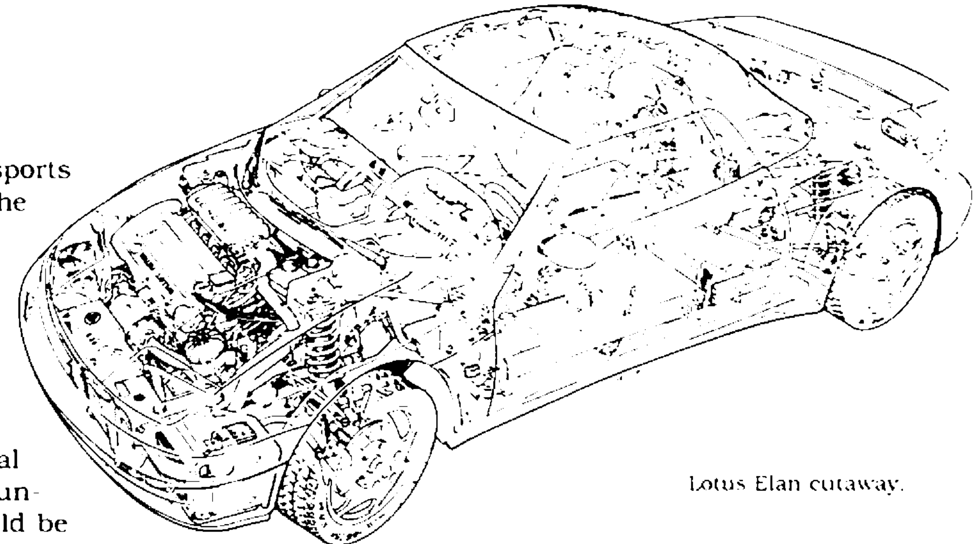
GLOBAL VIEWPOINTS

Britain's return to sports cars

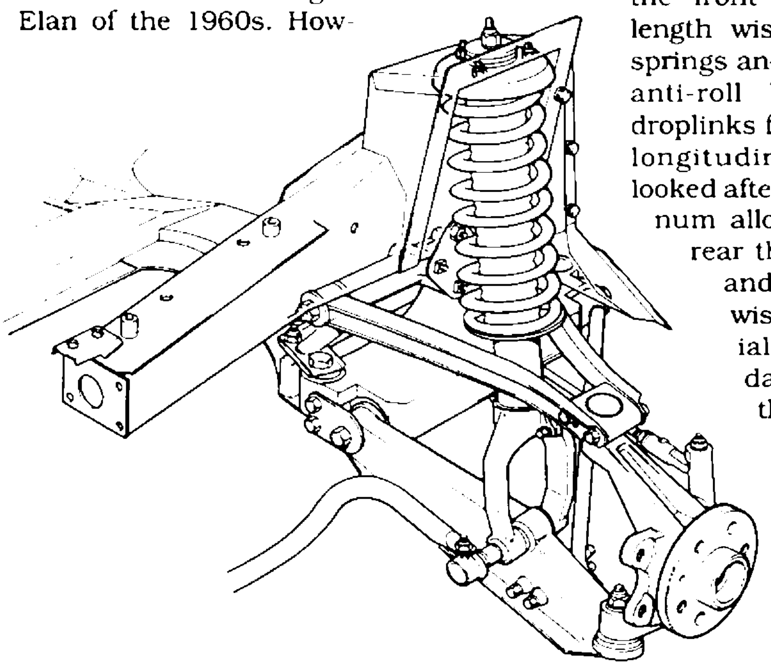


Lotus Elan cutaway.

