achieve by mechanical means, but the resulting improvement could be significant. Some effective rate variation can, of course, be gained with a more conventional linkage than Bellamy's, simply by choosing an appropriate angle of attack between link and spring unit, as was achieved with the Lotus 72.

STIFFNESS/WEIGHT RATIO

In designing suspension radius arms, steering links and other external tubular components, I regard the stiffness/weight ratio as more important than aerodynamic considerations. Hence I favour the use of relatively large-diameter, thin-gauge tubing. For example, 1 in x 20 swg material has been found preferable to ¾ in x 16 swg (metric equivalents are approximately 25 mm x 0.9 mm and 18 mm x 1.6 mm).

Where the front springs are mounted within the body and are actuated by rocking levers, these are subjected to

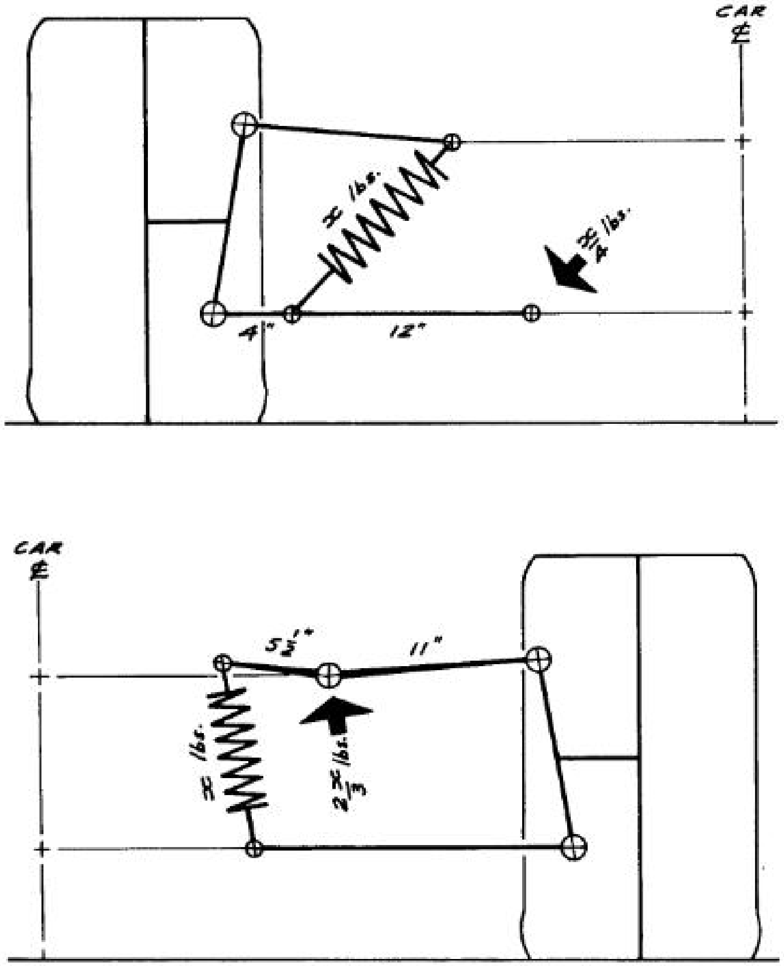


In suspension and steering linkages, stiffness is increased for a given weight by enlarging the tube diameter and reducing the wall thickness. The upper drawing shows the orthodox method of mounting the adjuster in the end of a large-diameter link, while below is one of the reduced-and-thickened ends of the aluminium-alloy links used on the BMW Formula 2 discussed in Chapter 3

considerable bending moments because of the wheel thrust at one end and the spring resistance at the other. Therefore they function as high-rate springs and consequently allowance has to be made for their deflection when laying out the suspension; bending of the levers affects ground clearance as well as effective wheel travel.

Because of the bending moments, the pivot bearings of rocking levers are much more heavily loaded than those of equivalent wishbone links. I have found from experience that adequately proportioned self-aligning ball-joints of the Rose type perform satisfactorily in this duty. Plain bearings could be used but would necessitate line boring or reaming to ensure the proper alignment that is essential to avoid unwanted friction in the pivots.

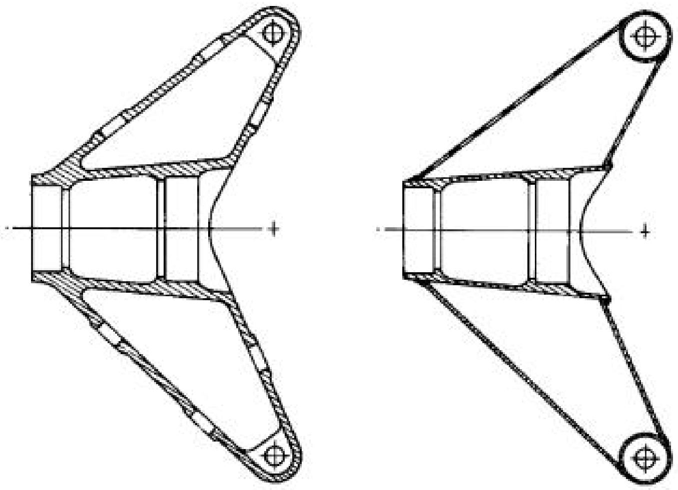
My method of getting the basic ride height correct is to fit the tyres that will be used and to set-up the suspension with 'slave links' of the correct nominal length in place of the spring/damper units which



For a given spring force, inboard mounting of the suspension units results in a higher pivot loading than does the equivalent outboard installation (above)

would introduce stiction effects. Ground clearance is then checked again with the actual units installed, in case these are not quite of the specified length.

In my search for minimum unsprung mass, I had considered adopting fabricated light-alloy suspension uprights, but had shied away from them because of the 'unknowns' involved; a designer cannot afford to take chances with such vital components. Fabricated steel uprights are, of course, relatively cheap and easy to produce but are heavy, a typical figure being 9 lb (4.3 kg) for a rear component fully machined. The usual alternative is magnesium castings which cannot give their full potential weight saving because of practical limitations on the accuracy of coring, and the consequent need to play safe on wall thickness. Even so, an equivalent magnesium upright should be quite a lot lighter than a steel component – say 5½ lb (2.6 kg) fully machined.



Comparative sections of cast-magnesium (left) and fabricated-aluminium rear-suspension uprights. Terry found that the fabricated components made for the LT25 were each almost 1½ lb lighter than their cast equivalents

Calculations indicated that a high-tensile aluminium upright should weigh well under 5 lb (2.4 kg) unmachined, as well as being stiffer than the magnesium casting. Since a weight saving of around 1 lb per component is worth having, Terry finally decided with the LT25 that the best way of coping with unknowns was to get to know them. Therefore he took courage in one hand and pencil in the other, with the results discussed and illustrated in the earlier section on that car. Since his second examples proved satisfactory, it seems likely that at some time they will be followed-up by light-metal front uprights in either aluminium or titanium. Clearly the weight saving here would be less spectacular but it would still be worth having.

Following the successful use of fabricated aluminium uprights, I now see no good reason why an even greater weight-saving should not be achieved by using uprights fabricated from wrought magnesium. Discussions with the people who produce the 'Melmag' wheels confirm that this is a feasible project, so I intend to develop the idea in due course.

8

Brakes, wheels and tyres

INFLUENCE OF SMALLER WHEELS

The use of 13 in diameter front wheels, initiated on Formula 1 cars in 1970, was extended to Formula 5000s during 1971 and 1972, when Terry was among those to use them in this category. Inevitably, the smaller wheels are significantly lighter than the 15 in type, so they help considerably to improve the sprung/unsprung mass ratio at the front. The reduction in drag also is another major benefit, particularly when the latest ultra-low-profile tyres are fitted.

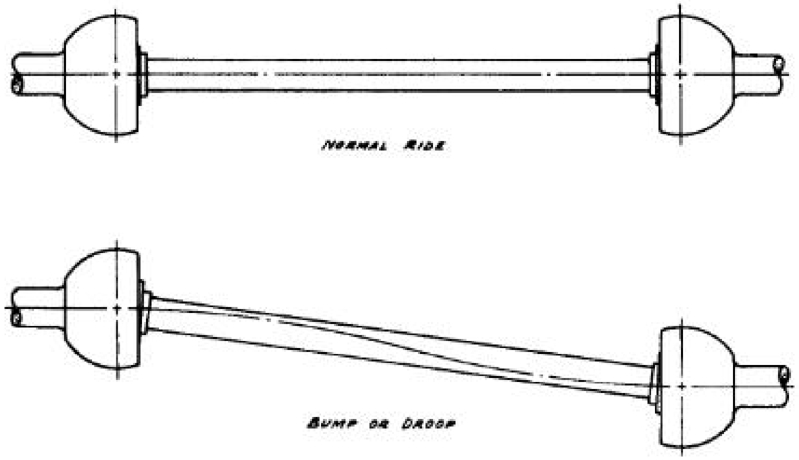
If you come down from 15 in to 13 in rims you must also reduce the brake disc diameter from 12 in to 10½ in, or put the brakes inboard. The 10½ in ventilated discs available at the start of the 1971 season were barely adequate for either Formula 1 or Formula 5000 cars in terms of heat-sink capacity as well as surface area for cooling.

Here undoubtedly was one of 1971's problem areas, the existence of which was tacitly admitted in the case of the

Brabham BT34 Formula 1 car by the provision for the use of 15 in wheels, with 12 in discs, on those circuits where the brakes really took a caning. For the Lotus 72, though, the alternative solution of inboard brakes was chosen - an arrangement that enables the designer to fit larger brakes with proper cooling, but poses other difficulties. Ron Tauranac's decision to retain outboard brakes on the BT34 was rather surprising in view of the air pre-heating that must have resulted from his 'lobster-claw' radiator layout.

McLaren's Ralph Bellamy stated at the time that he had also chosen outboard brakes for the M19 because too little was yet known about half-shaft stressing for inboard discs. His caution was understandable because these shafts may well be more heavily loaded than rear drive-shafts. After all, modern tyres will give about 1.8 g deceleration on a good surface, and about 70 per cent of the torque necessary for such retardation will have to be transmitted by the half-shafts, because of the forward weight transfer. Hence, the front shafts could have to transmit the torque for producing almost 1.2 g deceleration. Acceleration, on the other hand, rarely exceeds 1 g and all the torque for this is transmitted by the drive-shafts.

Also you must not forget that shaft stress increases with the degree of articulation of the universal joints. If the input and output shafts are at an angle to one another, the half-shaft is subjected to only single-curvature bending; should the two be out of line, though, as is more likely in a suspension system, the shaft tries to adopt the more stressful reflex curvature. Under heavy braking, the additional bending load on the half-shafts must be considerable owing to the large bump deflection of the suspension, unless the latter incorporates a lot of anti-dive geometry. When the car is accelerating, though, the

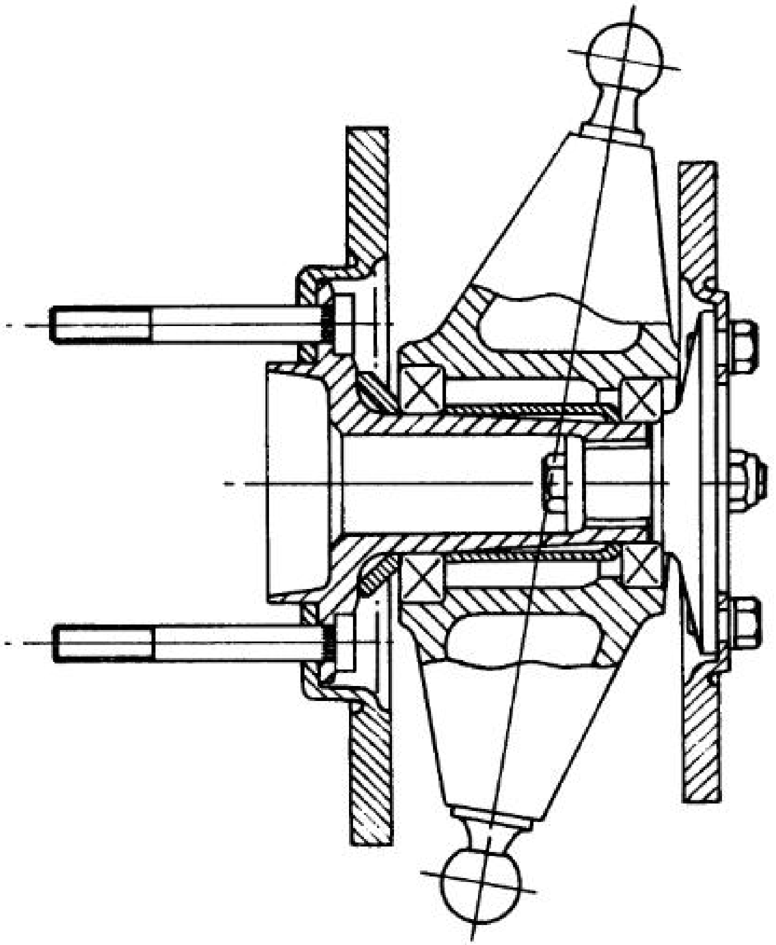


Out-of-line running of the input and output members of a double-jointed drive-shaft assembly makes the shaft tend to adopt a reflex curvature. The consequent bending loads cause the shaft to be more highly stressed than it would be due to torque alone

rearward weight transfer (and hence the suspension squat and drive-shaft articulation) is not as great. The fact that the front wheels are steered as well as braked does not seem likely to increase the shaft stressing significantly, because tyre adhesion limits the amounts of steering and braking that can be applied together.

TWIN-DISC BRAKE SYSTEMS

At the Monaco Grand Prix in May 1971, Jackie Stewart's Tyrrell appeared with Girling's latest experimental twin-disc brakes. These provided an increase in both swept area and thermal capacity, so it was hardly surprisingly that they were fitted, after further intensive development work, to both ends of Stewart's and Cevert's Tyrrells for the Dutch Grand Prix in June. The brakes were fitted again for practice for the French Grand Prix in early July, but were not used in the race after Jackie had experienced wheel-locking problems, nor did they appear again during the rest of that season or during 1972. Nevertheless, the



Terry's proposed twin-disc front-brake layout for the AAR Eagle, evolved more than five years before the first appearance of Girling's experimental unit of this type (see later photograph) twin-disc arrangement is sure to be developed further, and could find a ready application on the relatively heavy CanAm cars, although its greater axial length makes installation less easy.

I should mention at this point that my original intention for Dan Gurney's Eagle was to give it twin-disc brakes at the front. The scheme was to have a live stub-axle carrying one disc outboard of the upright and the other inboard, the former being the smaller to enable it to fit well inside the wheel. Separate calipers would have been used, one mounted in the leading position and the other trailing. I realized that we would have a temperature-differential problem between the buried disc and the exposed one, but I did not think this would be serious in view of the much increased area and heat-sink characteristics. The weight penalty, too, should not have been troublesome. Unfortunately, though, time proved too short for the experimental work necessary, so the system was never made.

Not the least important reason why the Girling twin-disc system went on to the 'reserve' list was the improvements effected by the brake manufacturers to existing single-disc equipment; these advances involved both calipers and discs. The 'four-pot' caliper was introduced as an advance on the 'two-pot' unit, as a means of obtaining a more even pressure distribution across the pads, thus ensuring that every square inch was doing its full share of the work. To make sure that this better pressure distribution was achieved, the rigidity of the caliper was improved; the lessons learned here, incidentally, were also incorporated on two-pot calipers. In addition, disc modifications led to better ventilating characteristics, and so a greater rate of heat dissipation without sacrifice of the necessary rigidity. As a result, most drivers found the 10½ inch single-disc outboard front brakes adequate during the 1972 season.

ATTENTION TO DETAILS

Whatever type of brake equipment and layout are chosen they will operate at maximum efficiency only if the chassis designer has paid close attention to the detail design of his installation.

One of the first essentials here is the rigidity of the brake pedal and the attendant bracketry. The pedal itself will have to withstand a thrust of up to 200 lb (about 90 kg) and incorporate a mechanical advantage of perhaps 4½ to 1. It follows that a stiff pedal and a bracket capable of withstanding 900 lb (over 400 kg) without flexing are necessary if spongy and therefore imprecise braking is to be avoided. This point was mentioned and illustrated in Chapter 4.

In the interest of precision rigidity is also highly desirable in the balance bar which proportions the effort between the front and rear brakes. This, of course, must also incorporate a ready means for varying the front-to-rear ratio to enable the best balance to be obtained on the circuit.

Although today's armoured hydraulic hoses are less sensitive than were earlier types it is still advisable to keep flexible brake lines as short as possible. Long hoses, apart from causing greater effort losses through fluid friction, are always liable in racing conditions to movement which can result in their becoming chafed or entangled. Also, the hoses must not be under tension anywhere in the range of wheel travel due to steering or suspension activity, while needless to say the pipes should not be led under the car where they would be liable to damage through grounding or from stones thrown back by the front wheels.

LOW-PROFILE-TYRE PHENOMENA

Although racing car tyres are too large a subject to be covered in any detail here a few points are worthy of comment. It would appear, for example, that difficulties of drag and weight will preclude any further increases in width, and although lower profiles have a beneficial effect on both these factors there are practical limitations to tyre-height reduction.

One phenomenon of ultra-low-profile tyres caused some concern in Formula 1 racing during 1971. This was the high-frequency vibration of the short sidewalls which occurred mainly on long, slow corners; in some cases the vibration was apparently severe enough to impair the driver's ability to breathe.

I understand that a slow-motion film made by one of the tyre companies showed that in these conditions wishbones can bend as well. Needless to say, this film would have been very informative to us car designers!

The tyre companies' response at first was that the problem was virtually inevitable, and that it was up to the chassis designers to look after the discomfort of the drivers; in their search for handling precision they had eliminated all compliance from their suspension systems, replacing rubber bushes by ball-joints, so that the tyre vibrations were being transmitted to the body structure without any attenuation.

For a while it looked as though we were to be faced with having to reintroduce compliance, and the attendant difficulty of providing sufficient vibration-damping without upsetting the handling by, for example, introducing rear-steering effects. But fortunately the tyre people were able to make modifications and the problem became noticeably less acute in 1972.

9

Aerodynamics

BASIC CONSIDERATIONS

Since this is an area where spectacular advances have been made in the last few years, it is one to which Terry has given considerable thought. There is always the risk that comments made on such a rapidly developing technology may appear to be naive a few years later, but this should not prevent two engineers from stating their conclusions based on the current state of the art.

Although the contemporary racing car starts off with several aerodynamic disadvantages, some designers seem to compound these by making things worse than they need be. After all, the drag of a moving vehicle varies as the *square* of its speed, whereas the power requirement varies as the *cube.* It follows that a given percentage reduction in drag would raise the maximum speed about twice as much as would the same percentage increase of power.

No designer in his right mind will fit larger-diameter wheels or wider tyres than he has to, so the suspension system, the body itself and its aerofoils are the only parts where significant drag reductions can be effected. The

body, being the biggest, deserves to be looked at first.

Three main factors influence the drag of the body - its shape, its frontal area and the things tacked on to it. Inevitably, there is no clear-cut best solution in any set of circumstances. Good aerodynamic shape and low frontal area are, to a considerable extent, mutually exclusive. The designer therefore has to choose what he regards as the best compromise between a well streamlined shape (with relatively large frontal and surface areas) and a smaller-section body with less surface area but a knobbly shape.

Excrescences of any kind will mar the airflow but may have to be more pronounced with a skin-tight body shape than one with fuller lines. In this respect Terry commends Frank Costin for his standard-setting Protos Formula 2 car of a few years ago, also Brabham's former designer Ron Tauranac, who usually managed to make his cars cleaner than most. On the other hand, the 1969-70 Matra Formula 1 cars looked as though, if a kitchen sink were needed, they would hang it on the outside with all the other bits and pieces; however, this French aerospace company later saw the error of its ways.

The 1971 March 711 had a strong Costin influence and, although its shape was not widely copied, it proved something of a trend-setter in pointing designers back towards basically cleaner shapes. However, the streamlined form of the March looked as though it might generate more lift than most others, and so would need more aerofoil downthrust for the same cornering and braking powers. Certainly the car was relatively short-lived in its original form.

A smooth surface finish clearly has a lower drag than a rough one. As an example, the matt camouflage finish of aircraft in World War Two knocked several miles an hour off their top speed. In the case of a racing car, though, the effect of finish is likely to be swamped by others of far greater significance, for example the wheels.

For this reason the flush-riveting of the Lotus 72 hardly merits the publicity it received when the car first appeared; a lot of labour, which might have been more usefully devoted elsewhere, had to be expended on countersinking hundreds of rivet holes, all for a minute performance advantage.

By taking the bodywork outward to embrace the wheels, the parasitic drag of these whirling monstrosities could be considerably reduced, as on sports and CanAm cars (and some versions of the last Mercedes-Benz Formula 1 cars). Towards the end of 1970, Terry made the following prophetic comment to me:

Full-width bodywork is not permitted by current formula regulations, of course, but the fairing-in of the drag-inducing suspension systems could be of significant benefit without imposing a serious weight penalty. Tecno and BMW certainly found quite an advantage in fitting a fairing over the front suspension of their Formula 2 cars. Comments on the subsequent adoption of wide nose fairings (started by Tyrrell in 1971) are made later.

But as already mentioned on more than once occasion, design inevitably involves compromise, and in aerodynamics as much as in any other area. If the drag coefficient of a racing-car body is significantly reduced, for example, a corresponding increase in braking power is needed for the same rate of retardation. Hence both

tyre/road adhesion and brake performance and cooling are 'uprated', so unless there is a margin in these respects the lower drag would be a liability on circuits where braking is more important than maximum speed.

Here, of course, we have the great advantage of the air-brake system used on some of the Mercedes-Benz racing cars in the 1950s. These brakes, which reputedly produced decelerations of up to 0.3*g* on their own, did not depend on grip between tyres and road, so their effect was summative. From the overall performance viewpoint, a very clean body form which could be 'spoiled' by air-brakes would be well worth having, but unfortunately the latter are not permitted (being 'movable aerodynamic devices') by the present regulations.

Clearly we still have plenty to learn about the aerodynamics of racing cars, but equally obviously the rate at which we can acquire knowledge will depend to a considerable extent on the regulations governing the various categories. From this point of view, therefore, the fewer regulations the better, but good motor racing means plenty of competition, and unrestricted design almost always gives the advantage to the firms with the most money.

Peter Jackson, the managing director of Specialised Mouldings (who make many of Britain's racing car bodies), is to be congratulated on having built a wind tunnel to enable some of the problems to be evaluated at his Huntingdon establishment. This is not a cheap facility, though, and its success must depend on whether the constructors who use it find that the results justify their expenditure.