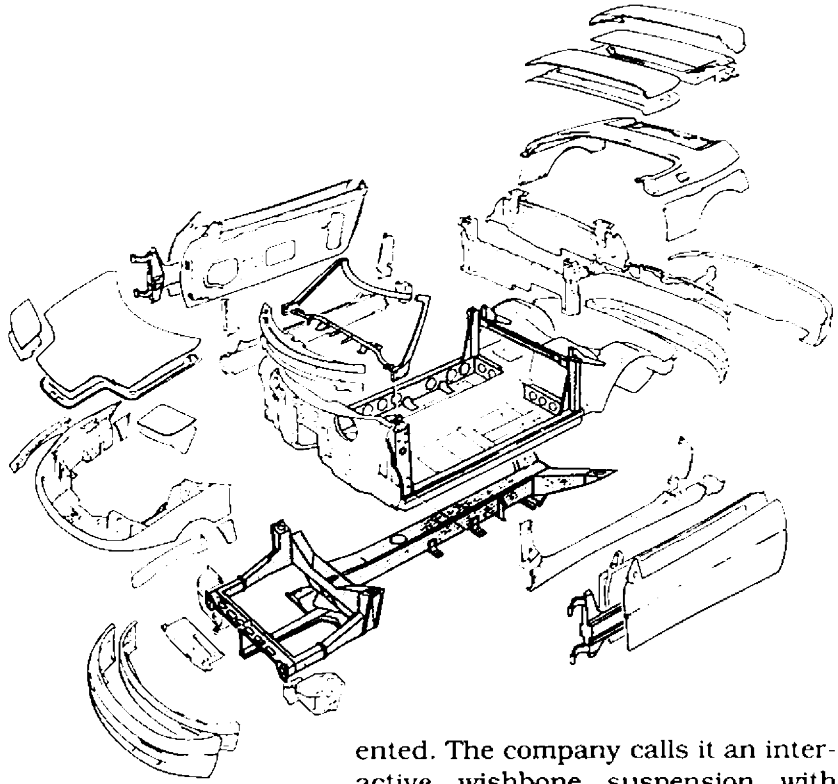
Design of small, two-seater sports cars was once a strength of the British motor industry. Their particular heyday lasted through the 1950s and 1960s when models such as the Austin-Healey 3000, MGA, MGB, MGC and MG Midget, Triumph TR series, Triumph Spitfire, and several others demonstrated that fairly unsophisticated mechanicals could be ed to create an inexpensive and enjoyable vehicle. But for reasons which included the effect of the U.S. DOT, the dollar/Sterling ratio, and the decline of the British motor industry, sports car production in the UK dwindled rapidly.

But now the situation has changed. Lotus has revealed its curvaceous new Elan, a 1.6-L, all-independently-sprung two-seater that fits closely the popular view of the British sports car. It is ironic that the car should emerge this year, just a few months after the Mazda MX-5 Miata, the exterior of which reflects the original Lotus Elan of the 1960s. However, in many ways the new Elan is a very different machine from its predecessor of a quarter century ago. Lotus, now part of General Motors, has opted for an Isuzu engine (with some Lotus input) in two forms: fuel-injected (but naturally aspirated) producing 97 kW at 7200 rpm, and a turbocharged and intercooled unit with 123 kW at 6600 rpm. Performance claims for the faster car include a 0-100 km/h time of 7.2 s and 220 km/h top speed.

Lotus is particularly proud of the car's all-independent suspension. At the front there are unequal-length wishbones, coaxial coil springs and dampers, a tubular anti-roll bar positioned via droplinks from the chassis, and longitudinal compliance is looked after by individual aluminum alloy subframes. At the rear there is an upper link and wide-based lower wishbone system, coaxial coil springs and dampers again — but this time, a solid anti-roll bar via droplinks from the chassis. The system is described by Lotus as representing "new technology" and it has been pat-

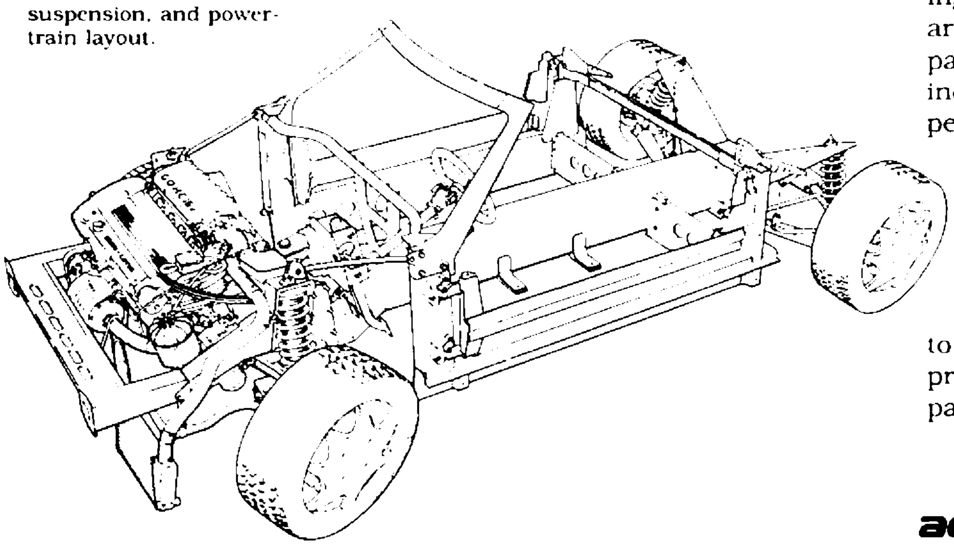


Lotus Elan left-hand suspension.



Lotus Elan body components, steel sub-structure shaded grey.

Lotus Elan chassis, suspension, and powertrain layout.



ented. The company calls it an interactive wishbone suspension with each front suspension assembly mounted on a separate raft manufactured from heat-treated aluminum alloy. Lotus says the raft allows use of very stiff bushes for the wishbones to give accurate wheel control, without excessive road noise being transmitted to the structure. It also allows a very low caster angle to lessen steering effort and longitudinal wheel compliance without handling changes, and helps reduce torque steer. Suspension geometry is designed to give what Lotus describes as virtually constant roll centre heights relative to the chassis or ride level of about 30 mm front and 60 mm rear, regardless of vehicle roll angle.

The 1588-cc twin-cam, 16-valve engine driving the front wheels is transversely mounted and has a cast iron block with aluminum pentroof cylinder head. Compression ratio is 10:1 for the naturally aspirated unit, 8.2:1 for the turbo. A Rochester fuel-injection system and Delco electronic engine control are used.

Traditionally, Lotus has used purely a steel backbone chassis but the Elan has a composite platform and backbone. The reason for this was the need for great rigidity. So the Elan body platform is a one-piece, 3-mm nominal-thickness Vacuum Assisted Resin Injection (VARI) moulding riveted and bonded to the steel reinforcing outriggers which are comprised of inner sill, toe board, heelboard, and A and B posts. When bolted to the steel backbone chassis, torsional stiffness is 8940 N•m/deg. The steel components contribute to the bending and torsional stiffness of the vehicle and also provide rigid attachment points for seat runners, lower seat mountings, and door hinges. Body panels are manufactured using the Lotus-patented VARI system which now incorporates a constant curing temperature to reduce production time, the need for which has resulted in the company's developing new resins with suppliers. Panel manufacture includes a new patented preform system which has allowed designers greater freedom to utilise sharp corners — something previously unattainable by the company.

ae —Stuart Birch

TELEFAX

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Subject:

Dear Herr Pelz,

During your recent visit to Lotus you expressed interest in the new Lotus Elan suspension system. I have obtained the attached paper which describes the concept in some detail.

Best regards,

C. Hodgson
Associate Director - Business Strategies

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New Suspension System for High Performance Front Wheel Drive Car

K. J. Sears, Lotus Engineering

ABSTRACT

THE NEW LOTUS ELAN is a 165bhp front wheel drive sports car. It may be the first example of a vehicle designed from the outset primarily as a sports car for which front wheel drive was selected, when there was free choice between front and rear wheel drive. This paper explains the reasoning behind this decision, and describes the technology of the new suspension system devised for the car.

THE REQUIREMENTS FOR THE NEW CAR were that it should maintain and enhance the Lotus heritage of outstanding roadholding, safety, ride comfort, controllability and feeling of security, and great 'fun to drive'.

Many factors were considered leading to the commitment to front wheel drive, which was a very big decision for the vehicle programme.

All Lotus vehicles before the new Elan are rear wheel drive, as are 'traditional' sports cars. However, Lotus, through engineering consultancy work for client companies had applied our traditional ride and handling development and tuning techniques to several front wheel drive series production cars, with results which indicated potential levels of performance significantly higher than had previously been imagined. It seemed that the benefits for which front wheel drive is renowned when applied to high production volume cars in small and medium size categories could be used in the regime where ultimate handling qualities and responsiveness are of greater relative importance, and where skillful and experienced drivers expect that the vehicle will allow them to fully exploit their expertise. This was confirmed during extensive testing programmes in all kinds of road conditions such as dry tarmac, wet tarmac, loose surfaces, snow and ice. The front wheel drive test vehicle proved consistently faster and more controllable than rear wheel drive comparator cars of similar or sightly greater power/weight ratio for all classes of driver including highly skilled high speed test drivers.

Two non-technical factors were the wide choice of basic powertrains (engine and gearbox) which could be developed to suit the vehicle, another was the observation that a large proportion of the potential owners and drivers of the new car may well never have driven rear wheel drive, and would feel more comfortable at high levels of road performance without the ultimate handling balance tendencies of rear wheel drive cars which tend to demand more highly developed driver skills to exploit the maximum vehicle potential.

Benefits of front wheel drive which are significant in this context include inherant general stability under almost all conditions, especially if traction grip is broken and particularly if this happens in a cornering manoeuvre.

This gave Lotus the initiative for the Elan performance driveability objective. Ninety percent of the performance should be achievable by ninety percent of drivers ninety percent of the time on the road.

SUSPENSION DESIGN

Front and rear suspensions were designed with mutually complementary characteristics, and suspension design was allowed relatively high priority in vehicle packaging considerations.