During its first year of use no major successes could be chalked up to this tunnel; in fact the 1971 CanAm Lola, which was designed with its aid,

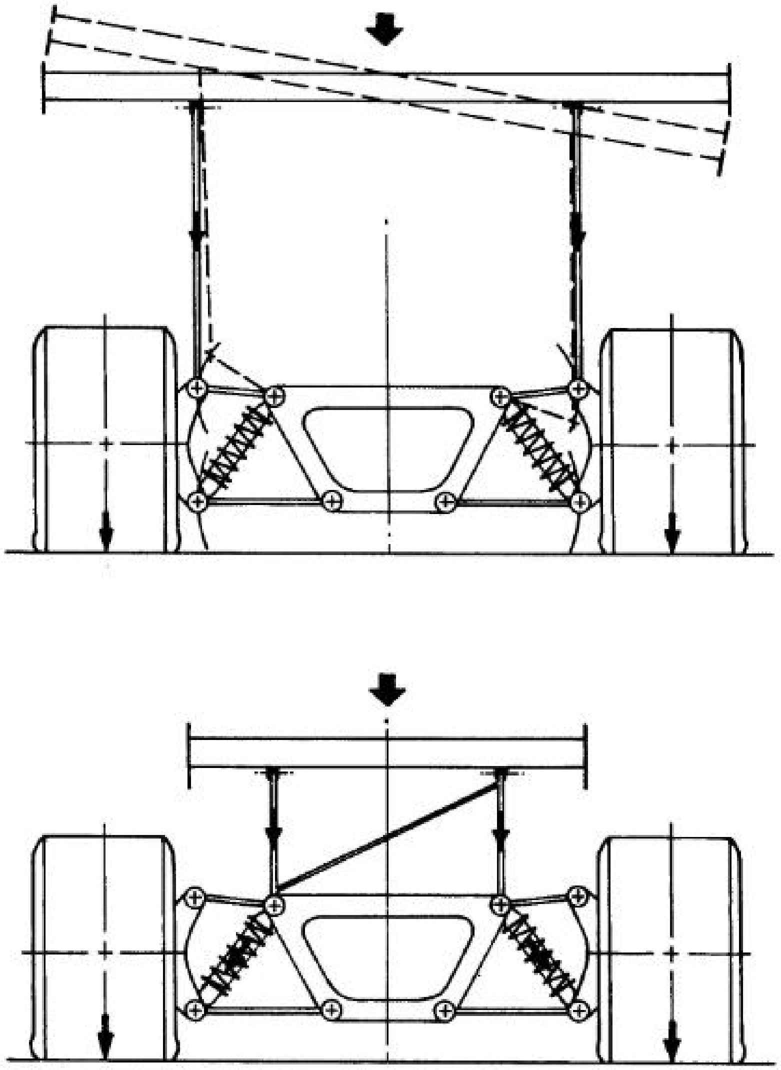
proved unable to beat the then-successful McLaren equivalent, even when fitted with a Leda-style full-width front wing.

WINGS AND THINGS

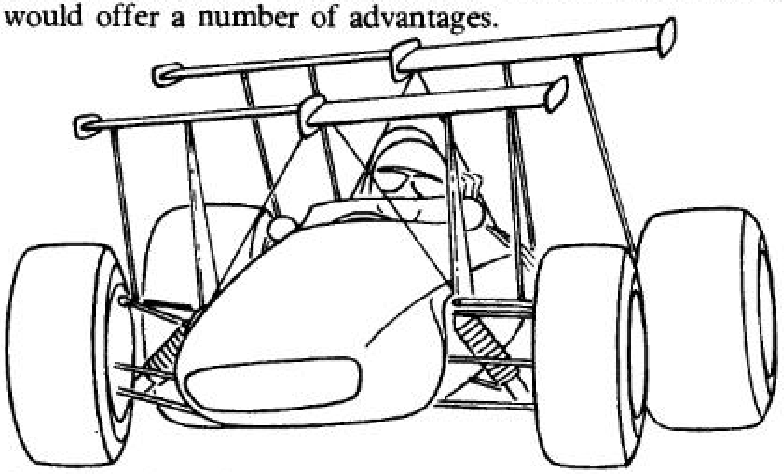
Little did American Jim Hall realise, when he mounted his first 'negative-lift' aerofoils on a Chapparal back in 1965, that he was initiating one of the most controversial and far-reaching developments in motor-racing history. Wings began to sprout on Formula 1 cars early in the 1967 season, and soon we had huge devices at both ends, jigging about with suspension movement and collapsing with frightening frequency. So the *FIA* felt it had to step in; it did not ban 'aerodynamic aids' altogether, but limited their height and width and vetoed the unsprung mounting. This brief history is recalled because it leads to a number of interesting lines of thought.

The first of these is my opinion that until recently too many constructors were devoting too much time and energy to aerodynamic additions and not enough to fundamentals. Next is the point that the most logical place to mount aerofoils is undoubtedly on the suspension uprights, in spite of all the trouble it caused. Attached in this way, a wing exerts all its downthrust directly on the wheels, so spring rates and so on are unaffected.

Mention has already been made of the difficulties that arise when the variable thrust has to be transmitted through the suspension; the effect is exactly as though passengers were constantly getting into and out of a normal road car while it was on the move - only a lot more critical! Had the *FIA* not acted as it did, designers probably could have solved the structural and vibrational problems of the unsprung wing by now, though the risk of loss of life in the meantime would have been in-



The original aerofoils were mounted on the suspension uprights (above) so the downthrust was applied directly to the wheels. Because of failures due to suspension articulation, the FIA ruled that, from 1970, wings had to be attached to the body structure; as a result, the thrust was applied through the springs which therefore had to be stiffened tolerable. Naturally, Terry has given a great deal of thought to mounting aspects and he evolved a compromise solution which, if the regulations were to be relaxed, would offer a number of advantages.



Original rough sketch made by Terry in 1969 for what he called his 'self-compensating quad-wing' system. This layout is not quite as described in the text, but it embodies the same principles – four wings with a combination of body and suspension mounting, the latter arranged so that the incidence of each wing became less on bump movement of its wheel but increased on droop

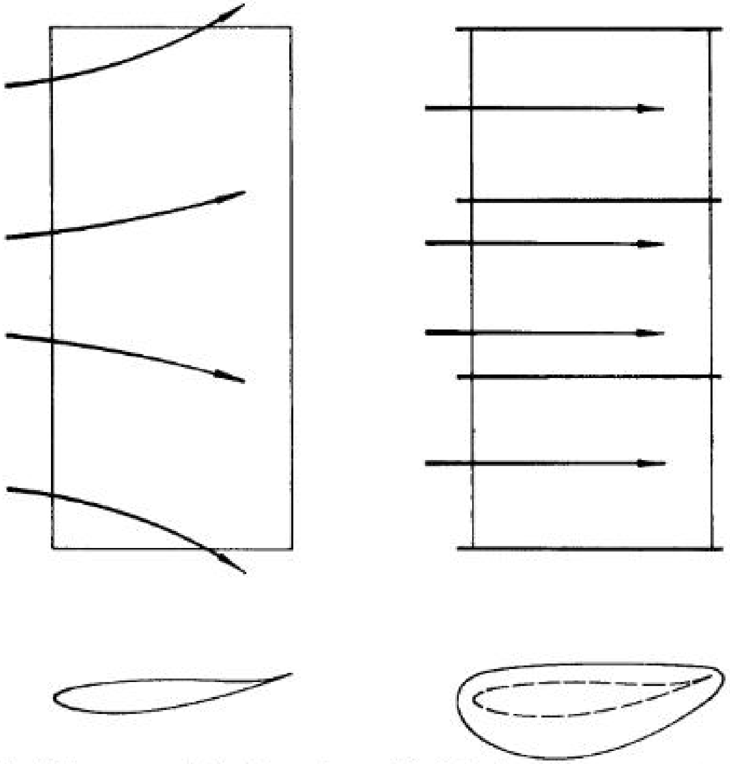
This scheme covers one aerofoil per wheel, each connected to the suspension upright at one end and pivot-mounted on the body structure at the other. The suspension connection would be arranged so that the wing incidence would reduce on bump and increase on droop of the wheel.

Although part of the downthrust would still be taken by the springs, the layout would give us three distinct benefits. First, cornering would be assisted in two ways; the drag would be increased on the inner side and reduced on the outer, and some downthrust would be transferred from the already very heavily loaded outside wheel to the inner one, giving an increase in the combined cornering power of the tyres. Secondly, the greater drag and angle of incidence when the car left the ground would push it back down again more quickly - an advantage on 'yumpy' circuits such as Nürburgring and Clermont-Ferrand. The third advantage would be the system's combined anti-dive, anti-squat and anti-pitch function. A nose-down attitude would result in higher wing incidence at the rear and less at the front, whereas a tail-down attitude would cause higher incidence at the front and less at the rear - both changes tending to correct the departure from level riding.

Nissan and Porsche have both tried divided spoilers, suspension-operated, on the tails of sports-racing cars, but clearly the scheme outlined here goes a lot further. But first the *FIA* would have to reopen the door to aerofoils that are both suspension-mounted and movable when the vehicle is in motion!

A front-end downthrust device is able to develop its maximum efficiency because it operates in undisturbed air. In contrast, by the time the air reaches a rear wing it has been very thoroughly turbulated by the wheels, cockpit and engine.

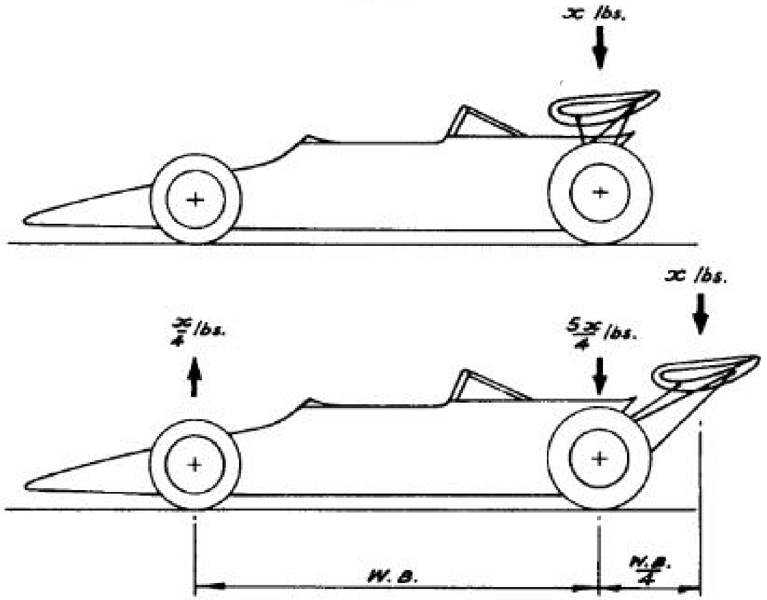
Such an aerofoil system therefore is likely to be working in far from ideal conditions; in fact, I believe that some of them produce their downthrust by deflecting the air upward rather than by generating actual negative lift. In such cases the aerofoil section used is not really critical, and comparable results could be obtained from flat or slightly curved plates. The upswept rear surfaces of the original Leda body were quite effective as downthrust producers but had the disadvantages of operating in a disturbed airflow and, as we mentioned earlier, of not being adjustable to suit different circuits.



The airflow over a plain wing tends to spill off the tips (left) thus reducing the downthrust produced. End-plates and intermediate 'fences' have come into widespread use to overcome this phenomenon, as shown in the right-hand drawing

End-plates undoubtedly enhance the effectiveness of a rear wing, by preventing 'spillage' off the tips, and therefore are still tending to increase in size. In respect of the body, a similar function is performed by the engine/air-intake fairings common on Formula 1 and other open-wheel cars, and by the longitudinal 'fences' now used on CanAm and Indy cars; in the latter case a recent move has been to integrate fences and end-plates by sweeping-up the former at the rear so that they also form the wing supports. This arrangement restricts the wing-span (unless the body is of full width) but does eliminate the not-inconsiderable drag of separate supporting struts.

Since rear wings can no longer be hoisted high above the body into undisturbed air, designers have tended to move them rearward in the search for less turbulence and the ability to get air under as well as over them. However, the further a wing is moved behind the rear wheels the greater is the overturning moment of its downthrust. More downthrust therefore is needed at the front to achieve the correct front/rear balance of the car.



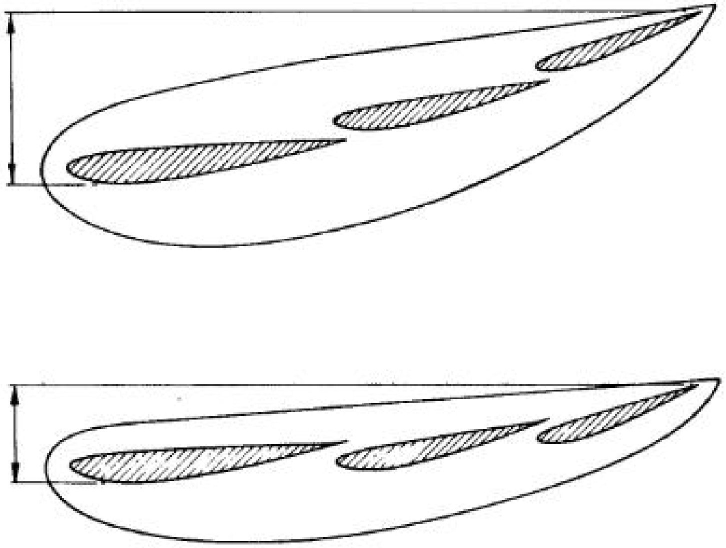
Many present-day rear wings are mounted further aft than their predecessors, so that they are in less turbulent air. These drawings show how an installation behind the rear wheel actually produces a front-end upthrust which has to be countered by additional downthrust at that end

Apart from causing slightly increased rolling resistance, this set-up is in theory more likely to impair the car's handling in the event of damage to the front aerofoils. For this reason it might be advisable to make the front wings stronger than is now customary but to attach them through shearpins. In the event of a 'shunt', the shearpins would

break, without the wing being damaged, and could be quickly replaced at the pits.

During the last three seasons, several constructors of Formula 1 and Formula 5000 cars have tried biplane and even triplane rear wing systems, but in every case the rearmost aerofoil was set above the other(s).

However, I think this was wrong; the leading aerofoil should be at the top, and two are enough anyway. With this configuration (see sketch) the overall height - and therefore the frontal area - is less and the leading aerofoil, being higher mounted, operates in less disturbed air. Towards the end of 1972, Frank Matich tried putting the second aerofoil nearly at ground level behind the car, but this seems to me to be just asking for turbulence.



Two multi-wing layouts; although the lower has not been tried, Terry considers it superior because of its smaller frontal area and the higher position of the leading wing

A short-lived 1971 tendency was to raise the front aerofoils, the object being to reduce interference with the airflow between them and the ground. In some instances (Surtees and earlier Tyrrell, for example) there was in effect a continuous wing flush with the top of the nose, while in other designs - March, Ferrari, Matra and Terry's own LT25 - the wing was separate from the body and mounted above it.

A feature of the March 711, of course, was the elliptical 'Spitfire' front wing which, in spite of its good looks and classical origins, seemed unlikely to be more efficient than a rectangular end-plated one of the same area and aspect ratio, and was probably more expensive to make. With a single, central support, too, it is less easy to get adequate structural stability (to cope with the turbulent wake of a preceding car, for instance) than where the wing is carried on two relatively widely spaced brackets. Another thought that occurs to me is that so far as I am aware no-one as yet has tried a narrow (110 cm) wing mounted at the maximum height of 80 cm permitted by the regulation. It seems logical to assume that such a wing could have a relatively small chord, and consequently minimal drag, operating as it would in completely undisturbed air.

During the 1971 season, Tyrrell's Derek Gardner became 'the designer to copy' by integrating the front aerofoil into a nose fairing that shielded the suspension and promoted better airflow over the wheels. After a couple of try-outs in practice, this had its first success in the French Grand Prix that year, and it certainly played its part in gaining Jackie Stewart another World Championship and Ken Tyrrell his first Constructors' Championship. Quite a lot of work had to be done to set-up the car properly for the altered characteristics, but once this was accomplished the fairing gave complete satisfaction. Its blunt profile was reminiscent of the nose of Derek Bennett's Chevron 2 litre sports car of a year or so before. The idea, if not the actual form, was subsequently taken up by several other constructors, including Ferrari and Surtees.

Although Brabham, BRM, March and others have used wind tunnels to evaluate wing designs and installations, such testing has been found to be of only limited value. This is primarily because of the inability to reproduce the continuously varying conditions applying on any racing circuit. The wind tunnel can certainly be used to eliminate the impossibles and improbables (even as the computer can do in the case of, say, suspension design), but extensive track testing is still essential.

Ideally, the team should take a batch of perhaps five wing systems to the circuit and test them all on the same day, to minimize the variables. The difficulty then, of course, is to find enough time to optimize ride height and other suspension settings for each system, but such care is essential if the comparisons are to be valid.

As these aerofoil systems become more effective and more complex, their adjustment to suit different circuits tends to become more critical. Means of varying the incidence at both front and rear is virtually essential, but even so it is not always possible to find settings that give satisfactory handling all round a circuit. Inevitably, the greater the speed range of a track the more one has to compromise on wing settings. The curve of aerofoil progress is certainly flattening out, after its rapid rise during the last few years.

Obviously, changes to the regulations - in any racing category - could lead to another upsurge, or perhaps some ingenious designer will find a significant improvement within the present rule framework. Possible themes for exploration here might be a series of stub wings along each side of the car, and a frontal deflector aimed at creating the converse effect to that of a rear spoiler.

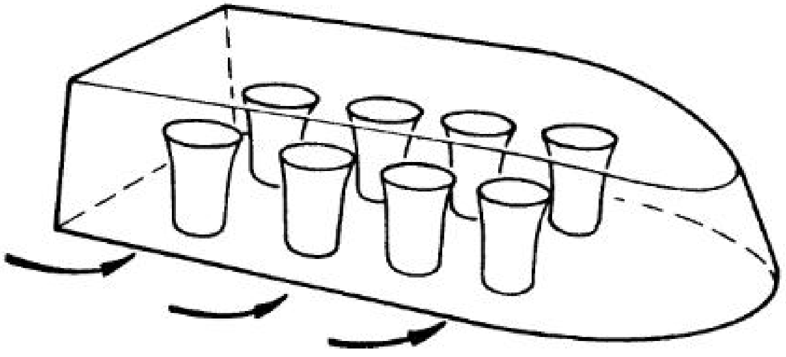
INTAKE RAM EFFECT

Until mid-1971, little had been done to take advantage of the considerable induction ram effect that could result at high speeds from having forward-facing air intakes for the engine. On existing open-wheel and CanAm cars, the intake trumpets were of course situated vertically behind the driver's head. Terry and I first talked about this aspect in January 1971, and here is what he said at that time:

The airflow is clearly disturbed but its general direction is across the tops of the trumpets, where it must tend to have an extractor rather than a ram effect. This fact could well account for the inability of the Formula 5000 cars to show any performance advantage over Formula 1 vehicles in spite of the higher test-bed outputs of their engines; on the dynamometer an engine is drawing-in 'still' air, so must breathe more easily than when it is in a moving car, and the effects of turbulence and airflow across the trumpets will be more upsetting for carburettors than for petrol injection.

Clearly one should be able to improve matters by feeding the trumpets from a plenum chamber which is ram-pressurized from a forward-facing air intake, but there are two problems here. First is that of installing a plenum of adequate capacity without making the rear-end aerodynamics even worse than they are already. Secondly, the air intake has to be sited in a region of clean airflow and positive pressure, yet not far from the engine; a remote intake would mean lengthy ducting, the friction in which would slow down the air and thus diminish the ram effect.

The first significant step towards induction ramming on Formula 1 cars was in fact taken during the 1970 season by Ron Tauranac on the Brabhams. He introduced a plenum with a 'horseshoe' intake arrangement, the openings to which were situated one on each side and just to the rear of the driver's head. No 'before and after' performance figures are available, but Tauranac was sufficiently convinced of the improvement to continue with the scheme for 1971.



This 'cool air-box' arrangement for the engine intake was tried on the LT25 early in 1971 and raised the car's maximum speed

I had decided independently to try a half-way air-box scheme on the LT25, and this arrangement is illustrated. During the early testing of the car in March 1971 we found that, with one of the 1970 engines, it was significantly quicker on the straight although the basic aerodynamics had not been appreciably changed. However, the altered induction characteristics initially gave rise to mixture variations, and therefore hesitancy, in certain running conditions.

By the middle of the 1971 season, most other designers also were trying to obtain some benefit from ram-assisted induction. At the French Grand Prix, in early July of that year, several of the teams were following Matra's lead by experimenting with scoops projecting above the driver's head - an arrangement used on Stewart's and Cevert's Tyrrells, which gained first and second places respectively. A few weeks later, at the Woolmark British Grand Prix, the overhead intake had become virtually standard equipment.

In terms of getting the air to the engine, it is probably impossible to find a better place for the scoop than above the driver's head - provided that it really does stick up high enough to clear the local turbulence round the cockpit. However, some of the earlier examples must have had a considerable masking effect on the rear wing. During 1972, though, designers began to appreciate that, if you combined the intake and plenum chamber with a properly shaped engine cover, you could actually smooth-out the airflow behind the cockpit and lead it more effectively on to the wing.

John Surtees took this train of thought to its logical conclusion in 1972 by extending the cover so that it actually divided the aerofoil into two discrete portions. As a final comment on intakes, it is worth recording that the flat-12 Ferrari was the odd man out during that year in having no induction scooping. One assumes that the distance between the inlet ports of the two banks was too great to allow a single forward-facing intake to be used, and suitable sites could not be found for separate intakes.

'GROUND EFFECT' VEHICLES

In 1970 Jim Hall created a sensation at least as great as that caused by his earlier introduction of aerofoils; his

Chaparral CanAm car gained additional adhesion by what is called 'ground effect'. This effect was first used for the hovercraft which is held clear of the ground or water by a cushion of pressurized air retained by a peripheral skirt round the bottom of the hull. In Hall's application this principle was inverted, air being sucked out of the underneath area instead of being blown into it. The suction fans were driven by a separate engine and on full load produced a down-force of about 2000 lb (950 kg), which virtually doubled the effective weight of the car.

Unfortunately, the SCCA proved as reactionary to this remarkable innovation as did USAC to the gas turbine and four-wheel drive; the Chaparral was soon banned as not complying with regulations. There is no doubt that ground effect has considerably greater potential in the automotive field than have aerofoils, but the SCCA has stifled progress yet again.

I think the principle could be applied successfully to Formula 1 cars but would be too costly for the less exotic open-wheeled vehicles. It remains to be seen, though, whether the FIA will eventually adopt a progressive attitude concerning ground-effect devices. However, the Formula 1 car would be a different proposition from the CanAm car in which there is no restriction on engine size, and consequently the extra weight and bulk of the additional power source is acceptable. For a smaller, lighter vehicle, such as a Formula 1 car, it looks as though we should have to find other means of creating the required suction.

One method would be to use electrically driven fans, which would mean having a large and power-consuming generator. Another possibility is the exhaust-driven turbine which in theory makes use of only the waste energy

from the engine. Again, it might prove practicable to use the engine's air intake to exhaust the underbody area.

This may sound wildly optimistic but you must realize that the necessary pressure reduction is actually quite low because of the large area over which it operates. If a sub-atmospheric pressure of only 0.5 lb/sq in (0.035 kg/sq cm) could be maintained over an area of 15 sq ft (1.4 sq m), the resulting downthrust would be over 1000 lb (480 kg). This is quite a lot more than even the best of today's wing systems are producing. After all, an internal-combustion engine is basically an air-pump and today's Formula 1 engines consume around 10 to 12 cubic ft (0.28 to 0.34 cubic m) of air per second when in full song.

Inevitably such a scheme would pose a number of problems. One of these would be to develop a skirt system that would maintain a small enough ground clearance to prevent excessive leakage of air from outside - and hence loss of the pressure differential; the skirt therefore should be operated from the wheels, not the body, to minimize gap variations due to dive, squat, cornering roll and fuel load. Also, because the engine would be inhaling air drawn from a volume in contact with the road surface, an efficient form of filtration would be essential. A snag common to this method and the exhaust-turbine one would be the fact that the air-removal rate would vary with engine speed and load.

I had hoped during the Leda Cars days to investigate the possibilities of this scheme, using one of my own Formula 5000 cars as the guinea-pig. The carburettors would have taken in air from a sealed plenum chamber connected to the underside of the car, within the skirt area. As an interim measure I

even considered connecting the carburettors to a bottom-mounted plenum with its intake underneath, so that their 'suck' was at least working in the right direction.

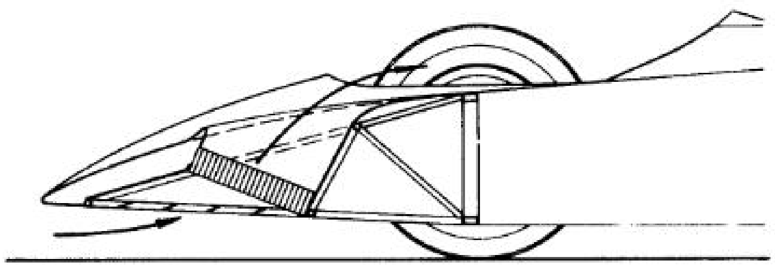
10

The cooling system

RADIATOR LOCATION

A racing car's cooling system has a major influence on the overall aerodynamics. Its efficiency in this respect falls between those of an ordinary road car and an aircraft with a liquid-cooled piston engine. The former is woefully inefficient aerodynamically. Air enters through a large nasal hole which itself wrecks the 'entry' characteristics of the body; it then receives heat energy from the radiator but all this is dissipated against the bulkhead behind the engine. In contrast, the radiator systems of the last of the piston-engined aircraft (the Hawker Tempest, for example) were so well ducted that the heated - and therefore higher-pressure - air was accelerated on leaving the matrix and so exerted a thrust which helped the machine along.

Because a racing car has wheels and suspension, and runs on a track, it is fundamentally more difficult to cool efficiently (in the aerodynamic sense) than an aircraft. Even so, quite a lot of progress has been made in this area of design during the last few years. While it is virtually impossible with a frontal radiator to gain any real forward



Terry was a pioneer of the inclined radiator which not only enables the nose to be lowered but also can provide some downthrust because of the heat energy taken up by the air. The 'shark's-mouth' intake shown here was used on the LT25

thrust from the outgoing air, most designers now manage to get some downthrust by having the exit(s) on top of the nose.

Because of the basic ram effect of the moving vehicle, I regard the intake to the radiator as less critical than the exit. This does not mean that the air intake can be of any old size and shape; on the contrary, it must have the minimum ill effect on the body's aerodynamics. For a nose-mounted radiator, the opening must be as small as possible consistent with adequate flow capacity at low ram speeds (as in Frank Costin's Vanwall and Protos). This flow capacity is, of course, also affected by the characteristics of the ducting between the opening and the matrix itself.

Leaning the radiator forward has become common practice with the recent trend towards the wedge profile. Apart from enabling the nose cone to be shallower, a considerably inclined radiator helps the through-flow slightly by convection, the air tending to rise as it is heated. The better the airflow characteristics through the radiator system, the smaller the matrix for a given rate of heat dissipation.

Any size reduction is welcome both as a direct weight saving and as a means of reducing the dimensions of the nose. A case in point here is the Lotus 25 which originally had an oil tank with a rounded nose installed behind a 10-row radiator matrix. Because of the obvious masking effect of this tank, I reduced its size from 6 to 3½ gallons and gave it a V-shape front. The better airflow enabled me to reduce the radiator thickness by four rows.

Almost 40 lb (19 kg) weight was saved by these changes, because of the lighter tank, smaller amount of oil, lighter radiator and reduced water volume. And this was all pure gain because oil and water temperatures stayed where they had been with the old set-up. Then came a power-unit change from carburettors to petrol injection which brought the weight back to almost exactly the original figure!

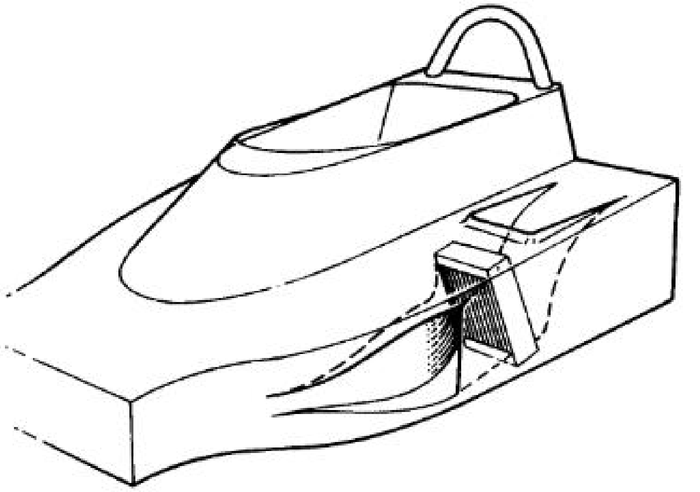
Colin Chapman and Maurice Phillippe set the Formula 1 cooling fashion in 1970 with the side radiators on the Lotus 72. Remember, though, that the Terry-designed Gulf Mirage-BRM sports car embodied a similar feature back in 1967-8. The layout enables the body to have a much cleaner entry and, in the case of the Lotus, it allowed the thin end of the wedge to be really thin. Inevitably, though, side-mounting the radiators produces disadvantages as well as benefits:

The intakes are less favourably sited in terms of airflow, because this has been well and truly disturbed by the front wheels and suspension. Fences on the body sides can be used here to control the flow, but fairing-in the front suspension to reduce drag can mask the intakes and so make matters worse. Also, the normal straight-through flow path brings the air out into the disturbed area round the rear suspension and drive-shafts. For this reason I

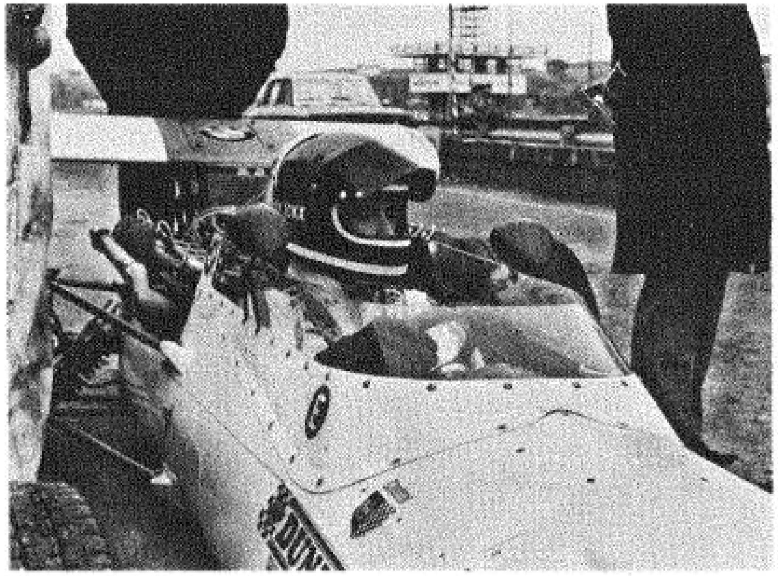
would prefer to lean the radiators forward and take the air out on top, as with a nasal installation. Again, this would give a small downthrust to help adhesion.

Side radiators were a feature of one of the first 1971 Formula 1 cars to be announced, the already-mentioned March 711. In this instance rather too much seemed to be expected of the air, some of which had to 'bend' inward into channel-shape cut-outs in the body sides to get to the intakes – and this after the flow had already been turbulated by the fully exposed front suspension. Proof that this intake arrangement was not very efficient came in the 711's first race, the Spanish Grand Prix, when some of the bodywork had to be removed to cure overheating. In June 1971 Terry commented:

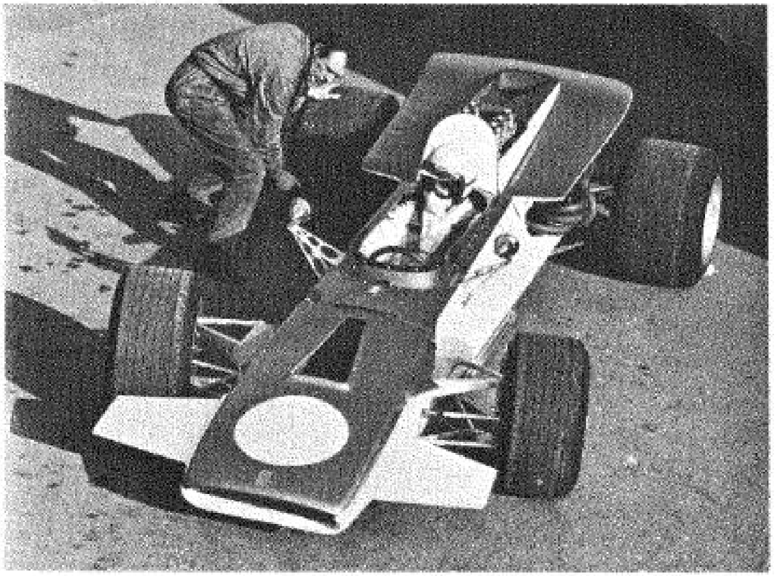
In my opinion, Herd and Costin should have used NACA ducts (see illustration) instead of the cut-outs. These ducts, which were developed for high-speed aircraft, have proved highly effective at vehicle



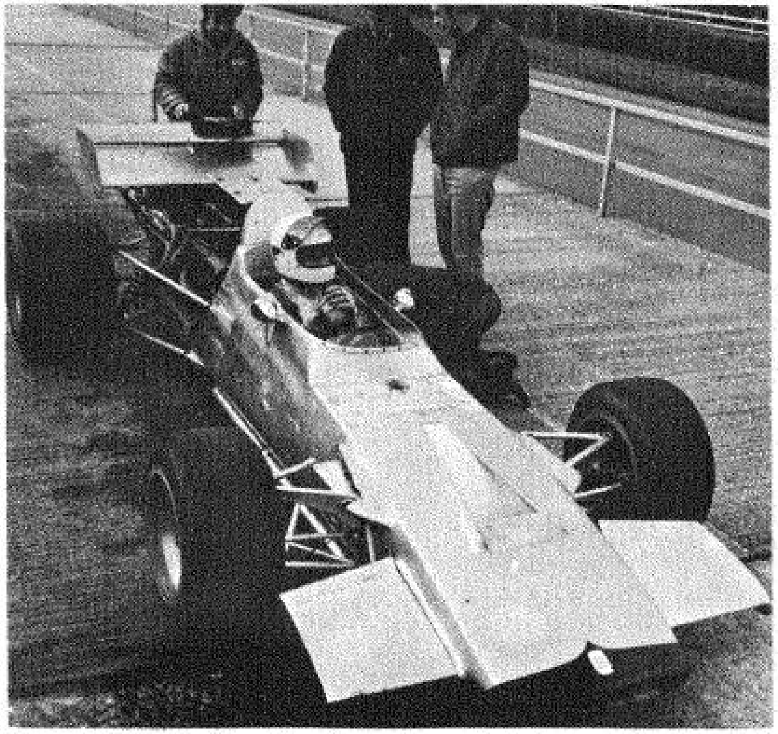
Perhaps the best method of getting the air into a side-mounted radiator, without having this fully projecting, is to use NACA ducts of the form illustrated



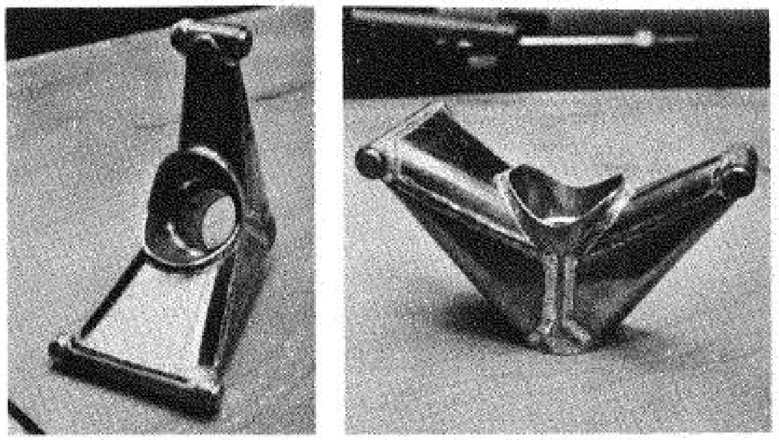
Jacky Ickx in the cockpit of the Terry-designed BMW Formula 2 car. It was built by Dornier, who modified the body structure by making the cockpit top portion detachable



An overhead view of the first Leda 5000 displaying its sloping rear surfaces for built-in down-thrust. This model had an unfortunate 1970 season

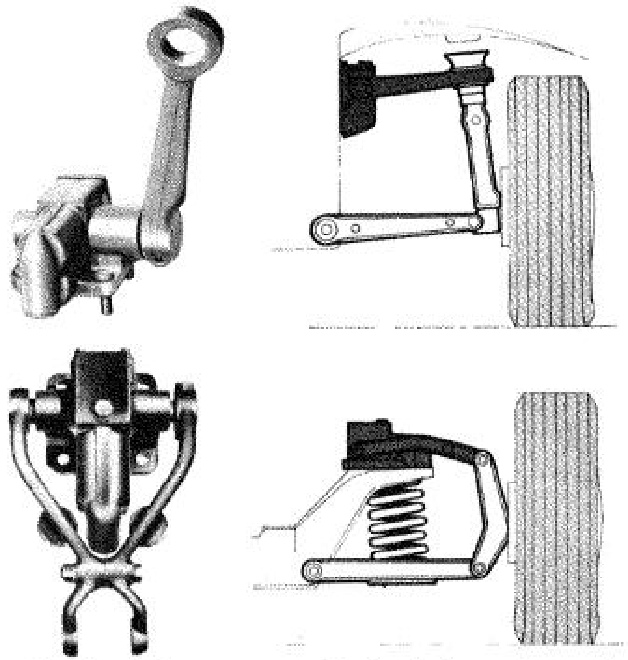


The Leda Mark 2 differed from its predecessor in having non-interchangeable suspension systems and stiffened booms projecting from the rear of the monocoque

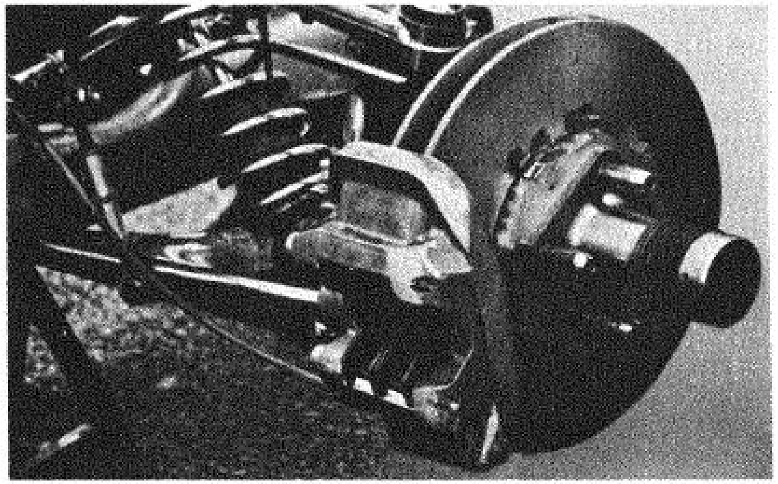


Two views of the improved type of fabricated aluminium rear-suspension uprights designed by Terry for the LT25. Hub barrels were machined from the solid, and the structural portions were of double-box construction

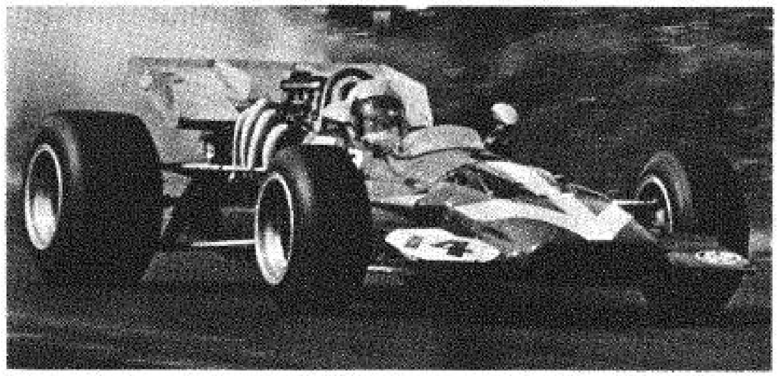
In laying down the guide-lines for the McRae Leda, Graham McRae specified a bulged mid-section for the monocoque, for good torsional stiffness and a low position of the fuel load. The upper panels were welded together, not riveted, to save weight



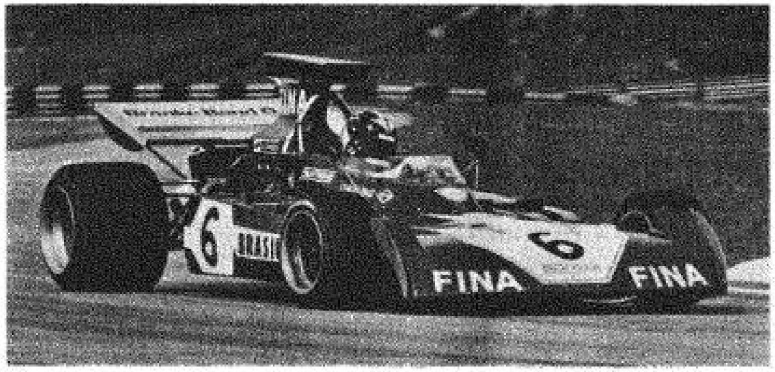
Terry considers that the lever-arm type of hydraulic damper has an advantage over the telescopic in terms of unsprung weight. Here are two typical Armstrong layouts, the upper with a single lever (as used on the Morris Marina) and the lower with a double lever



Girling brought out this experimental twin-disc front brake in 1971 when the adoption of smaller front wheels resulted in a corresponding reduction in disc diameter. It was tried by Tyrrell but then withdrawn for further development

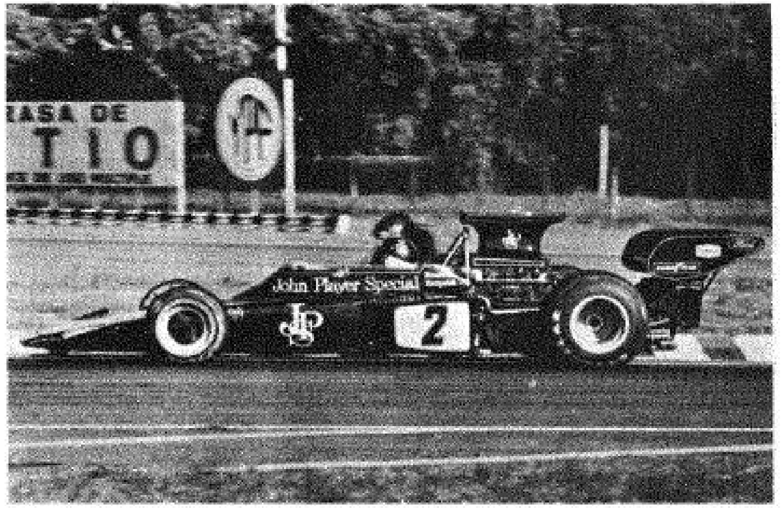


Trevor Taylor winning the 1970 Rothmans Dublin Grand Prix despite a leaking rocker cover: the highly successful Surtees TS5 Formula 5000 car was a slightly modified version of the Terrier Mark 17 design which was sold to Surtees in 1969

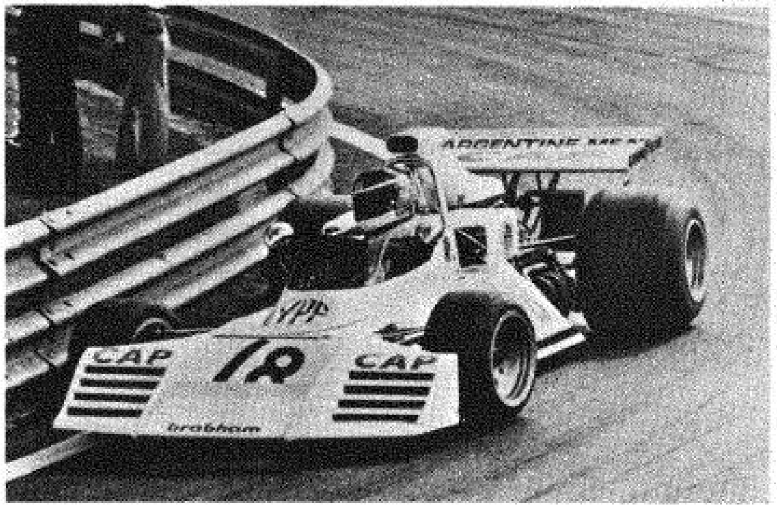


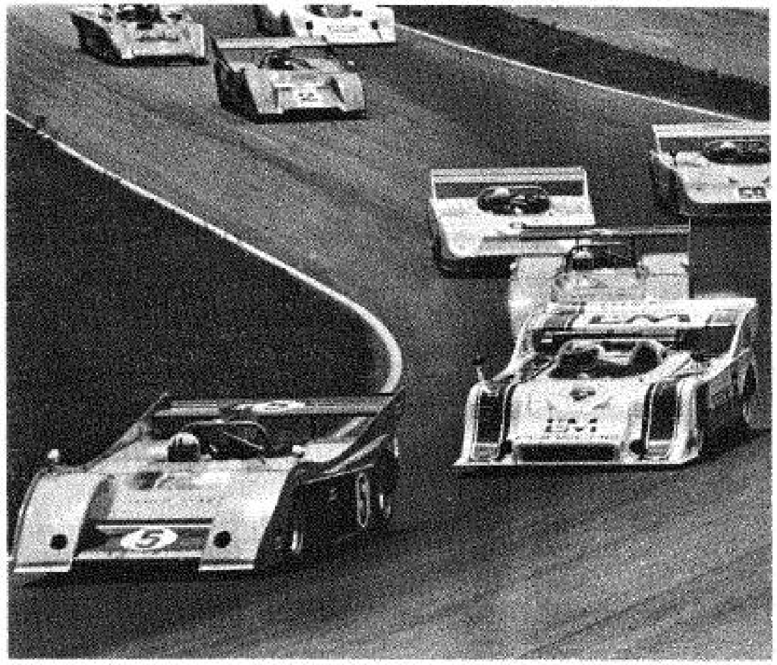
Surtees is one of the constructors to have followed Tyrrell's 1971 lead of replacing the front aerofoils by a combined down-thrust-producer and fairing to reduce suspension and tyre drag