REAR SUSPENSION

The rear suspension is similar in concept to the well proven design used on the Lotus Excel. (Fig 1) It is a double wishbone geometry, but the upper link has almost no stiffness in the longitudinal (fore and aft) direction. The lower wishbone is pivoted to the chassis at two wide based isolating bushes, and to the hub bearing carrier at two points. It is thus able to control wheel steer alignment consistantly throughout suspension movement. Longitudinal compliance is provided by the lower wishbone twisting out of the horizontal plane when the rearward load at the wheel hub acts through the lever arm of the hub bearing carrier. Long link lengths allow accurate control of roll centre movement and minimise track change variations.

FRONT SUSPENSION

The design of the front suspension (Fig 2) reflects consideration of many factors, all of which are familiar to automotive design engineers. In this case however, particular importance was given to certain factors, which resulted in a novel solution to the design problem.

<u>General factors</u> (not in order of priority)
Integration into vehicle (Packaging).
Manufacturability
Ease of assembly
Cost-effectiveness
Unsprung mass

<u>Geometric characteristics</u>
Camber
Castor
KPI
Ground offset
Hub offset
Hub trail
Roll centre height
Anti-dive
Spring ratio (mechanical advantage)

<u>Kinematic characteristics</u>
Camber change
Castor change
Roll centre movement
Track change (scrub)
Toe steer
Lateral compliance
Longitudinal compliance

DESIGN PHILOSOPHY

The design philosophy was prioritised around idealised goemetric and kinematic characteristics, the most important being camber characteristic, roll centre height and movement, and minimum unsprung mass. These requirements indicated conclusively that a double wishbone geometry would be appropriate. Lotus has many years experience designing and developing such systems, and so was aware of the performance potential of this type, and the correct design rules to achieve this. However the total requirements for the suspension system for a contemporary, sophisticated prestige car also include provision at the design concept stage of system characteristics which will ensure high levels of ride comfort and isolation from road shocks. The classical double wishbone system mounted directly on the chassis frame cannot achieve this, without compromising geometrical accuracy and performance.

All kinds of suspension configuration were considered at the concept stage, but no other could provide the purity of geometry which was considered essential, for example although strut types provide compliance possibilities with small castor change, the roll centre movement characteristic is inappropriate. The double wishbone with very high top link can be a worthwhile solution, but for this car the packaging demands of the low hood line, and the desire for rigidity of the hub bearing carrier and other suspension links with absolute practical minimum unsprung mass ruled it out.

UNSPRUNG MASS

Unsprung mass has been confirmed on many occasions to have a major influence on ride comfort and road adhesion on bumpy surfaces. A wheel or even a ballast weight which increases hub mass by only 1kg has been repeatedly shown to make a noticeable detriment to ride quality.

SUSPENSION GEOMETRY.

Lotus experience provided information from which datum values for characteristics were chosen, and analysis performed. Because the vehicle target performance standards were particularly exacting, especially in subtle characteristics such as on-centre feel, linearity of response and tracking stability under random input conditions, great experience of correllation from predictive work was not available. Therefore a research vehicle was constructed by adapting an available car onto which the new suspension system was fitted. This provided a running test-bed for 'hands-on' evaluation. The vehicle used was a so-called 'hot hatch' front wheel drive car, with torsional and bending response frequencies and modes approximating to the targets for Elan. In fact target responses were modified as a result of experience with this vehicle. Important lessons were learned regarding the effects of structure responses on ride quality, especially at the higher levels of load input which result from tuning the suspension for a high degree of controllability and vehicle dynamic response. Following analysis of the acievements of the first, relatively conventional suspension system, the priorities for design of the definitive system were established. This resulted in a novel mechanical arrangement.

THE FUNDAMENTAL REQUIREMENT of the suspension characteristics is to maintain stability and consistency of the tyre/road contact patch. Ideally a fully Active suspension system is desireable for this, but the Elan is defined for a market sector where passive suspension is appropriate for reasons of cost and simplicity. As far as possible therefore the geometry of the suspension is arranged to ensure the smoothest possible transition through any variations of loading condition to which the system is subjected.

LONGITUDINAL COMPLIANCE.

It is established that contemporary standards of ride comfort and isolation from road shocks require accurately tuned longitudinal compliance. When attempting to provide this, the designer is faced with achieving the desired characteristic in two distinct loading conditions. The first is under driving forces when the suspension is subjected to a forward force at hub level (no torque input to hub bearing carrier). The second is during braking when the rearward force is effectively applied at the contact patch (with outboard mounted brakes as in this case which apply a wheel turning torque to the hub bearing carrier). Clearly these two conditions result in widely different reaction forces at the upper and lower connections of the hub bearing carrier.

CASTOR.