Ram-type overhead air intakes for the engine became common wear in 1971, and by the following season were being integrated with engine covers to smooth out the airflow to the rear wing. Jackie Stewart's Tyrrell is typical of that approach

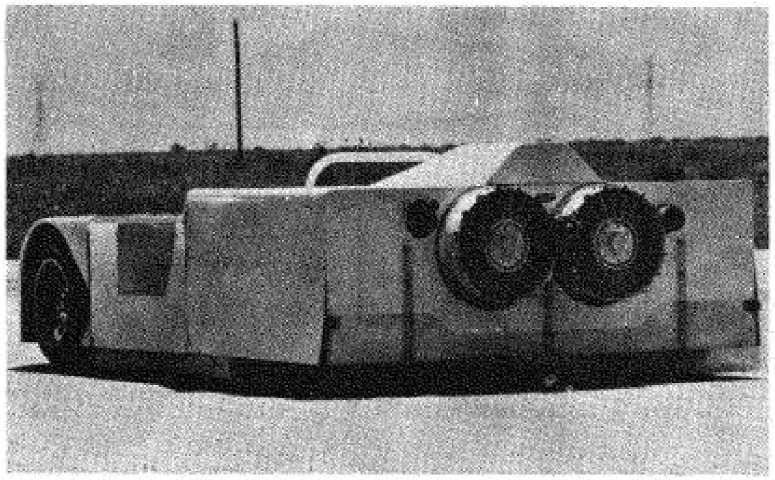


Opinion is still divided on whether open-wheel racing cars should have lateral or frontal radiators. Although the successful Lotus 72 (above) started the fashion for side-mounting, several Formula 1 constructors, including Brabham (below), have remained faithful to the nasal installation

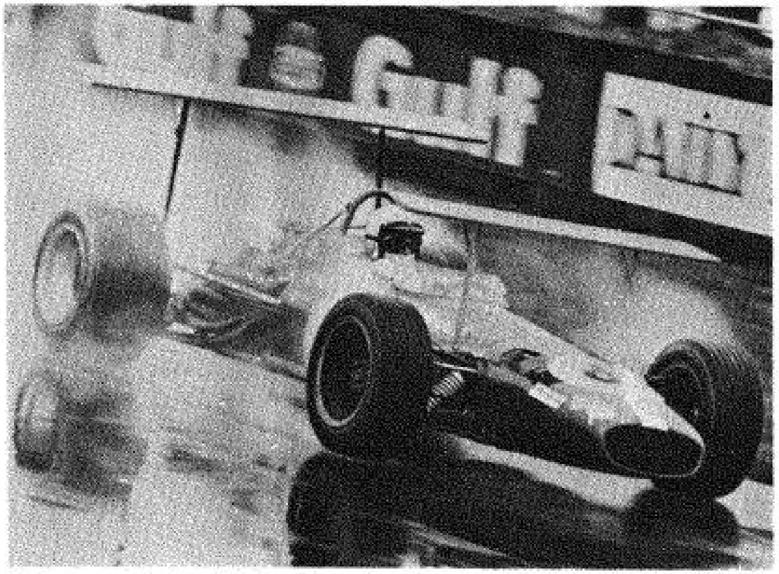




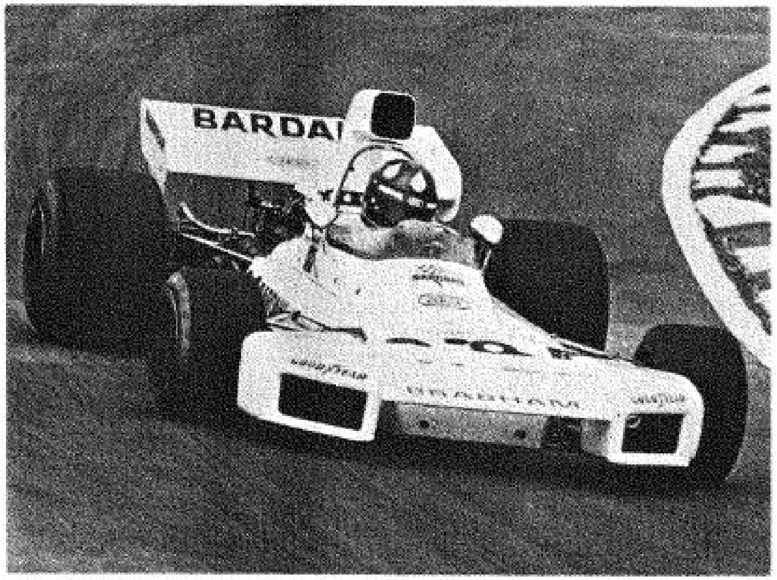
Knowledge of aerodynamics learnt mainly in the field of Grand Prix racing has been applied most successfully to CanAm-type sports cars, where the integration of full-width wings into the bodywork has achieved particularly good results.



Having demonstrated the effectiveness of wings on his Chaparral sports cars in the 1960s, Jim Hall broke more new ground in 1970 with his ground-effect car in which a pair of fans sucked air from within a flexible skirt with the aid of an auxiliary motor. The following year the ingenious concept was outlawed by legislation



High-mounted wings front and rear became the Formula I fashion before new legislation banned them in 1969. Jack Brabham demonstrates their effectiveness in the wet a few weeks before they were outlawed



An interesting if not entirely successful departure from convention. With its twin cowled radiators ahead of the front wheels the BT34 became known as the 'lobster claw' Brabham. Inadequate cooling of front suspension and brakes was a drawback

speeds. It is worth pointing out that they were used on two of the leading 1971 CanAm cars for supplying the air to side-mounted radiators.

One of these cars was the McLaren M8F, which had the ducts on the sides, and the other was the Lola T260, which had them on the top; the latter disposition should have been rather the better of the two because of the greater likelihood of a positive pressure over the ducts to help the entry of air. Since then, of course, NACA ducts have come into quite widespread use.

However, the most striking of the 1971 radiator dispositions was on Ron Tauranac's 'lobster claw' Brabham BT34. He adopted twin radiators mounted one on each side of the nose so as partially to overlap the front wheels. The radiators were in individual 'pods' which formed the end-plates of the front aerofoil, sited ahead of the blunt nose of the body. Tauranac's objectives here were to make the most efficient use of the radiators and aerofoil, and to reduce the drag of the front wheels. Certainly the air intakes and the aerofoil were in undisturbed air and so had a high built-in 'success factor', helped in the wing's case by the end-plating.

Two aspects of the layout were more dubious, however, as Terry pointed out when we discussed the design shortly after the car first appeared:

First, the radiator intakes are very vulnerable, and damage to one in a bit of 'jockeying for position' could result in overheating and consequent engine failure. Secondly, the air heated by passing through the matrices is led out horizontally to the rear, as on the Lotus 72 and March 711. Therefore it must raise the temperature of the dampers to some extent, and probably of the outboard front brakes, too, since I would expect the latter to draw more of their cooling air from the inboard than from the outboard side of

the discs. Because of these possible cooling problems, I feel that here again top outlets, to give downward rather than horizontal thrust, might have been a better solution; a smaller, lower-drag aerofoil might then have been practicable, which would have helped the performance. In fact, a more orthodox front end was adopted for the Brabhams in 1972.

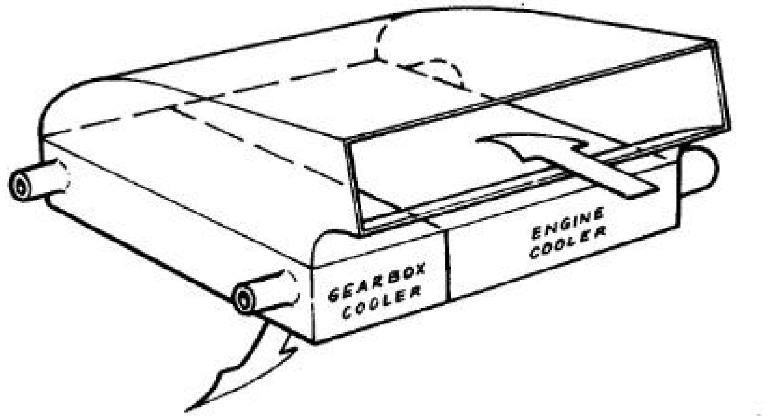
COOLING THE OIL

It is vital for the well-being of a highly stressed racing engine that its oil should be adequately cooled. Yet because the amount of heat to be extracted is substantially less than that from the water, the oil-cooler installation often becomes something of an afterthought and so is not very efficient. Part of the difficulty here, of course, is that the matrix has to be mounted in the already crowded engine area; the alternative frontal position requires long pipe runs, and therefore more powerful pumps, and leads to other complications if the water radiator also is in the nose.

Too high an airspeed through the oil matrix does not help the cooling because of the short time in which the air can pick up heat. A small, well-shaped intake is therefore better than a large hit-and-miss one.

If the flow through the matrix is at right-angles to the car's longitudinal axis, the entry duct can be shorter and lighter than for undeflected flow (see sketch). I used this layout on the Leda LT25, which had paired engine and gearbox oil coolers fed by a common duct. They sat on the rear sub-frame over the gearbox, with the intake well back from the engine to give the airflow room to smooth out.

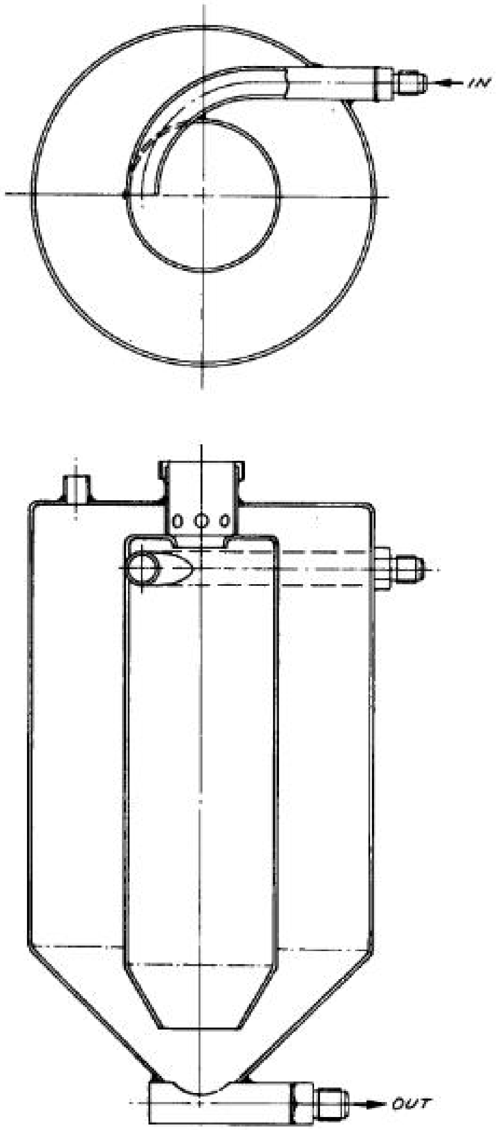
An important function of the oil tank is to separate entrained air from the oil. Few designers seem to be other than empirical in their approach to achieving good separation. In the case of the LT25 it was achieved by having a relatively tall and slim tank (8 in diameter by 16 in tall) with a conical base and containing a 4 in diameter swirl-pot which reached from the top almost to the bottom.



A short and light air intake for oil cooling is possible if the flow is turned through a right angle. This is the layout employed on the LT25 but the unit could equally well be inverted or mounted on edge

Assuming a good cooler installation, the tank capacity does not have to be large; we had only 2 gallons (9.1 litres) **of oil in circulation round the LT25's engine yet its oil temperature was about 8.5°C (15°F) lower than that of several competitors. Pipe sizes, though, must be adequate on the suction side of the tank, or pump cavitation – perhaps starvation – can occur.**

Even so, ideas differ considerably as to what constitutes 'adequate'. Cosworth fit pipes of ⅝ in bore (just under 16 mm) on their Formula 1 engine, and these are used also on the Chevrolet Formula 5000 unit, whereas BRM's Formula 1 V12 has 1½ in (38 mm) pipes. BRM use these large pipes because they have long favoured a high circulation rate. This *penchant* seems hard to justify. A fast-moving stream of oil is not in contact with a hot area long enough to pick up much heat nor, as already mentioned, does it



Oil-tank details of the LT25; the tank is considerably 'undersquare' and contains a swirl-pot for reducing aeration

have time to give up much in the cooler. In addition, the power absorbed in the pump is directly related to the circulation rate, so a high rate means less power available to drive the car. Clearly one could go too far in the other direction, when the oil would become locally overheated in the engine, but there would seem little point at present in exceeding a rate of two gallons per bhp per hour.

11

Safety and comfort

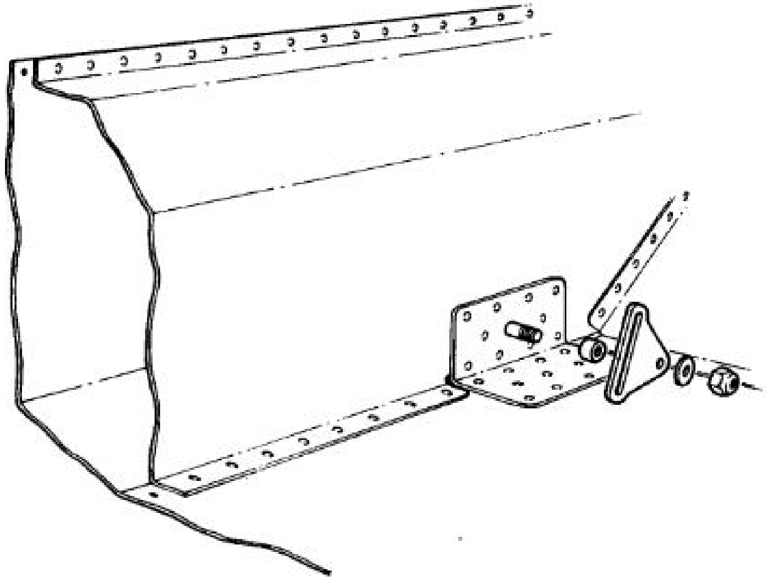
PRIMARY AND SECONDARY SAFETY

My own crash in the Terrier at Oulton Park made me acutely aware that motor racing is dangerous, and I have safety considerations very much in mind when laying down a new car. It goes without saying that I make every effort to give the car the highest possible level of primary safety; my aim is to ensure that the structural strength and stiffness, the suspension and the steering and braking systems are all up to their job, so that the driver has the maximum degree of control at all times. In practice, like any other designer, I've sometimes fallen short of the optimum, but I have not lowered my sights on that account.

Much can be done, too, in terms of secondary safety – minimizing the injury to the driver if he does get involved in a crash. As with a modern road car, the chassis has to be designed to collapse progressively in a collision, thus reducing the driver's rate of deceleration. Therefore it must not be too strong in compression or much of the

impact will be transmitted directly to the driver. However, it is vital in the case of a racing car that, in imparting collapsibility, the designer does not sacrifice the torsional stiffness he must have for good handling, and this conflict between primary and secondary safety is not easy to resolve satisfactorily.

Is a monocoque safer in a crash than a spaceframe? This question can be answered only if the type of crash is specified. In general, the monocoque is better in a frontal impact because of the more energy-absorbing collapse characteristics of the front end. Even here, though, you cannot be sure. When Trevor Taylor hit the bank at Oulton Park in the LT25 at the Rothman's Gold Cup meeting in August 1971, the monocoque buckled inward sufficiently under its compressive collapse



Recommended method of attaching a safety-harness anchorage to a monocoque structure: the bolt and rivets are loaded in shear, and the plate has ample area

to injure Trevor's leg and trap him in the cockpit. In the case of side impacts, however, the space-frame will often provide greater resistance to intrusion than will the monocoque.

Safety harness is a 'must', though even now quite a number of drivers seem reluctant to wear it. The anchorage points for the harness must be properly sited in relation to the driver's body, and they must be strong enough not to break away in a heavy impact.

To ensure this, any bolts or rivets must be in shear, not tension, and attachment plates should be as big as possible to feed the loads into the main structure over a good area.

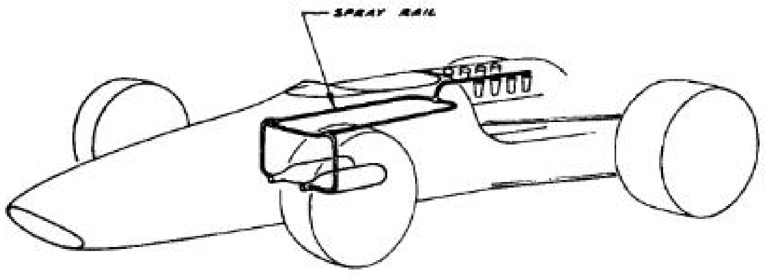
The suspension should form part of the secondary safety system. This means assessing the strength of the wishbones and anchorages so that they will absorb some of the impact energy and will then break off before the wheel can be forced into the main structure.

Bag-type fuel tanks considerably reduce the fire hazard, and the foam filling now used by some constructors is a further help, though naturally it reduces the capacity a little - about 5 per cent. The plain bag tank is more likely to split when full than when partially empty, but in the latter case it contains more flammable vapour. Also, these tanks tend to seep a bit after a time, so should be checked regularly during the season.

Conventional fuel-pipe connections are frequently damaged in a crash, so they leak and add to the fire risk. Therefore there is a good case for the aircraft-type self-sealing connections which pull apart under abnormal loading, leaving each pipe-end sealed. Colin Chapman is known to have been investigating such fittings, and it is to be hoped that the *FIA* will seriously consider making their use mandatory.

For the actual fire-extinguisher system I favour the use of two smaller bottles, each with its own switch, rather than one large one. The argument is simple: if there is only one bottle, which is actuated by the driver immediately after a crash, a delayed-action fire (by no means unusual) could well start up when the bottle is empty or nearly so. Two bottles, on the other hand, give the driver a double safeguard - one against an immediate fire and the other against a delayed one.

Since the battery - which normally operates the extinguisher system - can come adrift in a crash, my usual practice is to have a separate small Mallory (dry-cell) battery for this purpose, mounted behind the driver. Inertia-switch operation of one of the bottles is a good idea in theory, but there is still too little information on the appropriate g loads, so inadvertent operation could occur. It might be



Twin-bottle fire-extinguisher system; each bottle has its own actuating switch

worthwhile incorporating an inertia switch in the lead from the main battery, though, because many fires are started electrically.

Magnesium is not the fire risk that some people believe it to be. Although it *will* burn fiercely, its high thermal conductivity means that it catches fire readily only in thin sections, with a high exposed surface area in relation to their volume. This is evidenced by the fact that magnesium sheet can readily be gas welded without igniting. The swarf produced when magnesium is machined is much more likely to catch fire than the large lumps of it used for wheels, for example.

Strategically placed padding within the cockpit is desirable to reduce the severity of crash injuries, though there is a limit to the amount that can be applied without restricting the driver's freedom of movement. A collapsible steering column is another valuable safety feature and one which Terry has incorporated on all his cars that have incorporated the Triumph Herald-based steering gear.

I am doubtful whether the present type of tyre-retaining studs used on racing-car wheels represent the best solution to this particular problem. The Trevor Taylor accident mentioned earlier underlines this point. One of his front wheels locked up under braking for Knicker Brook Bend, on a slippery bit of newly laid surface; then, when the tyre came on to the old higher-grip surface again, its adhesion was sufficient to cause it to revolve on the wheel, ripping off the studs and letting out the air. This trouble could not have occurred with one of the earlier narrow tyres running at perhaps 35 psi pressure. It is a very real risk, however, with the present-day highly adherent tyres inflated to only 16-20 psi. Because of this, I think the time is ripe either for some basic rethinking on wheel design or perhaps for investigation of trials-type security bolts as an alternative to the retaining studs.

Safety regulations have often been laid down by people with little design knowledge. Fortunately there are now signs of increasing consultation with designers, but the situation will not improve markedly until scrutineers, too, have a better idea of what is safe and what is not. The designer is surely entitled to have rational interpretation as well as rational regulations.

In the safety sense, minimum-weight regulations are not very effective. The items that break and tend to cause accidents (wheels, hubs, brake half-shafts, wishbones etc) are mainly unsprung and, being relatively light anyway, have little influence on the overall weight. A chassis breakage is rare, so lightness is not synonymous with fragility. Extra weight, too, means that greater stopping power must be provided, which can hardly be regarded as a step towards safety. Another dubious piece of regulation-making is the specification by the FIA and other racing bodies of the loading to be withstood by roll-over hoops. While any such regulations are better than none, of course, arbitrary loading figures are meaningless because one cannot also specify what type of accident a car is going to have! The roll-cages built into US stock cars are really good, but could hardly be adapted to single-seaters because of the risk of trapping the driver if the cage became distorted in a crash. It is much better to have an orthodox type of hoop but to ensure that it is braced and mounted to withstand loadings in all directions.

For 1972, the *FIA* took an important safety step in specifying minimum dimensions for both the cockpit interior and its opening, to ensure that a driver can get out or be got out without undue difficulty. The interior dimensions inevitably must be a compromise because what is an easy fit round Jackie Stewart might be skin-tight on John Surtees. However, in opting for a minimum cockpit opening width of 18 in, maintained over a minimum length of 12 in, the *FIA* has been much more sensible than the Indianapolis authority whose stipulation of a minimum opening area of 500 sq in does not specify a minimum width.

DRIVER COMFORT

Surprisingly many people think that, because a racing driver is concentrating hard on what he is doing, he has no time to notice whether he is comfortable or not, so the designer need not worry unduly about this aspect. Nothing could be further from the truth. Unless the driver is comfortable, in the broadest sense, he is bound to tire quickly during a race, and fatigue is one of the greatest enemies of concentration. Other things being equal, the driver who is fresher at the end of a race will take the chequered flag.

Comfort in this context is not merely a matter of the immediate physical surroundings. It embraces the whole ergonomics of operating the car - gearshift, steering, pedals, vision, ventilation and vibration, as well as the actual seating.

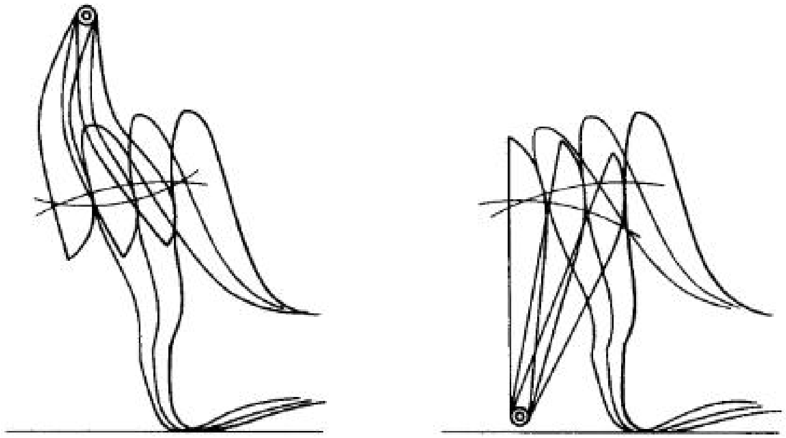
The latter, of course, is the starting point, and the seat contour should be tailored to the individual driver, because spine formations and individual preferences vary considerably. There is no need to have thick padding on the seat, but you may need more at the sides to limit and cushion lateral movement; polyether foam is better than latex foam because of its slower recovery rate which makes it less bouncy.

Restriction of the circulation must be avoided, and the driver must have full freedom of movement. Equally, though, he should not have so much room that he can float about, since it is very tiring to have to resist any such tendency under the *g* loads imposed by the high cornering powers of present-day cars. In these respects the designer of a car for a small team is clearly better off than one evolving a racer for general sale.

Today's crash helmets are heavy (about 4 lb or 1.8 kg), so the driver's head has considerable inertia which, without support, has to be resisted by the neck muscles. There is a good case, therefore, for an anti-acceleration headrest.

In the case of Formula 1 cars, which have the highest cornering powers of any, this rest could well be extended round the sides, though not far enough to risk impairing lateral vision. For Indianapolis, however, where all the corners go the same way, an extension on the right side would be sufficient. Unfortunately nothing can be done to help the driver regarding braking forces, except perhaps a course for developing his neck muscles!

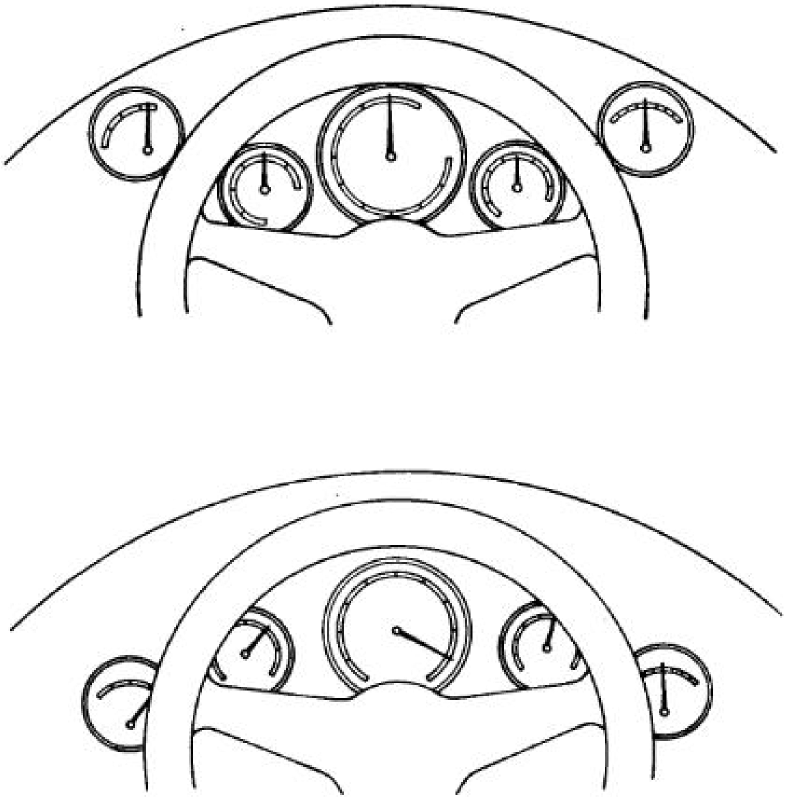
It is advisable to allow plenty of length adjustment on the steering column, together with some vertical adjustment to ensure that the wheel does not obstruct the driver's view yet is high enough to clear his thighs when he operates the pedals. The arcs of movement and pad angles of the latter must be carefully worked out to avoid excessive articulation of the ankles or unnatural foot angles.



Good and bad arcs of pedal movement; that on the left is satisfactory since the foot rolls on the pedal instead of sliding as it does in the other case

A rest for the left foot alongside the clutch pedal is a useful provision; correctly positioned it will help the driver to brace himself against cornering forces, particularly on twisty sections where he is going from one lock to the other. Also valuable is a heel-stop on the floor under the brake pedal, since it enables the pilot to avoid over-braking due to his own inertia.

Rear-view mirrors should be positioned so that the driver can glance at them without moving his head, thus reducing fatigue as well as the time his eyes are off the road. Here again there is a need for compromise, since mirrors can and do cause considerable air disturbance; if they are wrongly positioned they can induce undesirable wind buffeting around the driver's head. Location of the instruments is important, too, though the cramped cockpits of single-seaters make it difficult to obtain a layout where something is not partially obscured by the steering wheel, especially when this has a diameter of only 11 in. Switches



The driver should have a clear view of his instruments through and past the steering wheel (top). It is a help, too, if all pointers are vertical at optimum readings. The second layout is deficient in both these respects

should be within easy reach of the harnessed driver; the best place for the ignition cut-out button is probably on the steering wheel itself but if not it should at least be very close to hand.

I regard windscreen design as having a major influence on comfort and efficiency. A badly shaped or positioned screen on an open-cockpit car can cause wind buffeting around the head, as well as

interfering with vision. Wind-tunnel trials can help to eliminate the 'impossibles' but, as so often, actual circuit driving is the only really valid test. In addition the cockpit must be adequately ventilated to help keep the driver fresh. It is difficult to strike the right compromise between under- and over-ventilation, so again testing must be done in racing conditions. For long-distance events, some means of ventilating the seat can add considerably to the driver's comfort.

An unduly high cockpit temperature is another source of fatigue. Front-engine cars, with frontal radiators, were particularly bad in this respect because the hot air tended to get blown back into the cockpit, and any serious attempt at insulation would have incurred an undesirable weight penalty. A worthwhile advantage of the now-popular side-mounted radiators for mid-engine cars is that the second source of heat also is situated behind the driver. This configuration therefore is well worth considering purely from the comfort viewpoint.

Vibration undoubtedly contributes significantly to driver fatigue, though the designer is severely limited in what he can do to reduce it where the engine is mounted rigidly in the chassis or forms part of the structure. Relatively slow-revving four-cylinder units are notably worse in this respect than high-speed V8s and V12s. The engine man, of course, must ensure that the power unit is as well balanced as possible, but beyond that not much more can be done than to provide really stiff mountings which are widely spaced and feed the loads properly into the chassis.

Resonant vibration of components such as the gear lever and pedals, in sympathy with engine vibrations, can

usually be cured by altering the mass or the stiffness of the item concerned. Either method changes the natural frequency of the component and, if the difference is big enough, resonance can be moved outside the normal speed range of the engine. The techniques one can adopt include using a tube instead of a rod, increasing the diameter or wall thickness of a tube, and welding-on a rib or gusset plate.

Finally, I must stress again that the proof of the pudding is in the eating; the designer's and development engineer's success in achieving a really comfortable and easily driven car can be proved only on the circuit. It follows that the driver should have a final fitting for the driving position, and a final consultation on the other matters we have discussed, only after at least half an hour of continuous driving at racing speeds.

12

Materials

THE THREE PRIMARY MATERIALS used in racing-car construction are steel, aluminium and magnesium. Because of their different characteristics, each has its own role to play and there are relatively few cases where a choice exists; one or two such instances will be mentioned as we go along. In general terms, steel is used where the maximum strength and stiffness are required, magnesium where lightness is the main criterion and strength is secondary, and aluminium where a compromise between strength and low weight is necessary. For equal volumes, aluminium weighs about one-third as much as steel, while magnesium weighs about two-thirds as much as aluminium.

There is, of course, an enormous range of steels available today. The spectrum extends from ordinary mild steels, with a carbon content below about 0.2 per cent (and not much else other than iron) and an ultimate tensile strength of around 28 ton/sq in (44 kg/sq mm), up to costly alloy steels containing chromium, molybdenum, vanadium; these may have a strength as high as 90 tons/sq in (142 kg/sq mm) but are usually difficult to process.

Because these special alloy steels, apart from their strength, often have very good resistance to high temperatures and/or corrosion, they lie more in the province of the engine designer than the chassis man.

Steels of medium grade and below are used for highly stressed components in the car and are available in many different forms, such as sheet, tube, bar, plate and rolled sections. Typical applications include hubs, drive-shafts, rack-and-pinion steering gears, steering columns, suspension wishbones (tube, sheet or a combination), tubular bulkheads for monocoque structures, crash hoops and, of course, space-frames.

Another important steel duty is for anti-roll bars. Originally these were made of high-grade spring steel, but as stiffnesses increased it became more economic to use an ordinary medium-grade steel (such as En16T in the British Standards Institution range). In fact, now that there is a tendency to adopt tube instead of rod for these bars, to save weight, it would be practicable to use ordinary mild-steel seamless tubing.

It is worth digressing from the main theme for a moment to look at the weight advantage of tubular anti-roll bars. A tube of 1 in diameter and 16 swg wall thickness would have a torsional stiffness of about 24 lb ft/degree, measured over a length of 30 in, and that length of tube would weigh 1.6 lb. Approximately the same torsional stiffness would be given by a round-section bar (of the same steel) of 13/16 in diameter and weighing 4.3 lb, so the tube gives a weight saving of around 63 per cent. A more detailed look at the comparison between bar and tube is given in an Appendix.

Aluminium, too, has a widespread application on racing cars. Here again there is a wide range of alloys, having tensile strengths of from about 9 ton/sq in (14 kg/sq mm) to over 30 ton/sq in (47 kg/sq mm), and the material is supplied in all the usual forms. In sheet form aluminium is used for virtually all monocoque structures as well as for aerofoils and for the one-off 'masters' from which GRP (glass-reinforced plastics) bodies, nose cones, air intakes and so on are made. Although aluminium-tube space-frames have been built, they have not achieved any real popularity, for two reasons. Aluminium has less favourable fatigue properties than steel, and so is more likely to fail through vibration; and since it is a less rigid metal than steel a considerably greater bulk of material is necessary to achieve a given structural stiffness, so the weight saving is appreciably less than might be expected.

Aluminium tubing could, I think, be used more than it has been for sub-frames, wishbones and radius arms, wing struts and so on, as an alternative to steel, provided that the designer keeps the fatigue aspect in mind. We have already discussed my fabricated aluminium suspension uprights, and it might prove practicable to fabricate wheels in the same material instead of casting them in magnesium. One could have a spun rim/web portion on a cast centre, or even two spun half-rims bolted together.

Other applications of aluminium are engine plates, oil tanks and catch tanks, ducting, water pipes for the engine cooling system, the piping of the fire-extinguisher system and fuel tanks, pipes and filler caps. The last-named could be produced from castings, as would the rack-and-pinion housing for the steering gear. In addition, some designers increase the stiffness of steel-tube bulkheads by double-skinning with riveted-on aluminium sheet between the tubes.

Aluminium is used also for proprietary oil-cooler elements, since it gives a more favourable ratio of weight to heat-dissipation properties than the traditional copper/brass construction. For the same reason it has been tried for water radiators, but where these are fabricated by brazing there is the likelihood of electrolytic corrosion which can lead to partial blockage and consequent overheating. Also, because of the softening effect of the brazing process, thicker sections have to be used for adequate strength, so the weight saving is not great. However, Covrad Ltd, in the giant Associated Engineering Group, have been working for some years on the adhesive-bonding assembly of aluminium radiators. They have now perfected the process which not only is claimed to obviate electrolytic corrosion but also enables the full weight-reducing potential (near 50 per cent) of aluminium to be realized. At the time of writing, production facilities for road-car radiators were being set up, and the indications were that units for racing cars would follow not far behind.

Magnesium has a more limited usage than aluminium in the racing car, because although, as mentioned earlier, its specific gravity is two-thirds that of aluminium its tensile strength is roughly only half as much. It is available in cast and wrought (sheet, plate, tubing, etc) forms, and costs considerably more per pound than the equivalent aluminium alloy.

Today magnesium is most commonly used in the cast form, for wheels, suspension uprights, gearbox/transmission casings and some engine castings, such as cam-box covers. Cast bulkheads have been tried also, notably on the original March Formula 1 and the Hallibrand Indianapolis cars.

However, such bulkheads are unlikely to be lighter than the conventional type because of the wall-thickness limitation (about 0.2 in or 5 mm) discussed previously in connection with uprights. In sheet form magnesium was formerly employed by some

designers for chassis work, but it is no longer viable because of the minimum thickness limit now enforced by the FIA. I have never favoured it for monocoques because it work-hardens and consequently is a tricky material for a riveted structure.

During the last few years a fourth metal, titanium, has come into increasing prominence in the search for strength with lightness. Titanium sounds a wonderful material since it has the strength of steel for about half the weight, and has excellent fatigue resistance, but at approximately £10 per pound in 1973 it was very expensive (although the cost was coming down with rising demand). A further difficulty is that titanium can be difficult to machine and weld. This last characteristic obviously can impose problems should a quick repair 'in the field' be necessary.

Apart from its use in engines, for connecting rods and various smaller components, titanium has been used successfully for hubs, by BMW and others, and has been tried for suspension wishbones and radius arms:

I am not very happy about these suspension applications because the material is more elastic – that is, it has a lower Young's modulus – than steel. Consequently, one might be in bother over inadequate stiffness in compression; certainly, relatively large diameters and thin gauges would be necessary, but the fabricating difficulty remains in the case of wishbones.

I have the feeling, too, that designers are tending to be 'carried away' by the glamour of titanium, to the extent of using it unnecessarily. In his search for lightness the designer must know where to draw the line. He must consider the cost-effectiveness of his solution as well as the actual saving in weight, and in working out the former he has to bear in mind such practicalities as manufacturing delays and difficulties, and the already mentioned aspect of repairs at the circuit. As I have said before, an approach based on simplicity and cheapness often gives better results than a striving for maximum sophistication.

Other materials, such as copper, brass, rubber and plastics, are used in racing cars, of course, but usually in bought-out components. However, the designer is directly concerned with a number of the plastics items – for example GRP nose cones, wings and ducts, and nylon bushes for the steering column. The plastics field has not yet been fully explored, and some of the new materials and techniques might well prove useful. A recent development is the use of very light and cheap standard plastics containers as oil catch-tanks. These were formerly aluminium fabrications, but the regulations now require them to be translucent, for quick verification of the level.

Materials manufacturers in general produce comprehensive literature on their products, and any established racing-car designer will have a shelf stacked with catalogues and leaflets covering those he commonly uses. Most of this literature is based on the material itself, the application being secondary. Therefore, in the hope of saving the aspiring designer some time, we have prepared a materials table (reproduced as an Appendix at the end of this book) in which the application is the primary consideration. Against each duty in this admittedly not exhaustive list are scheduled the requirements, suitable materials and the forms in which they are available, plus any special comments.

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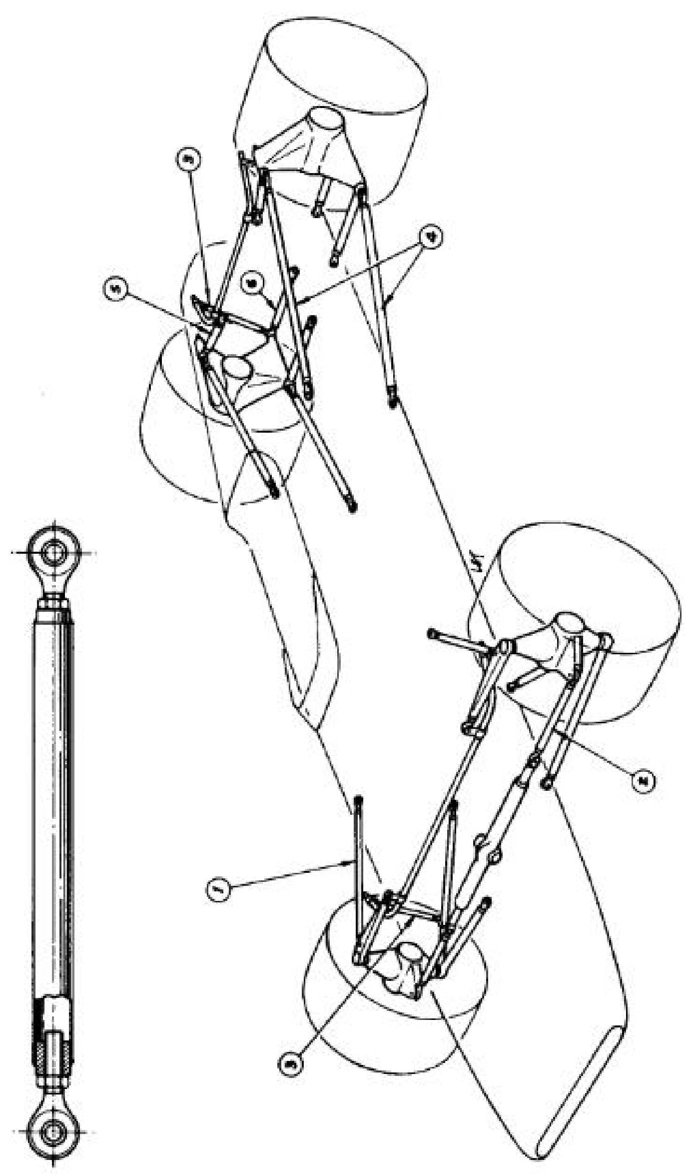
Components

ALTHOUGH ANY RACING CAR will contain a liberal quantity of specially produced parts, the designer, in order to save money and time, has to incorporate as many standard bought-out components as possible. Therefore he needs to know all the relevant suppliers and must establish his lines of communication with them at the earliest stage. Fortunately Britain is well endowed with component manufacturers, and this section gives guidance on the leading specialists in the various areas of interest; reference is also made to some foreign companies.

Ball-joints: These are widely used in suspension and steering systems, and for throttle, brake pedal and gearchange linkages. The two largest manufacturers are Rose Forgrove and Ampep, both of whom make a comprehensive range of sizes. Two qualities are produced, the aircraft grade being the stronger and more durable but costing three or four times as much as the standard grade. There are also various tightness grades, in which connection it should be appreciated that suspension joints must be just nipped-up initially. Another variation is that the



Tubular links with ball-jointed ends, having left-hand and right-hand threads for adjustment purposes, are widely used in racing-car steering and suspension linkages. Here are six typical applications and the nature of the adjustment to be effected in each:

1 *Front radius arms – castor angle*
2 *Track rods – wheel toe-in or toe-out*
3 *Drop links – anti-roll bar setting*
4 *Rear radius arms – roll/bump-steer*
5 *Rear upper links – wheel camber angle*
6 *Rear lower links – wheel toe-in or toe-out*

static portion of the joint can be either male or female. The Automotive Products Group is another manufacturer specializing in ball-joints for suspension uprights; they make two types, one being intended to carry spring loads while the other is not.

Batteries: The semi-dry aircraft type is most commonly used and Varley is the leading supplier.

Brakes: Girling and Lockheed (Automotive Products again) are the two specialists here; since they are in hot competition there is generally little to choose between them. They produce a wide range of brakes for competition cars and both are co-operative at the design stage and in the field. Incidentally, both makes are available in the USA where Airheart is their indigenous rival.

Clutches: A virtual monopoly in this field is held by Borg & Beck (AP again), and the same comments apply as for brakes in respect of both the range and the assistance available.

Dampers: The prime contenders here are Armstrong and Koni (a Dutch company), and the choice seems to be mainly one of personal preference. However, some constructors use Spax (British) or Bilstein (German) dampers with apparently satisfactory results.

Drive-shafts: Hardy-Spicer and BRD (both in the GKN group) make conventional needle-roller universal joints and shafts, BRD specializing in roller-spline anti-friction couplings for variable-length geometry. Hardy-Spicer also produce constant-velocity joints, under the Birfield name, especially suitable for use with inboard front brakes; these joints are used by Lotus among others. Hewland have begun to market their own frictionless splined-shaft assemblies including orthodox universal joints. As a means of accommodating a small amount of plunge, Dunlop Polymer Division (formerly Metalastik) have their Rotoflex rubber 'doughnut' joints which also serve as drive-line shock-absorbers. These joints, made in a variety of sizes, are popular in the smaller racing classes but tend to be too bulky and heavy for Formula 1 and Formula 5000 use, presenting space problems where the brakes are inboard. A practical point in their application is that they act as two-way suspension springs, adding to the rate of the main springs on bump and reducing it on droop; also they must not be installed near the brakes because of the harmful effect of heat on the rubber.

Electrics: Though these fall mainly in the province of the engine man, it is worth mentioning that Lucas are the concern for such items as ignition switches and of course lighting on sports prototype cars.

Flexible bearings: These were once used extensively for suspension pivots and engine/gearbox mountings, but since 1960 they have been largely replaced by spherical bearings for the former application, while it is now accepted practice to mount engines and gearboxes rigidly. However, flexible bearings can still be useful in certain instances, as for example when a radiator has to be mounted resiliently. Both Howard Clayton-Wright and the Polymer Engineering Division of Dunlop make a wide range.

Flexible fuel cells: Marston Excelsior and FPT Industries are the two top British producers, and they will make cells to any requirement. Firestone and Goodyear are their counterparts in the USA, and other recognized manufacturers are listed in the *FIA Yearbook of Automobile Sport*. In 1973, Formula 1 cars were making wide use of the UniRoyal aircraft-type tanks.