One of the most significant factors determined during early testing was the benefit of low values of castor angle, to ensure good linearity of steering response and good free steer stability. This results in good yaw damping with low magnitude reaction forces returning the steering to centre which prevents overshoot and tendency to oscillation.

LOTUS NOVEL SOLUTION

The solution named "INTERACTIVE WISHBONE TECHNOLOGY" introduces a means of providing longitudinal compliance which does not reduce the accuracy of the wishbone geometry, particularly insofar as castor angle is concerned. The wishbones inboard mountings are on a specially arranged subframe-like structure which Lotus engineers have called the "raft". (Fig 3) This is mounted to the vehicle by isolating elastomeric bushes of specifically tuned characteristics in such a way that it is able to accomodate controlled movement about an approximately vertical axis on the front axle line through the centroid of the inboard wishbone pivots. This allows the wheelhub to precess rearwards by rotation of the raft together with both wishbones, as viewed from above. The wishbone pivot bushes have low torsional rate but very high radial and axial rates. This is achieved by a special bush design with a cylindrical interleaf. The "raft" mountings strongly resist movement about any axis in the horizontal plane and thus maintain extremely good control of castor and camber alignment.

CAMBER.

The initial values selected for camber and camber change are based on previous experience and prove to be well judged. Static camber is set to ensure no positive camber within production tolerances and is adjustable to compensate for cumulative tolerances amongst components. Camber change on bump travel is calculated to provide a degree of compensation for vehicle roll on cornering and is minimised on droop (rebound) travel. (Fig 4) The desireability of negative camber in bump movement to compensate for vehicle roll in cornering and so maintain the outer wheels perpendicular to the road surface is unfortunately mutually exclusive with the desire for no camber change during single wheel bump movement in straight running conditions. The ultimate solution here is rollfree cornering but unless fully active suspension is available this is not practical with good overall ride comfort. The chosen characteristic is biased more towards stability on bumps than towards seeking the absolute maximum of lateral force capability on smooth test tracks. The tyres developed for the car ensure that there is no practical sacrifice of cornering ability on this account.

ROLL CENTRE HEIGHT

Front and rear suspensions were naturally considered together. Low roll centres provide freedom from the evils of jacking effect under lateral loading, but increase the roll moment on the vehicle body which has to be reacted by the springs and anti roll bars, and in the transient situation by damper effects. Low roll centres with long radius to the instantaneous centre of rotation of the suspension linkage are also compatible with low rates of camber change which are desireable for this application.

The movement of the roll centres with suspension travel also received very careful examination during the design of the suspension systems. Roll centre vertical movement is minimised, but allowed to fall slightly in roll. (Fig5).

KING PIN INCLINATION

Relatively low values of KPI are desireable in the interests of stable steering with well controlled reactions to changing road loads and shocks. There is often a conflict between achieving a low KPI with low ground offset whilst accomodating adequate brakes within the wheel envelope. Testing some quite radical arrangements revealed however that very good overall system characteristics could be achieved with attainable KPI at the same time without compromising the styling design opportunities for the outside (visual) face of the wheel.

HUB TRAIL

Hub trail is the offset of the wheel hub centreline rearwards of the steering axis. Hub trail creates a self aligning torque which combines with the similar effect of castor to give the steering system desireable self-centring characteristics, but in a way which avoids the rising steering efforts created by castor angle. Hub trail provides steering load increasing with lateral force, but independant of lock angle. This avoids the compromise between good feedback to the driver at high cornering rates and steering effort when parking which may become undesireably high.

GROUND OFFSET

Modern standards of tracking and braking stability and general insensitivity of steering to disturbing influences are achieved by arranging near-zero ground offset. The best overall system stability under almost all driving conditions is achieved with small negative values of ground offset, but the most satisfying steering feel under conditions of only small disturbing forces is achieved with moderate positive offset. The apparent compromise of zero offset is revealed by testing to be less satisfactory than either positive or negative offset when judged on the criterion of steering feel and sensitivity, and increases steering efforts for parking considerably. For the Elan the final choice was a small negative offset with other characteristics optimised to enhance steering response and feel to the level demanded for a truly sporting car.

HUB OFFSET

Hub offset is part of a set of geometrical relationships connecting KPI, ground offset and wheel rolling radius. An attraction of low KPI is that for a given ground offset a low hub offset is achieved which reduces the turning moment caused by driving force about the steering (king pin) axis.