Gearboxes and final-drive units: Hewland Engineering provide at least 90 per cent of the racing-car transmissions used throughout the world. They make a wide enough range for most requirements and keep a good stock of spares even for earlier models. The German ZF company (which has British representation) and Weisman in the USA supply most of the balance, a new British company, Metso Transmissions, has also appeared on the scene.

Gear-shift linkages: Apart from the ball-joints already mentioned, the designer might need small Hooke-type universal joints. These can be obtained from Mollart Engineering Co and Motor Gear & Engineering Co.

Instruments: Smiths Industries' Motor Accessory Division provide most of these.

Non-return valves (fuel system): Flight Refuelling are experts in this field, or one might try firms selling Government-surplus aircraft equipment, Coley of Hounslow for instance.

Non-spill fuel fillers: These pit essentials are manufactured by Avery-Hardoll who, of course, are well known for their garage fuel-delivery pumps. Also, Shaw Aero Devices (an American company) make a flush-fitting filler cap.

Nuts and bolts: For these simple but vital components, GKN can supply if the quantities involved warrant going further afield than the local engineering supplies shop (which probably stocks GKN anyway).

Oil and fuel pipes: It is customary these days to use armoured flexible hose for a racing car's oil and fuel lines, popular products being Aeroquip, which are relatively lightweight and supplied by Trist Draper.

Perspex mouldings: One should really say 'acrylic', but ICI's trade-name has become synonymous in Britain. There is a wide choice of moulders throughout the country, but Terry can recommend Suntex and White Ellerton.

Radiators (water and oil): Water radiators are built to the car designer's requirements, and Serck have a big lead over the opposition - even Ferrari comes to them. They make an excellent matrix and are very helpful; you give them the engine details and they will supply you with the appropriate area/thickness data. Covrad may come into the picture here when their bonded-aluminium radiators for racing cars are in production. For oil radiators, it is best to take Serck or Marston standard items which are cheaper and quicker to get than 'custom-built' units.

Springs: For suspension springs some designers rely on the manufacturer of the spring/damper units, since an adequate range of rates is usually available. However, there is no reason why our man should not design his own if he thinks he can do a better job. These and any other special-purpose springs can be entrusted for manufacture to such firms as Park Spring Co. or International Spring Co.

Steering gear: For minimum cost and no waiting, Terry modifies a standard rack-and-pinion unit of the Morris Minor, Mini or Triumph Herald type. The column, too, can be Triumph Herald; it is light and adjustable for length, and has a splined end to take a universal joint. The latter could be provided by Torrington, who make a range of cheap and efficient Hooke-type components.

A Buyers' Guide to racing-car components is provided in the form of an Appendix at the end of the book.

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Design versus development

IT USED TO BE SAID that the true function of the development engineer was to rectify the inadequacy of the designer. This may have been true in the racing car field up to 10 years or so ago, but it certainly is not so today. Whereas the designer was the star and the development man played a supporting role unless the designer slipped up somewhere, contemporary chassis design has become a much more exact business (hardly a science yet, but approaching it) and so there is less reliance on the individual brilliance of the man at the drawing board.

Taking this thesis a stage further, the characteristics of previous generations of racing tyres allowed wider margins of error on the design side than is now the case. Today's very wide tyres make the correct setting-up of the car more important than the basic design of the suspension etc, so the development engineer/driver has to a large extent become the king-pin. But to fulfil his function properly, this man must now be a competent racing driver, which he did not have to be in earlier years.

This is because a car may handle satisfactorily when driven at eight-tenths but become lethal at ten-tenths, when the greater amount of roll uses up more of the suspension geometry and may bring the tyres 'on to the edge' so that they lose adhesion. The only way to determine whether a car can be raced at the limit is to test it at the limit.

It follows that the number of men who can really cope with the duties of development driving is becoming smaller; the technical demands of the job have not diminished but the driving demands have increased. The development driver has to be able to set-up the car for each circuit in turn, which means analysing its behaviour on virtuay every corner and modifying until the best compromise is found. If he knows his stuff, even a relatively mediocre (but sound) design can become competitive; but if he does not, even the most brilliant design can fail.

As a case in point, consider the Tyrrell's wide nose which appeared early in the 1971 season. Initially it was disliked in practice and so was not raced. However, the team then settled down to some serious development work, concentrating on setting-up the suspension to suit the different characteristics of the nose in comparison with the old winged type. Once this work was completed, Derek Gardner's sound thinking was rewarded with a World Championship.

The first-class development driver must first and foremost be able to analyse precisely what the car is doing at any particular time, and why it is behaving in such a way. He must then be able to report accurately and, if his engineering experience is sufficient, indicate what changes should be made to improve matters. The better his *rapport* with the designer the quicker will the problems be solved, and this is one of the reasons for the earlier successes of the Brabham and McLaren teams.

Both Brabham and McLaren were high-grade engineers as well as drivers, and they had the ability to communicate. You could perhaps look on the other side of the coin for the failure of certain teams to make the grade in 1971, for example, in spite of their having top designers and some of the quickest drivers.

The matter is further complicated by the continuing development of tyres. A change of mix or profile can convert a good-handling car into a complete 'pig', or *vice versa*, and the tyre companies may make as many as four or five design changes in one season.

Generally speaking, each design change produces a tyre that gives better grip, but taking full advantage of the improvement often entails a complete revision of the suspension geometry, so teams that work very closely with the tyre companies tend to have an advantage here. This problem can also account for the fluctuating fortunes of some teams during a season.

When one considers the many variables that affect a car's handling and cornering ability, it is hardly surprising that arriving at the right permutation is such a difficult task for both the designer and the development man. These variables include tyre size and pressure, suspension geometry, spring rate, anti-roll bar stiffness, damper characteristics, wing angle and position, anti-dive and anti-squat, roll-centre height, ride height, toe-in and bump-steer effects, and even gear ratios. The situation is complicated by the fact that most of the variables apply to both the front *and* the rear of the vehicle, and the behaviours of the two ends have to be related correctly.

15

The competition

Len Terry's personal assessment of nine contemporary racing car designers

WHEN MY CO-AUTHOR first discussed this chapter with me, he suggested that it should be a commentary on other designers' successes and failures - something like 'I wish I'd designed that' or 'I'm glad I didn't!' This idea did not appeal to me, because without being unduly big-headed I cannot think of any competitor's car for which I would be happy to claim 100 per cent credit. Most cars by other designers embody individual features that I admire, but others that I can criticize. Because racing-car design is something of an art-form, too, each designer's solution to a set of problems is a manifestation of his particular personality, and we are each egotistical enough to prefer our own answers to the other man's.

Therefore I have decided to lead with my chin and talk about my fellow-designers, as revealed through their vehicles. In this I shall try to be objective, but if I should offend anyone he should remember that opinions cannot be libellous, only misguided!

After discussion, Baker and I decided that I should

spotlight the following nine designers as having achieved the appropriate eminence in their field: Colin Chapman, Maurice Phillippe, Ron Tauranac, Eric Broadley, the late Bruce McLaren, Robin Herd, Tony Southgate, Derek Bennett and Derek Gardner. There are other good men, of course, and I hope they will not feel hurt by their omission, but the line must be drawn somewhere.

COLIN CHAPMAN

For my money, Colin ranks at the top of our list of present-generation designers, primarily because he is one of the very few real innovators. His most important contributions have been in the realms of weight reduction and roadholding/handling, and here he was the first to adopt what I call the semi-scientific approach - the drawing board first and then the workshop. In this respect he could be said to have founded a new school of philosophy, since the majority of later designers, having adopted the same approach, can be regarded as Chapman's disciples.

He has had his failures, as have all of us, but his successful cars have been far more numerous. I think that on several occasions the failures have been due to trying too hard to prove a particular point. Most of the time I was at Lotus, Chapman and I worked well together. We had our differences, often on the weight/strength theme, but usually we found a successful compromise. Looking back, I would say that we formed a good design team because, for all his brilliance, he is not always the most realistic of men and needs a feet-on-the-ground character to back him up.

MAURICE PHILLIPPE

Maurice was of course my successor at Lotus. He comes, I think, from very much the same mould as Chapman, being an innovator but a bit short on the practicalities. As a result he sometimes tends to go for too many novelties at once, for example on his first Indy car for Parnelli Jones; this had not only the controversial (and apparently unsuccessful) dihedral rear aerofoil but a very triangular body section as well as a suspension-carrying front crossmember which continued the dihedral theme, together with fairly complex suspension systems. Each of these features on its own would have been worth investigating, but together made too much of a meal.

The Lotus 72, which Phillippe designed to Chapman's brief, exemplifies my earlier comment about my not being completely sold on other people's cars. I approved of the very wedge shape but not the side-mounted radiators, which I still do not really like because of the disturbed airflow reaching the inlets; the elements therefore have to be bigger and heavier to get the desired rate of cooling. The torsion-bar suspension was another thing I liked, for reasons that have already been explained, but the actual application was marred by its complexity, which I believe could have been reduced by a more practical approach.

RON TAURANAC

Our Australian friend is to a large extent the antithesis of Colin Chapman. He is an admirably sound and practical engineer, but essentially conservative in outlook. Here he may well have been influenced by his long sojourn with Jack Brabham (whose innate conservatism Jack would be the last to deny), because his only real innovation appeared after Brabham retired from the company; it was the 'lobster claw' front end on the 1971 Formula 1 cars.

Because of his practicality and good sense, Tauranac is more of a design/development engineer than a pure designer. Were it not for an almost certain clash of personalities, I would expect him to be the ideal foil for Chapman because their abilities would complement each other so well.

ERIC BROADLEY

Eric has produced a considerable number of excellent overall concepts in several racing categories, but often they seem to have been spoiled by inadequate attention to the detail design. Some of his bracketry, for example, leaves me with the impression that the mounting of certain essentials was tackled as an afterthought rather than forming an integral part of the main design exercise. Eric undoubtedly has been very successful, but his success in recent years has been more significant in commercial terms - building and selling a lot of cars - than competitively. I think it is fair to say that his most successful cars have run in classes where the competition has been not particularly strong, for example, in the earlier CanAm races before the McLaren takeover, and more recently in the 2 litre sports class. His Formula 2 and Formula 5000 cars, on the other hand, have been relatively less successful against stronger competition.

BRUCE McLAREN

When Bruce was killed the world lost one of its best combinations of driver and development man. Apart from being a first-class engineer he was a stickler for detail and had enormous tenacity - he wouldn't let any problem baffle him for long. His designs were relatively conservative, but careful attention to detail and painstaking development made them into successful racing cars.

If you put the pure designer at one end of the scale and the equally pure developer at the other, I would rate McLaren as having his location towards the development end, as does Ron Tauranac. That his example lives on in his company is underlined by the competitiveness of their Indy, CanAm and Formula 1 cars, all of which are the products of long-term evolution rather than revolutionary design changes.

ROBIN HERD

At the other end of the design/development scale stands Robin Herd, who of course was McLaren's first designer. He is highly intelligent and technically better qualified than most, but his technical ability sometimes tends to be a handicap in that he tries to be too scientific for his medium. Although as an innovator he is in the Chapman class, his background is less practical and his growing experience, in my opinion, has yet to point him sufficiently towards real practicality.

Herd's originality was demonstrated by his use of plastic-sandwich structural material for chassis while at McLaren, and his four-wheel-drive work afterwards for Cosworth Engineering. His first March cars were mainly ultra-conservative, but this was a policy decision based on the need for 'instant winners'. Having established himself, Herd sparred with unorthodoxy again, in the form of the 1971 'aerodynamic' Formula 1 March 711 and the 1972 low-polar-moment March 721X, but success eluded him - the latter car was too new. Therefore he was obliged to return to convention, putting the Cosworth-Ford V8 into the Formula 2 chassis to obtain the light, straightforward March 721G. A bit of a yo-yo performance so far, but maturity is really all that Herd lacks.

TONY SOUTHGATE

I find Tony something of an enigma because of his alternation between success and mediocrity. He had been involved at the top level with only two makes - Eagle and BRM - before his move to the new UOP Shadow team. His 1968 Eagle (based largely on my 1966-7 car but with a monocoque of different section, outboard front-suspension units and the geometry modified for wider tyres) was a good racer. The 1969 car, which he designed from scratch, did less well for reasons unknown; it might have been developed to success but, as was mentioned in an earlier chapter, Dan Gurney came to me again for his 1970 Indy vehicle.

Then Southgate went to BRM and designed the P153 (1970) and P160 (1971) cars, of very different shape from the Eagle; they were straightforward and successful, with excellent handling. The more radical 1972 P180, with its concentration of weight at the back, was not a success, and apart from the unreliability aspects I would suspect the handling. According to my calculations, anything over 65 per cent of weight on the rear wheels means almost airborne front wheels out of slow corners, so how can you steer? In spite of these fluctuations, though, I feel that Southgate, too, will be very good when he has the benefit of more experience.

DEREK BENNETT

Chevron's designer has one valuable attribute in common with Chapman, Phillippe, Tauranac, Broadley and myself; in our earlier days we all built specials and raced them ourselves. Although Derek has had less of the limelight than some of his contemporaries, he is a designer/engineer for whom I have a high regard, and he deserves wider acclaim. He is not a particularly radical thinker, but his cars show some originality; for example, he pioneered the snub nose which became general wear on sports cars before it was adopted in modified form for the 1971 Tyrrells and subsequently for other Formula 1 cars. All of Bennett's cars (from his pre-Chevron 1172 special) have been sound and practical, well built and well detailed, and virtually all of them have also won races, which is really what it's all about. What is more, he has been commercially successful, too!

DEREK GARDNER

The second Derek is harder to assess than the first, purely because his experience in the racing-car field has been restricted to Tyrrell; he was previously a transmission engineer at Harry Ferguson Research. He was successful at the first attempt - when again an 'instant winner' was necessary - through not trying to be too clever. His 1972 car, too, was in effect a logical progression from 1971, bearing in mind the changes to regulations. I think Gardner appreciates that today the actual designer is less important than he used to be, and that the right relationship with the driver is the vital keystone of the operation. It is worth speculating whether he would have done so well with the same car in another team and with another number-one driver.

SELF-APPRAISAL

As a tailpiece to these potted personalities, perhaps I should try to stand back and take a look at myself in the context that I have been using for the others. In the first place, if I had to consider only my 1970-1 record, I wouldn't think much of me; otherwise, the picture is not a bad one. I see myself, I hope accurately, as standing midway between the Chapmans and the Tauranacs on the designer/developer scale, able to innovate, but only doing so when there is a good, practical reason for it. Most of the time I put my considerable experience to good use but, as with most of us, there have been the odd lapses. However, I consider that some of my designs could well have shown better results had I been more deeply involved in the development stages.

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A look into the future

Some closing thoughts from Len Terry

LOOKING AT THE PRESENT generation of racing cars I feel that there is still scope for considerable improvement in terms of lap times and speeds. Obviously, much progress has been made during the last decade, shown by an improvement in lap speeds at Indianapolis of over 50 mph. I see no reason why this progress should not continue, since there are several areas of improvement that are virtually untapped at present.

A typical 1973 racing car allows a very large amount of energy to go to waste; if only a portion of this energy could be utilized, a worthwhile improvement in performance would result. Consider, for example, the amount of heat dissipated to the atmosphere from the exhaust system. If only this waste heat could be converted into usable energy it could be employed in several ways. Already it is being put to work in turbochargers on USAC Championship cars, but one could go a stage further and couple the turbocharger to the crankshaft, as was done on certain aircraft engines.

Where turbocharging is not really a practical proposition - when pumping fuel is mandatory, for instance - there seems to me no reason why an exhaust-driven turbine should not be used in some other way. Again, it could be coupled to the crankshaft or could drive a suction pump, Chaparral fashion. Alternatively, a way possibly could be devised to use it for decelerating the car or producing side-thrust during cornering.

Other heat sources that are mainly wasted and that could possibly be transformed into useful energy producers are the radiators (both water and oil) and the brakes. An enormous amount of heat is generated in a very short space of time under braking, and this potentially valuable energy is just thrown away. Braking generally occurs just before a corner; if its energy could be retained for only a very short period of time, it might be converted into downthrust for use in the corner. Referring again to aircraft practice, several World War Two aircraft had their exhaust and radiator systems designed so as to provide additional thrust, and there appears to be no reason why the same principles should not be applied to racing cars.

In the field of aerodynamics, racing cars are still rather crude devices and there is certainly scope for improvement. The typical vehicle without its aerofoils would still produce a certain amount of lift, whereas it should be possible to design a shape that would give downthrust without having an inferior drag factor. And it should be feasible to reduce the drag factor even under the present regulations governing single-seaters. Steps are already being taken in this direction, as witness the spate of full-width fronts and general 'cleaning-up' taking place on the open-wheel cars. While the underside of most cars is fairly flat and smooth, the

upper surface tends to be covered in excresences which, however small, create airflow disturbance and consequent drag. As an example, rear-view mirrors can create considerable turbulence if poorly placed, and it was significant that both Alpine and BRM completely faired them into the bodywork on their 1972 cars.

Again on aerodynamics, rear aerofoils could be made more effective if greater thought was given to cleaning up the airflow leading to them, and it is interesting that the majority of Formula 1 teams have followed the lead of Tyrrell, Surtees and Ferrari in this direction. However, as is the case with tyres, a lot will depend on what measures (if any) the CSI adopts to reduce cornering speeds in the interest of greater safety.

Although great strides have been made with tyres, little real progress has taken place in the area of suspension generally, and I believe that a great deal can yet be achieved. Apart from the Lotus torsion-bar development, suspension layouts have not changed significantly over the last decade; they have merely been modified slightly to cope with the very wide tyres and the extra loads imposed by the aerofoils. A self-levelling anti-roll system might provide the means for a significant advance in handling generally, while silicon springs could be worthy of investigation as they appear to offer considerable size and weight advantages which would be valuable even in the case of a torsion-bar layout.

Brakes are an area where a good deal of progress has already been made, and Formula 1 and equivalent cars are now approaching 2g rates of deceleration. Once more, there is little reason to suppose that this progress will not continue, especially if some of the present wasted energy can be utilized in this direction. Why cannot the engine power be used to decelerate the vehicle as well as accelerate it? Or be used in cornering or braking to generate a vertical thrust like a VTOL aircraft in reverse? Also, tests carried out with anti-locking devices indicate that there may be a case for their application to racing cars, especially in wet conditions.

Another point that occurs to me is that the present trend of Formula 1 cars to become even larger may be reversed. At the start of the 3 litre formula the average wheelbase and track of the cars were probably 6 inches (152 mm) less than today, and the overall width perhaps even 10 in (254 mm) less. This difference represents a 10-15 per cent increase in frontal area alone, although it is partially compensated by the contemporary lower-profile tyres. Here we come to another area of possible development. Because of the trend towards inboard front brakes, it seems possible that in the not too distant future we could see smaller front wheels being used, in place of the present 13 in size. These would reduce even further the unsprung weight and frontal area, as well as increase the effective brake leverage. Reverting to the smaller-car theme, an important step in this direction has already been taken by the March and Lola companies, who have developed Formula 5000 cars out of Formula 2 designs, while Lola's 1972 3 litre sports car obviously owed a lot to their 2 litre.

One area of design where I cannot see much room for improvement is with regard to lowering the centre of gravity. Most of the major masses seem to be placed as low as possible in today's racing cars, especially the Ferraris with their flat-12 engines. Although lowering the C of G in relation to wheelbase and track dimensions means reducing the tendency to dive, squat or roll, I doubt if any further worthwhile handling gain could materialize from whatever could be achieved in that direction. Something along the lines of the Automotive Products roll-free self-levelling suspension mentioned in an earlier chapter could well prove considerably more effective.

Finally, I envisage significant improvements in transmissions. The possibility of an infinitely variable automatic system does not seem too remote in view of the research and development taking place in the general automotive field. One such system did, in fact, appear during 1972 and it seems to have much the same level of mechanical efficiency as a manually controlled gearbox. It was not designed as a racing unit, but then neither was the DAF Variomatic which performed surprisingly well in a Formula 3 car during the late 1960s.

APPENDIX 1

The Terry cars

LT No.	Year	Designation	Engine	Type description
1	1957-8	Terrier Mark 1	Ford E93A 1,172 cc (side-valve)	Sports car, space-frame
2	1958-9	Terrier Mark 2	Ford 100E 1,172 cc (side-valve)	Sports car, space-frame
3	1960	Gilby A Type	Coventry Climax 1,100 cc	Sports car, space-frame
4	1960	Terrier Mark 4	Ford 105E 1 litre (ohv)	Formula Junior' space-frame
5	1961	Gilby B Type	Coventry Climax 1½ litre four and BRM 1½ litre V8	Formula 1, space-frame, mid-engine
6	1962	Terrier Mark 6	Ford 105E-based 1.2 litre four	Sports car, space-frame, mid-engine, crossover suspension
7	1962	Terrier Mark 7 (not built)	Austin 7 (side-valve)	750 Club, modified frame and transmission
8	1962	Terrier Mark 8 (for Alpine)	Gordini Renault 1½ litre	Sports car, based on Mark 6
—	1964-5	Kincraft (basic layout only by LT)	Ford 4.7 litre V8	*Formule Libre*, based on Gilby B Type
—	1965	Lotus 38 (90% Terry, 10% Chapman)	Ford 4.2 litre V8 Indy (4 ohc)	Indianapolis car, monocoque
9	1965-6	AAR Eagle	Coventry Climax 2.7 litre four, Gurney-Weslake 3 litre V12 and Ford 4.2 litre V8 (4 ohc)	Formula 1/Indianapolis, monocoque
10	1967	Shelby CanAm (TAC project)	Ford 5.7 litre V8	CanAm sports car, monocoque, crossover suspension
11	1967	BRM P126 (TAC project)	BRM 3 or 2½ litre V12	Formula 1/Tasman car, monocoque
12	1967-8	Gulf Mirage-BRM (first Design Auto project)	BRM 3 litre V12	Prototype sports car, monocoque
14	1969	Honda Formula 1 replica	Honda 3 litre V12	Formula 1, monocoque
15	1968-9	Terrier Mark 15	Chevrolet 5 litre V8	Formula 5000, monocoque
16	1968-9	Terrier Mark 16 (not built)		Formula 2, monocoque, generally similar to Mark 15
17	1968-9	Terrier Mark 17 (became Surtees TS5)	Chevrolet 5 litre V8	Basically as Mark 15
18	1968-9	BMW Formula 2	BMW 1.6 litre four	Formula 2, monocoque (modified to bathtub by Dornier)
19	1968-9	Gulf Mirage-Ford	Cosworth-Ford 3 litre V8	Prototype sports car, monocoque
20	1969-70	Leda Formula 5000	Chevrolet and Ford 5 litre V8s	Formula 5000, monocoque
21	1969-70	AAR Eagle Indianapolis	Offenhauser 2.7 litre four and Ford 4.2 litre V8	Indianapolis car, monocoque
22	1970	Leda Mark 2	Chevrolet and Ford 5 litre V8s	Formula 5000, monocoque
23	1970-71	LT23 (design project only - not built)	Offenhauser 2.7 litre four	Indianapolis car, monocoque
24	1971	LT24 (for Malaya Garage - prototype built)	Ford 3 litre V6	Road-going sports car, space-frame, mid-engine, side radiators
25	1971	LT25 or Leda Mark 3	Chevrolet 5 litre V8	Formula 5000, monocoque
26	1971-2	LT26 or McRae Leda (Graham McRae's basic specification)	Chevrolet 5 litre V8	Formula 5000, monocoque
27	1971-2	LT27 or McRae Leda replica (as modified by LT)	Chevrolet 5 litre V8	Formula 5000, monocoque
28*	1972	Leda/Tui FB/F2 (based on design by Allan McCall)	Ford-based fours	Formula B/2/3/A, monocoque
29*	1972	Leda/Tui FS-V (based on design by Allan McCall)	VW-based flat-fours	Formula Super-Vee, monocoque
30*	1972	Eifelland (design completed but not detailed)	Cosworth-Ford 3 litre V8	Formula 1, monocoque

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* LT28 and LT29, being designed originally by Allan McCall, involved only minor work by Terry, so have not been included in the model-by-model Terrier descriptions. LT30 may yet appear in a revised form so has not been described as originally conceived.