ANTIDIVE

Some anti-dive characteristic is built in to the suspension geometry to preserve as consistently as possible the attitude of the car to the road under changing conditions of drive and braking. This is important particularly when soft springing is used in the interest of ride comfort, to maintain optimised aerodynamic and suspension behaviour for maximum vehicle stability under all conditions. As with other aspects of suspension design there is a conflict between different objectives here which must be resolved. To maintain invariant castor angle the axes of the upper and lower wishbone mountings must be parallel. If these axes are then aligned in a sense which will provide anti-dive tendencies the axes will be angled downwards to the front of the car. This means that the wheel hub will move forwards in bump travel which is directly contradictory to the requirement of longitudinal compliance for good ride comfort. If the wishbone axes are not parallel, castor angle will change with bump travel. There is some consolation in this situation however that under braking the reduction in castor due to nose-down pitching of the vehicle can be compensated by an increase in castor due to bump travel of the suspension. The preferred arrangement has 5deg inclination of the upper wishbone pivot axis, 1deg inclination of the lower wishbone pivot axis, giving 14% antidive effect. The wheel hub moves rearwards 4.mm in 70mm bump travel.

TRACK CHANGE

Track change is kept to a minimum especially in bump movement with only 2,7mm deviation through the total bump travel. Rather greater scrub movement is tolerated in rebound, up to 6,0mm decrease in track at maximum travel. (FIg6).

BUMP STEER

Bump steer has been confirmed to have a major influence on straight running ability particularly on roads with uneven kerb-side surface, a condition often found on minor roads. The bump steer characteristic has been tuned for this condition rather than the concomitant effect of roll steer as an aspect of handling behaviour in cornering manoeuvres. The bump steer effect which was chosen (Fig 7) to give optimum tracking stability creates a slight tendency to understeer with vehicle roll, but this is accurately compensated by the slight steer characteristic which results under lateral force at the tyre contact patch during cornering so that steering precision and cornering capability are not sacrificed.

SPRINGS AND DAMPERS

Good performance is normally achieved when the damper reacts to wheel movements with constant velocity ratio near unity.This can be very difficult to arrange within packaging limitations.In this case the springs and dampers are co-axial, so the spring has identical ratio. The ratio is very consistent throughout the suspension travel, enabling accurate tuning of the damper characteristics. The importance to total ride and handling of the exact values and characteristics of damper behaviour cannot be over-emphasised. Linear rate springs use tuned bump stops to provide a progressive increase in rate as maximum bump travel is approached. Spring loads are passed to the chassis structure through isolating rubber abutments. Suspension frequencies are lower at front than rear, as normal, front 1,2hz rear 1,34 which is in the ratio 1:1,2. The frequencies are relatively low for sporty cars, but not exceptionally so. This is very much the Lotus tradition where ride and handling qualities are achieved primarily through highly developed tyre and damper characteristics rather than by stiff springing.

ANTIROLL BARS

Antiroll bars are fitted to both front and rear suspension systems. The front bar is tubular, to reduce weight. Both bars are connected to their respective lower wishbones directly by ball joints, with almost no compliance. The connection to the vehicle chassis is through drop links with simple isolating bushes at both ends. Avoiding any lost motion or spurious reduction of stiffness in the antiroll bar system is most important to ensure accurate and consistant vehicle handling behaviour.

TYRES

One most important component of the suspension system has hardly been mentioned. This is the tyre. The tyre is itself a suspension system between the road and the vehicle wheel. It has its own characteristics of stiffness and damping in and around three axes all of which are in series with the characteristics of the vehicle suspension. Selection and development of the tyre must be an integral part of the development of the vehicle suspension and steering systems. This requires full back-up and commitment from the tyre manufacturer. This was absolutely true of the Lotus Elan.

ELASTOMERIC BUSHES

The final performance of the vehicle in terms of its suspension system is very much determined by the characteristics of elastomeric bushes and the degree to which they provide compliance stiffness and damping. This dissertation is not intended to describe in any detail the intricacies of such components but they are nonetheless as much part of the final result as the basic design characteristics. The most attractive handling qualities of the vehicle are in many ways the more subtle ones. For example, consistency of sensations to the driver in transient manoeuvres and at low but discernable levels of lateral force. Some unexpected subtleties were discovered during the development programme. Particularly notable is the dramatic effect that nuances of behaviour in the rear suspension have which affect steering feel and sensations which the driver has the impression are caused by the front suspension and steering. Tuning the side force steer characteristic of the rear suspension by quite small increments very markedly improves tracking stability and transient cornering behaviour. (Fig 8,9).

SUSPENSION PARAMETERS

	Front	Rear
Ride frequency (c/m)	72	80,5
Total travel (mm)	164	170
Bump travel (mm)	87	96
Castor (deg)	1,0	----
Camber (deg)	0,25	0,5
KPI (deg)	10,75	----
Ground offset (mm)	-3,0	----
Hub trail (mm)	5,0	----
Toe-in (deg)	0	0,6
Roll stiffness distr. (%)	55	45
Steering ratio	18,5:1	
Ackerman at 15deg lock (%)	45,6	
Tyre size	205/50x15	

CONCLUSION

The design and development of suspension systems for modern cars requires judgements of many conflicting parameters. Different types of car will require different relative weighting of the various factors. The decisions arrived at for the new Lotus Elan are the result of a focussed and far reaching programme of design study and experimental testing and development built on the extensive knowledge and experience of the design and development engineers. There is a saying in England that 'the proof of the pudding is in the eating'. For the Elan the proof is in the driving, which it is not possible to convey by the written or spoken word but the concensus of those who have driven the car is that the ambitious objectives have been completely achieved .

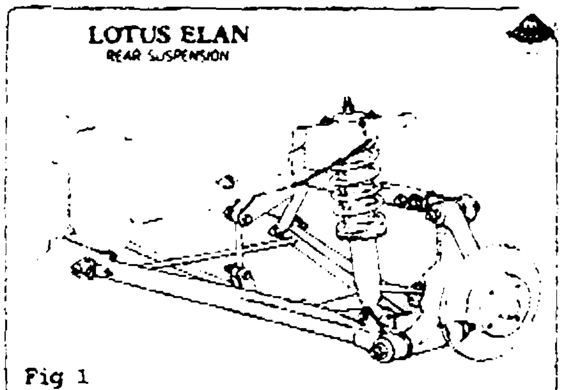

Fig 1

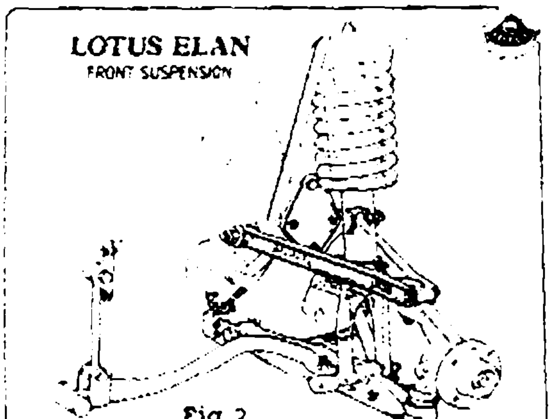

Fig 2

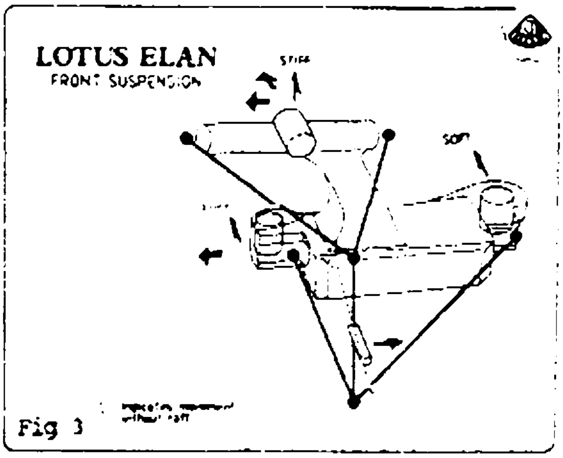

Fig 3

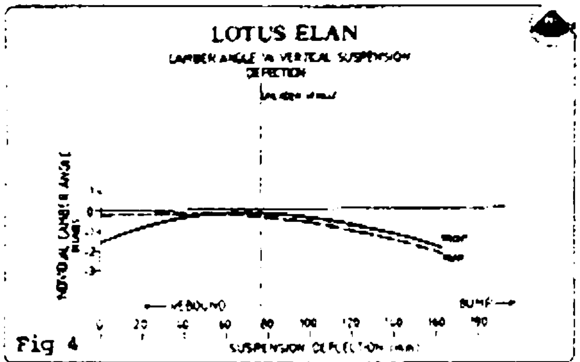

Fig 4

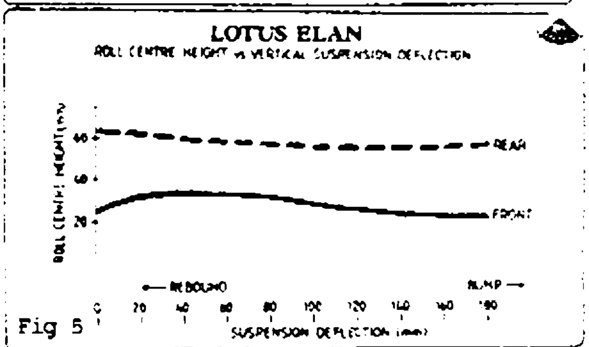

Fig 5

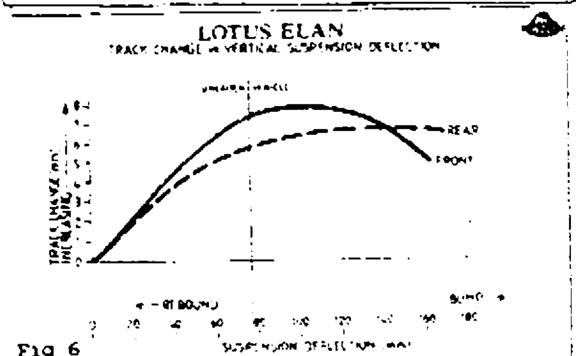

Fig 6

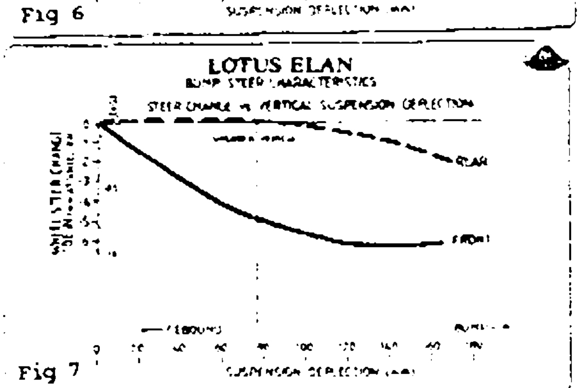

Fig 7

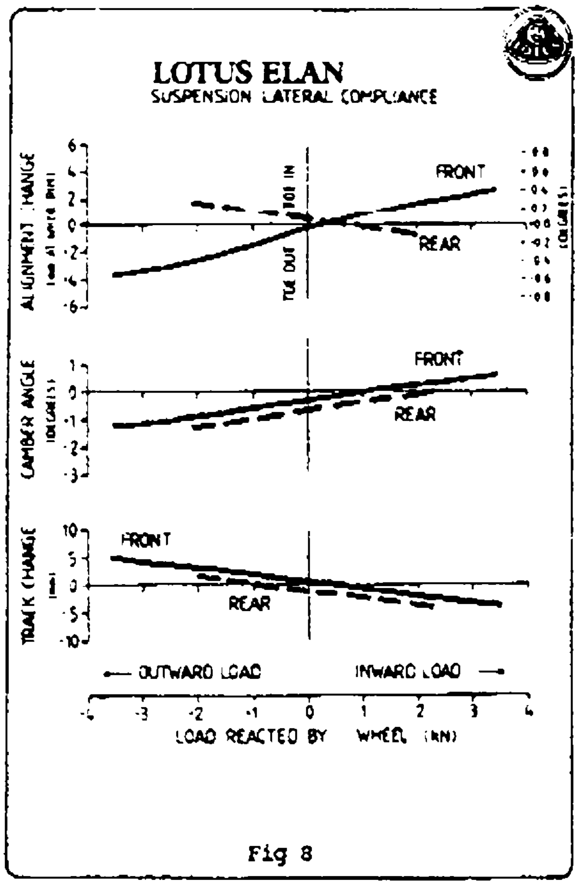

Fig 8

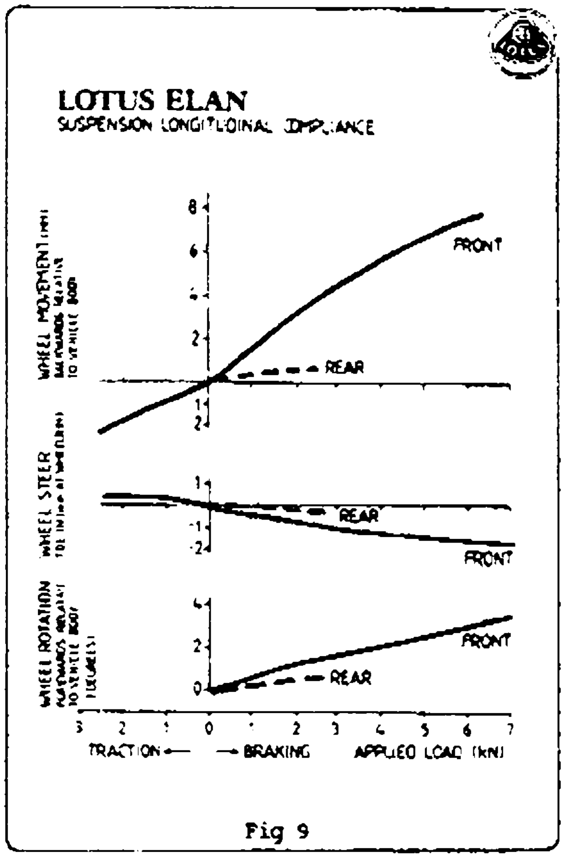

Fig 9