APPENDIX 2

Make-it-yourself guide to materials by usage

Component/ assembly	Required properties	Basic material	Form	Remarks*
Tubular chassis frames	Low weight, high strength and rigidity, weldability	Mild steel	Tubing	½-1½ in diameter (or square), 20-16 swg, ERW or solid-drawn
			Sheet	20-14 swg En2D
			Bar	En3B round
Sub-frames, bulkheads for monocoques	As above	As above	As above	As above, plus rectangular tubing for bulkheads
Panels for monocoques	Low weight, high strength, weldability for shaped panels	Aluminium alloy	Sheet	Inner panels: 20-16 swg HS-30WP or 2L-72 Straight outer panels: 16 swg HS-30WP or 2L-72 Shaped outer panels: 18-16 swg NS-4
Body panels and aerofoils	As above	Aluminium alloy	Sheet	18 swg NS-4
		Glass-reinforced plastics	Mouldings	May be reinforced with carbon fibres (expensive) if highly stressed
Hub spindles	Low weight, high strength and rigidity	Alloy steel	Bar or forging	En24 fully heat-treated to 'V' condition minimum (60-65 tons/sq in)
		Titanium	As above	**Extremely costly at present, so used only for Formula 1 or similar cars**
Hub carriers (uprights)	As above, plus weldability for fabrications	Magnesium	Cast	Various grades used; L122 is the most common
		Aluminium alloy	Tube, bar and sheet	Most suitable is NT/E/S-6
		Steel	Tube	Solid-drawn
			Bar	En3B
			Sheet	18-16 swg En2D
Wishbones, suspension links, anti-roll-bar drop links, track rods, pedals etc.	As above	Mild steel	Tube	¼ - 1 in diameter, 20-16 swg, ERW or solid-drawn
			Bar	En3B round
			Sheet	20-12 swg En2D
		Titanium	Tube, bar and sheet	See previous comment
Pivot pins, yoke pins, ball posts etc.	Low weight, high strength and rigidity	Mild steel	Bar	En24T or En16T; En8 can be used for ball posts welded into uprights
		Titanium	Bar	See previous comment
Water pipes	Low weight, corrosion resistance	Aluminium alloy	Tube	18-16 swg Nt-4
		Stainless steel	Tube	24-20 swg 'ordinary' grade

*Normal British specifications only are quoted in this column; to include all comparable specifications from other countries would require a second volume!

APPENDIX 3

Specialist suppliers of components and materials

The main problem in compiling a 'buyer's guide' of this kind is deciding where to stop. In order to keep the list down to reasonable proportions we have therefore limited it to those companies covered by Terry's own experience, and we apologise to the many others who may feel that they should have been included.

In this connection, it is worth pointing out that the *FIA Yearbook of Automobile Sport* contains an extensive directory of suppliers; this useful booklet, which was mentioned in Chapter 13 in connection with 'flexible fuel cells', can be obtained from Patrick Stephens Ltd, Bar Hill, Cambridge. The advertisement pages of the various motor-sporting magazines also can be helpful in locating sources of components.

For general materials and services, consult the Yellow Pages of your local telephone directory under the appropriate headings - Aluminium/Steel Stockists, Engineers' Supplies, Sheet-Metal Workers etc.

Adhesives

Araldite epoxy adhesives CIBA-Geigy (UK) Ltd, Duxford, Cambridgeshire. Tel. 022-03.2121.

'Aircraft' bolts

Aircraft Materials Ltd, Midland Road, London NW1. Tel. 01-387.6151.

Anchor nuts and bushes

Precision Screw & Manufacturing Co. Ltd, Longacres Industrial Estate, Willenhall, Staffordshire WV13 2JS. Tel. 0902-65621.

Armoured hose and couplings

Aeroquip hose Trist, Draper Ltd, 816-8 Bath Road, Brislington, Bristol BS4 5LH. Tel. 0272-77093.
Couplings Avimo Ltd, Taunton, Somerset. Tel. 0823-81071.

Batteries - aircraft dry type

Varley Dry Accumulators Ltd, Alfred's Way, Barking, Essex. Tel. 01-594.3346.

Bearings - flexible

Howard Clayton-Wright Ltd, Wellesbourne, Warwickshire. Tel. 0789-4222.
Dunlop Ltd, Polymer Engineering Division, Evington Valley Road, Leicester LE5 5LY. Tel. 0533.730281.

Bearings - rolling-element

Ball and roller RHP Ltd, PO Box 7, Chelmsford, Essex CM1 1PU. Tel. 0245-61722.
Needle-roller INA Bearing Co. Ltd, Llanelli, Carmarthenshire. Tel. 055-42.2288.
Needle-roller The Torrington Co. Ltd, Torrington Avenue, Coventry, Warwickshire. Tel. 0203-74241.

Bearings - spherical

Ampep Industrial Products Ltd, Clevedon, Somerset. Tel. 02757-3771.
Rose Forgrove Ltd, Saxilby, Lincolnshire LN1 2LW. Tel. 0522-702451.

Brakes

Lockheed Hydraulic Brake Co. Ltd, Automotive Products Group, Tachbrook Road, Leamington Spa, Warwickshire. Tel. 0926-27000.
Girling Ltd, Kings Road, Tyseley, Birmingham 11. Tel. 021-706.3371.

Circlips

Anderton Springs Ltd, Bingley, Yorkshire. Tel. 097-66.5121.
Automotive Engineering Ltd, The Green, Twickenham, Middlesex. Tel. 01-894.1161.

Salterfix Ltd, Spring Road, Smethwick, Warley, Worcestershire. Tel. 021-553.2929.

Clevis pins and clips
Springfix Ltd, 35 Kentish Town Road, London NW1. Tel. 01-485.7641.

Clutches
Borg & Beck Co. Ltd, Automotive Products Group, Tachbrook Road, Leamington Spa, Warwickshire. Tel. 0926-27000.

Coil springs
International Spring Co. Ltd, 41 Roundwood Road, London NW10. Tel. 01-459.3344.
Park Spring Co. Ltd, Park Works, Foley Street, Sheffield 4. Tel. 0742-20031.

Drive-shafts
BRD Co. Ltd, Red House Industrial Estate, Aldridge, Staffordshire. Tel. 0922-53371.
Hardy Spicer Ltd, Chester Road, Birmingham B24 0RB. Tel. 021-373.2191.
(Both these companies are members of the GKN Birfield Transmission Division.)

Electrics
Joseph Lucas Ltd, Great King Street, Birmingham B19 2XF. Tel. 021-554.5252 (extension 269).

Engines
Cosworth Engineering Ltd, St James Mill Road, Northampton NN5 5JJ. Tel. 0604-51802.

Fasteners
General Carr Fastener Co. Ltd, Frederick Road, Stapleford, Nottingham. Tel. 0602-39.2828.
Aircraft type for panels Dzus Fastener Ltd, Farnham Trading Estate, Farnham, Surrey. Tel. 025-13.4422.

Fire extinguishers
Intercontinental Equipment Corporation, 6 North Lane, Aldershot, Hampshire. Tel. 0252-314746.
Sicli Fire Extinguishers, 49 Church Street, Maidstone, Kent. Tel. 0622-65172.

Fuel caps – flush-fitting
Shaw Aero Devices, Industrial Road, East Hampton Airport, East Hampton, New York, USA.

Fuel cells – flexible
FPT Industries Ltd, The Airport, Portsmouth, Hampshire. Tel. 0705-62391.
Marston Excelsior Ltd, Wobaston Road, Fordhouses, Wolverhampton WV10 6QJ. Tel. 090-78.3361.

Fuel pumps
Bendix Motor Books & Accessories, 33 St Martin's Court, London WC2N 4AL. Tel. 01-836.5376.

Gearbox and final-drive units
Hewland Engineering Ltd, Boyne Valley Road, Maidenhead, Berkshire. Tel. 0628-32033.
Metso Transmissions, 38 Murray Mews, London NW1. Tel. 01-267.0779.
Zahnradfabrik Friedrichshafen AG, 799 Friedrichshafen, West Germany.

Instruments
Smiths Industries Ltd, Motor Accessory Division, Cricklewood, London NW2 6NN. Tel. 01-452.3333.

Magnesium
Magnesium Elekton Ltd, PO Box 6, Lumms Lane, Clifton Junction, Swinton, Manchester. Tel. 061-794.2511.

Non-return valves – fuel-line
Flight Refuelling Ltd, Wimborne, Dorset. Tel. 020-125.2121.

Oil seals and O-rings
Pioneer Oilsealing & Moulding Co. Ltd, Barrowford, Nelson, Lancashire. Tel. 0282-62241.
Charles Weston & Co. Ltd, Douglas Green, Pendleton, Salford, Lancashire M6 6FT. Tel. 061-736.5811.
Metal/nylon oil seals Ring-Belt Ltd, 42-8 Adelaide Street, St Albans, Herts. Tel. 0727-65118.

Over-centre latches
Protex Fasteners Ltd, Arrow Road, Redditch, Worcestershire. Tel. 073-92.3231.

Perspex windscreens
Suntex, Thorney Lane, Iver, Buckinghamshire. Tel. 0895-34970.
White Ellerton, Kings Yard, Moxon Street, Barnet, Hertfordshire. Tel. 01-449.3840.

Pip-pins
Avdel Ltd, Welwyn Garden City, Hertfordshire. Tel. 07073-28161.

Plastic hose
Griflex Products Ltd, 3 Vere Street, London W1. Tel. 01-493.8741.

Propeller shafts
BRD Co. and Hardy Spicer - see under Drive-shafts.

Radiators
Aluminium, for oil Marston Excelsior Ltd - see under Fuel cells.
Water and oil Serck SMS Co. Ltd, Coronation Road, London NW10. Tel. 01-965.5442.

Rivets
Avdel Ltd - see under Pip-pins.
Pop-rivets George Tucker Eyelet Co. Ltd, Walsall Road, Birmingham B42 1BP. Tel. 021-356.4811.

Safety harness
Britax (London) Ltd, Chertsey Road, Byfleet, Surrey. Tel. 093-23.41121.

Skin clamps - bodywork
Avdel Ltd - see under Pip-pins.

Spherical joints
Ampep Industrial Products Ltd - see under Bearings - spherical.

Steering mechanism - rack-and-pinion
Chinell Ltd, 1A Pickford Road, Bexleyheath, Kent DA7 4AT. Tel. 01-304.2576.
C T Wooler (Engineers) Ltd, 3B West Way, Walworth Trading Estate, Andover, Hampshire. Tel. 0264-4904.

Suspension units - spring-and-damper
Armstrong Patents Ltd, Gibson Lane, Melton, North Ferriby, Yorkshire HU14 3HY. Tel. 0482-633311.
Spax Ltd, 61 Fortess Road, London NW5 1AD. Tel. 01-485.6721.
Koni units J W E Banks & Sons Ltd, St Guthlac's Lodge, Crowland, Peterborough PE6 OJP. Tel. 073-17.316.

Throttle controls - push-pull
Morse Controls Ltd, 2nd Drove, Fengate, Peterborough, Northants. Tel. 0733-67191.

Titanium
Titanium Metals & Alloys Ltd, 2 Metal Exchange Buildings, London EC3. Tel. 01-626.4521.

Tyres - racing
Dunlop Ltd, Fort Dunlop, Erdington, Birmingham B24 9QT. Tel. 021-373.2121.
Firestone Tyre & Rubber Co. Ltd, Great West Road, Brentford, Middlesex. Tel. 01-560.4141.
Goodyear Tyre & Rubber Co. Ltd, Bushbury, Wolverhampton WV10 6DH. Tel. 0902-22321.

Universal joints

Gearshift and steering column Mollart Engineering Co. Ltd, Hook Rise South, Kingston By-Pass, Surbiton, Surrey. Tel. 01-397.4333.

Gearshift and steering column Motor Gear & Engineering Co. Ltd, Essex Works, Chadwell Heath, Essex. Tel. 01-590.7788.

Steering column The Torrington Co. Ltd (Universal Joints Division) - see under Bearings - rolling-element.

Transmission - Hooke and constant-velocity BRD Co. and Hardy Spicer - see under Drive-shafts.

Transmission - Metalastik Dunlop Ltd, Polymer Engineering Division - see under Bearings - flexible.

Wheels - magnesium

Magnesium Elektron Ltd - see under Magnesium.

Tech Del Ltd, 32-4 Telford Way, London W3 7XD. Tel. 01-734.0103.

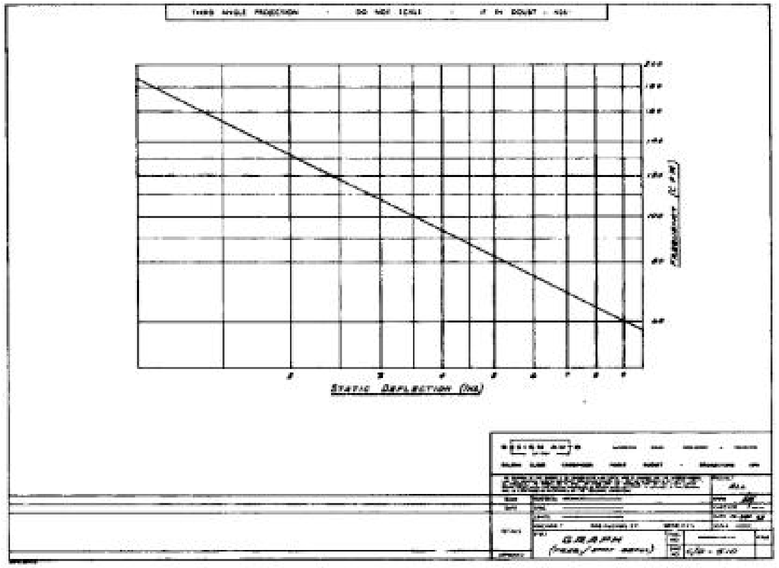
APPENDIX 4

Road-spring calculations

The main factor governing the calculations for a coil-type road spring is the frequency, so this figure must be determined at the outset. It is in fact the only valid basis for comparison between the springing of different cars, owing to the many variations involved - overall, sprung and unsprung weights, weight distribution and mechanical advantage, for example.

In the interest of keeping the wheels in contact with the road, frequencies should be kept as low as possible. However, low frequencies are synonymous with soft suspension so, as usual, a compromise has to be reached. The normal practice is to have the rear frequency 5-10 cycles per minute higher than that at the front, in order to minimize pitching.

Because of the advent of aerofoils and other negative-lift devices providing a considerable increase in dynamic weight without raising the static weight, the frequencies currently used tend to be much higher than previously; typical figures



for a Formula 1 car are in the region of 115 cycles front and 125 cycles rear. For a 'wingless' vehicle, though, they would be reduced to about 90/100 or even less. Reference to the accompanying graph of frequency against static deflection shows that the higher frequencies give a static deflection of only 2½ in or so, while the lower provide around 4 in.

To show how the designer arrives at spring rates from the chosen frequency figures and other data, here is an example of the calculations involved – in fact those for the LT27 Formula 5000 car of 1972:

From previous experience, frequencies of 118F/125R were adopted, and the overall weight and weight distribution were estimated at 1600 lb and 37/63 per cent respectively; the latter gave front and rear weights of 590 lb and 1010 lb. Subtraction of the estimated unsprung weights (130 lb at both front and rear) resulted in sprung weights of 460 lb (230 per side) at the front and 880 lb (440 per side) at the rear.

From the simple suspension-geometry drawings, the relationship between wheel movement and suspension-unit movement was plotted, indicating mechanical advantages (leverages) of approximately 1.87 front and 1.36 rear. These figures in turn gave the static loadings on the actual springs, as follows:

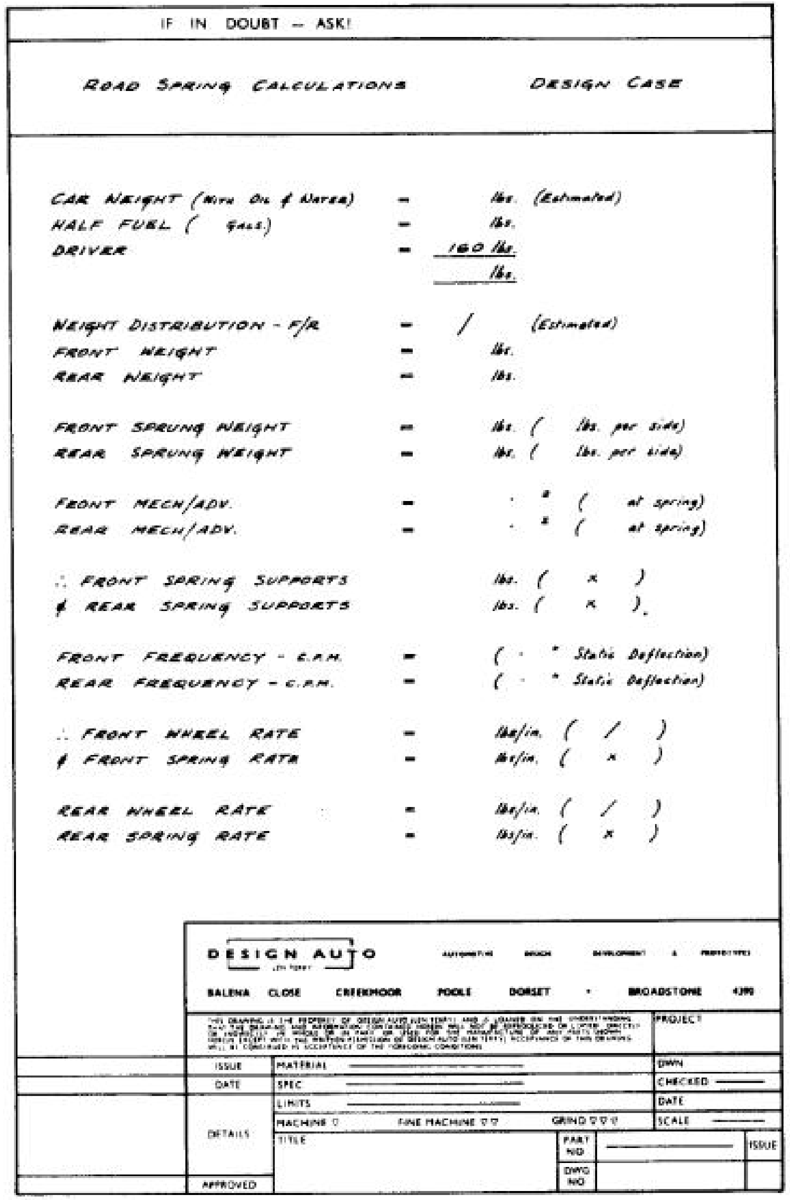
Front 230 × 1.87 = 430 lb
Rear 440 × 1.36 = 600 lb.

The graph indicated that our chosen frequencies provided static deflections of 2.6 in at the front and 2.25 in at the rear. From the sprung weights we were therefore able to calculate the wheel rates:

Front 230 ÷ 2.6 = 89 lb/in
Rear 440 ÷ 2.25 = 195 lb/in.

Our actual spring rates could now be calculated by multiplying each wheel rate by the *square* of the relevant mechanical advantage. Since the reason for this squaring may not be obvious, a few words of explanation are desirable:

Assume a simple lever with a 2:1 ratio and a load of 100 lb applied at the end of the longer arm, resisted by a spring at the other end. If the application of the load moves that end of the lever ½ in, then the other end moves ¼ in and the spring force is 200 lb.



IF IN DOUBT — ASK!

ROAD SPRING CALCULATIONS   DESIGN CASE

CAR WEIGHT (WITH OIL & WATER) = lbs. (Estimated)
HALF FUEL (GALS.) = lbs.
DRIVER = 160 lbs.
lbs.

WEIGHT DISTRIBUTION - F/R = / (Estimated)
FRONT WEIGHT = lbs.
REAR WEIGHT = lbs.

FRONT SPRUNG WEIGHT = lbs. (lbs. per side)
REAR SPRUNG WEIGHT = lbs. (lbs. per side)

FRONT MECH/ADV. = · ² (at spring)
REAR MECH/ADV. = · ² (at spring)

∴ FRONT SPRING SUPPORTS lbs. (×)
& REAR SPRING SUPPORTS lbs. (×).

FRONT FREQUENCY - C.P.M. = (· " Static Deflection)
REAR FREQUENCY - C.P.M. = (· " Static Deflection)

∴ FRONT WHEEL RATE = lbs/in. (/)
& FRONT SPRING RATE = lbs/in. (×)

REAR WHEEL RATE = lbs/in. (/)
REAR SPRING RATE = lbs/in. (×)

DESIGN AUTO

BALENA CLOSE CREEKMOOR POOLE DORSET · BROADSTONE

ISSUE	MATERIAL		DWN
DATE	SPEC		CHECKED
DETAILS	LIMITS		DATE
	MACHINE ▽ FINE MACHINE ▽▽ GRIND ▽▽▽		SCALE
	TITLE	PART NO	ISSUE
APPROVED		DWG NO	

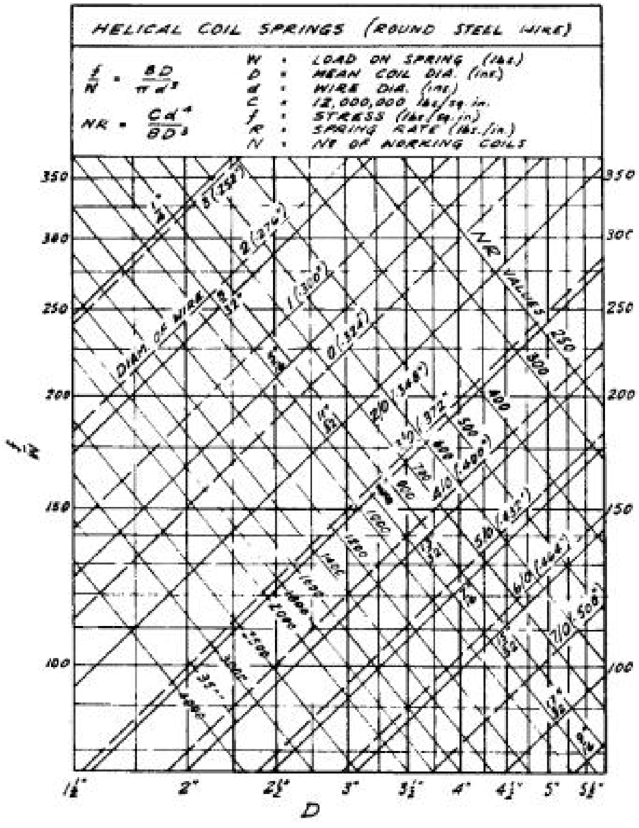
PROJECT

Rate at loaded end $100 \div \frac{1}{2} = 200$ lb/in
Rate at spring end $200 \div \frac{1}{4} = 800$ lb/in.

The ratio of spring rate to loading rate is therefore 4:1 which is the square of the mechanical advantage.

Returning to the LT27, we had
Front spring rate $89 \times 1.87^2 = 314$ lb/in
Rear spring rate $195 \times 1.36^2 = 361$ lb/in.

In practice, springs are usually available in 5 lb/in steps at this level, so we chose components of 315 and 360 lb/in as our starting point. It is noteworthy that, although the wheel rates bear some relationship with the front and rear sprung rates, the same cannot be said of the actual spring rates because of the different mechanical advantages of the two suspension geometries.



APPENDIX 5

Torsion-bar calculations

Reference was made in Chapter 12 to the weight-saving possibility of using steel tubing instead of rod for anti-roll bars – or any other torsion-bar spring of reasonable size, for that matter. For the mathematically inclined, the relevant design equations for round-section bars of both types are given below, and they are followed by an example with different values from those quoted in Chapter 12.

Solid bars	**Hollow bars**
a. Maximum torsional shear stress:	
$S = \dfrac{16\,T}{\pi D^3}$	$S = \dfrac{16TD}{\pi(D^4 - d^4)}$
b. Angle of twist:	
$\theta = \dfrac{584\ TL}{GD^4}$	$\theta = \dfrac{584\ TL}{G(D^4 - d^4)}$
$\theta = \dfrac{114.6\ SL}{GD}$	$\theta = \dfrac{114.6\ SL}{GD}$
c. Spring rate:	
$R = \dfrac{GD^4}{584\ L}$	$R = \dfrac{G(D^4 - d^4)}{584\ L}$
d. Energy-storage capacity:	
$E = \dfrac{S^2}{4G}$	$E = \dfrac{S^2\,(D^2 + d^2)}{4GD^2}$

Where
D = outside diameter (inches)
d = inside diameter (inches)
G = modulus of rigidity (lb/sq in)
L = effective length of bar (inches)
R = spring rate (lb in/deg)
S = maximum torsional shear stress (lb/sq in)
T = applied torque (lb in)
θ = angle of twist (degrees)
E = energy storage capacity (in lb/cu in)

Let us consider these two bars:

a. Solid - $\frac{3}{4}$ in diameter
b. Hollow - $\frac{7}{8}$ in outside diameter x 14 swg (0.080 in wall thickness)

If we take
$T = 2500$ lb in,
$L = 30$ in
and
$G = 11\,500\,000$ lb/sq in,

then for a,
$S = 30\,200$ lb/sq in approx,
$\theta = 12.3$ deg approx,
while for b,
$S = 34\,200$ lb/sq in approx.
$\theta = 11.9$ deg approx

These figures indicate that the hollow bar is slightly the stiffer of the two and its shear stress is a little higher. However, both these stresses are well within the capacity of good-quality mild-steel, and the two bars would give a spring rate of around 150 lb/in at the end of a 9 in lever arm.

Weights are of course proportional to cross-section areas, as follows:

W_a proportional to πD^2
$= \pi \times 0.75^2 = 1.77$ approx.
W_b proportional to $\pi(D^2 - d^2)$
$= \pi(0.875^2 - 0.715^2)$
$= \pi \times 0.254 = 0.8$ approx.

Therefore weight saving of tubular torsion bar
= 55 per cent approx.

APPENDIX 6

Chassis torsional-stiffness testing

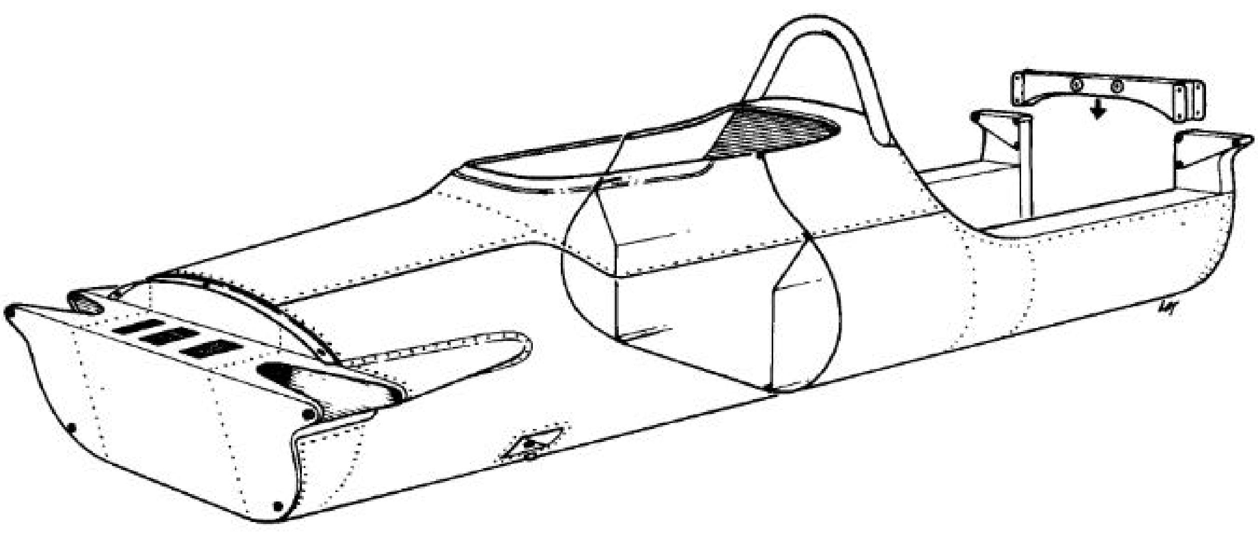
Determining the torsional stiffness of a chassis - whether a monocoque or a space-frame structure - is relatively simple if carried out by the following method:

First, one end of the chassis is firmly attached (using the suspension-unit anchorage points) to a rigid jig, and the other end is rested on a fulcrum positioned on the chassis centre-line. Ideally, the chassis-building jig should be used for this purpose, and a piece of solid round metal bar can form the fulcrum.

At the 'free' end of the chassis, a substantial bar is then loosely bolted across the other pair of suspension-unit pick-ups, with up to 10 ft (3 metres) projecting on one side. An inclinometer is placed on this bar, at the chassis centre-line, and its reading noted.

At an exact, predetermined distance out from the centre-line (10 ft is a convenient figure for calculation purposes) the bar is loaded until the inclinometer shows a reading of plus 1 deg over its original reading. Provided that the chassis has been really firmly fixed, the chassis has now been torsionally deflected over its working length by that 1 deg. Multiplying the loading by the arm length gives the torsional stiffness in pounds-feet or kilogramme-metres per degree. The loose bolting-on of the loading bar prevents the imposition of any undue restraint on the twisting of the structure.

Should the test cause the chassis to distort permanently - or to break - it was not strong enough anyway, so back to the drawing board and the slide-rule!



For stiffness/weight reasons, Terry has long preferred the full monocoque to the 'bathtub' type with removable top. The Lotus 38, Eagle, BRM P126 and Surtees TS5 all had full monocoques of the general design shown here

RACING CAR DESIGN AND DEVELOPMENT

Dialogue between one of the world's most experienced racing car designers and a technical author-graduate engineer on the theory and technique of racing car design and development.

Contents include: The anatomy of a racing car designer; biography of Len Terry; description of nearly 30 Terry designs from clubman's sports car to Indianapolis winner; a blank sheet of paper; handling characteristics; the theoretical aspects; oversteer and understeer; practical implications; structural considerations; space-frames and monocoques; the cockpit area; the structural engine; progress and legislation; suspension; changing needs and layouts; the torsion bar; self-levelling systems; anti-dive and anti-squat; progressive-rate springing; stiffness/weight ratio; brakes, wheels and tires; influence of smaller wheels; twin-disc brake systems; attention to details; low-profile tire phenomena; aerodynamics; wings and things; intake ram effect; ground effect vehicles; the cooling system; radiator location; cooling the oil; safety and comfort; primary and secondary safety; driver comfort; materials; components—ball joints, batteries, brakes, clutches, dampers, drive-shafts, electrics, flexible bearings, flexible fuel cells, gearshift linkages, instruments, non-return valves, non-spill fuel fillers, oil and fuel pipes, Perspex mouldings, radiators, springs and steering gear; design versus development; the competition—nine other racing car designers discussed; future developments.


Len Terry


Alan Baker

Authors: **Len Terry** has been designing racing cars since 1957. In addition to his own Terrier cars he has designed for Lotus, Eagle, BRM, Surtees, Honda and Leda. **Alan Baker** B Sc is former managing editor of *Automotive Design Engineering*, now freelance author, journalist and engineering consultant.

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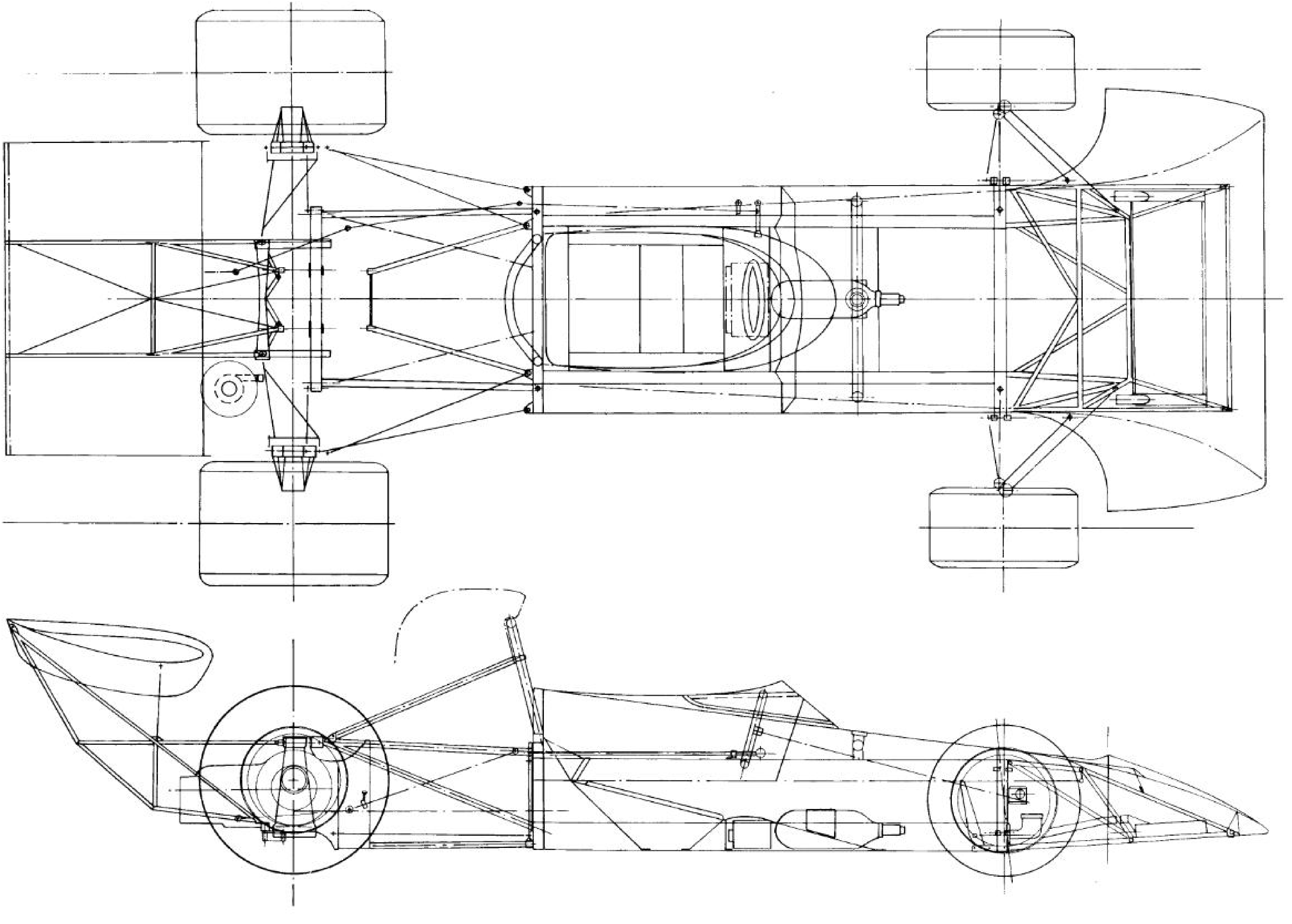
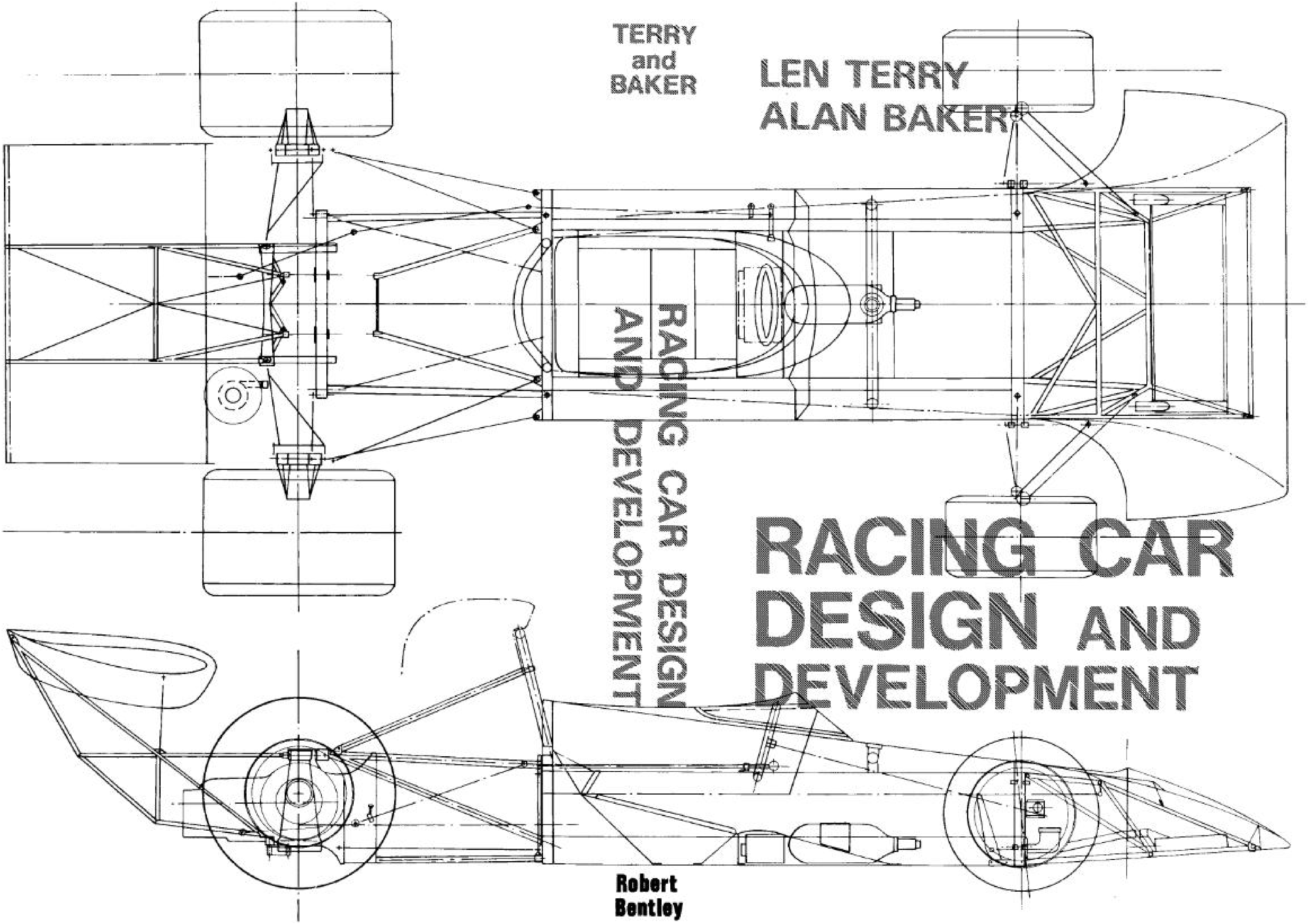
Volkswagen Fastback and Squareback Official Service Manual Type 3: 1968–1973
Volkswagen Dasher Service Manual: 1974–1979
Volkswagen Rabbit Diesel Service Manual: 1977–1980
Volkswagen Rabbit/Scirocco Service Manual: 1975–1979. Gasoline Models
Volkswagen Rabbit/Scirocco Service Manual: 1980. Gasoline Models
Toyota Corolla 1600 Service Manual: 1975–1979
Audi Fox Service Manual: 1973–1979
Capri Complete Service Manual: 1970–1975
Complete Official Triumph TR2 & TR3: 1953–1961
Complete Official Triumph TR4 & TR4A: 1961–1968
Complete Official Triumph GT6, GT6+ & GT6 Mk III: 1967–1973
Complete Official Triumph TR6 & TR250: 1967–1976
Complete Official Triumph Spitfire Mk III, Mk IV & 1500: 1968–1974
Complete Official Triumph Spitfire 1500: 1975–1980
Complete Official Triumph TR7: 1975–1978
Complete Official Austin-Healey 100-Six and 3000: 1956–1968
MG Workshop Manual: Complete Tuning and Maintenance for All Models from "M"-Type to TF 1500
Complete Official MGB: 1962–1974
Complete Official MGB: 1975–1980
Complete Official Jaguar "E"
Complete Official 948cc and 1098cc Sprite/Midget
Complete Official 1275cc Sprite/Midget: 1967–1974
Complete Official MG Midget 1500: 1975–1979





TERRY
and
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RACING CAR DESIGN
AND DEVELOPMENT

**Robert
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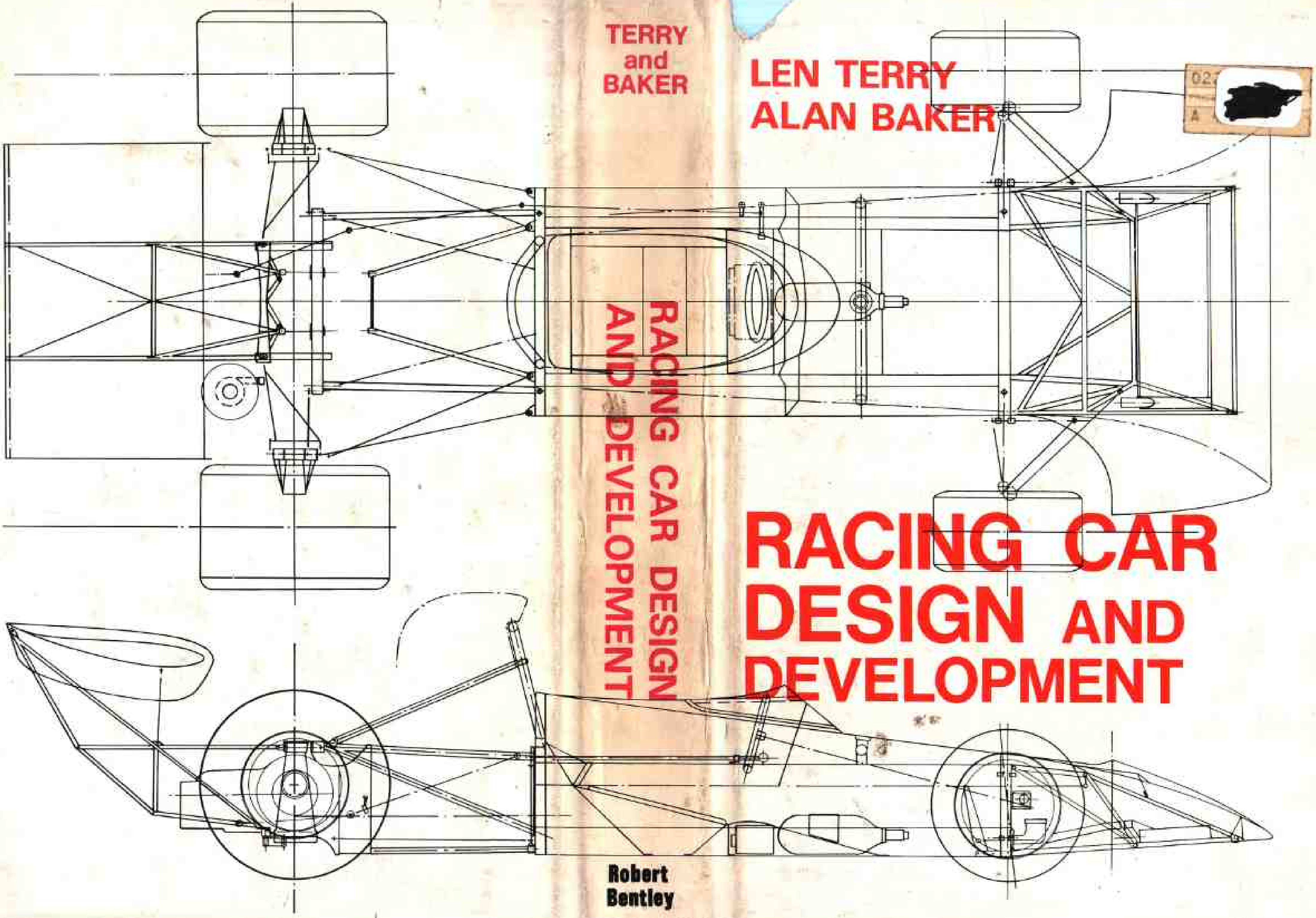

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