Optimized New Generation Steel Forgings In Auto Suspensions Systems

A Comprehensive Report on the Conversion of Suspension Uprights on the Lotus Elise to Steel from Aluminum, Including Design, Materials, Cost and Performance Results.

American Iron and Steel Institute

Executive Summary

Lotus Looks to Steel for Suspension Improvements:

After completing its work on the global steel industry's UltraLight Steel Auto Suspension (ULSAS) project in 2000, Lotus Engineering, a subsidy of Group Lotus Ltd., UK, decided to reevaluate the aluminum suspension components on its Elise sports car. Convinced that steel would be a viable, cost effective replacement for the incumbent aluminum system, Lotus engineers successfully redesigned the suspension uprights in steel and substituted the steel units for the previous aluminum design.

The redesigned suspension saved £130 (approximately $190), a component cost savings of 64 percent. The final steel design also met or exceeded all functional requirements, increased suspension stiffness and doubled the durability of the displaced aluminum design, all with a minimal weight increase of 3.5 pounds.

The approach required two phases. The first phase focused on benchmarking, design, testing and implementation, changing the uprights to a forged steel design from the original aluminum extrusion. The second phase included refining the design and rationalizing necessary parts.

The Lotus experience provides the first real-world validation of the results of ULSAS, which show that a combination of the latest steel material and process technologies and innovative design can reduce mass, save money and improve performance. The experience Lotus gained in conducting the ULSAS study was vital to its quick success in applying ULSAS technology.

Development and Testing:

The suspension is basic to the unique feel and identity of a vehicle and its design involves numerous trade-offs. Drivers want secure, smooth and vibration-free

performance. Engineers must meet these, and other driver preferences, while remaining within constraints for space and packaging, mass, cost and others. Accounting for both driver and engineering criteria, Lotus set design targets for the new steel uprights for its next generation Elise.

The design process began with CATIA software. The CATIA-based upright design was then exported to analysis software. A number of tests were then performed to ensure overall durability of the system. These included pave load tests with vehicle load sensors to measure longitudinal, lateral and vertical forces. Tests such as these assisted Lotus in refining the design, allowing the steel upright design to perform at optimal levels.

Material Selection:

Lotus determined that Air Cooled Forged Steels (ACFS) would be the optimal steel grades because of their hardness consistency from case to core (outer edge to center) and ease of machinability, compared to other forged steel grades. Benefits of ACFS include their greater durability under cyclic loads and the elimination of supplemental heat treating and annealing.

Lotus also realized that steel has other long-range benefits over the aluminum counterpart. With environmental responsibility an ever-increasing factor in automotive design, steel, the world's most recycled metal, offers unmatched recyclability. This means that the material has a very low through-life impact on the environment.

Steel - The Material of Choice:

By redesigning suspension uprights in steel for its Elise cars, Lotus not only has reduced part costs, but also has provided a superior product to its customers, while helping to protect the environment.

OPTIMIZED NEW GENERATION STEEL FORGINGS IN AUTO SUSPENSION SYSTEMS

BACKGROUND

In 1997, building upon the success of other UltraLight Steel Auto programs, the International Iron and Steel Institute (IISI) commissioned the UltraLight Steel Auto Suspension (ULSAS) project. Collectively, these activities form part of a cohesive, global steel industry strategy of meeting environmental demand for greater fuel efficiency. To execute this strategy, the steel industry has developed mass-optimized and recyclable products that foster the competitiveness of its automaking customers by providing lightweight, cost effective engineering solutions.

The ULSAS Consortium, comprising thirty-four major steel producers from fourteen countries, commissioned Lotus Engineering, the engineering consultancy division of Group Lotus Ltd, UK, to conduct the UltraLight Steel Auto Suspension program.

In common with all of the UltraLight series programs, the main objective of ULSAS is to realize and demonstrate the potential for cost effective weight reduction by exploring the full range of state of the art, yet implementation-ready, steel-based material and process technologies.

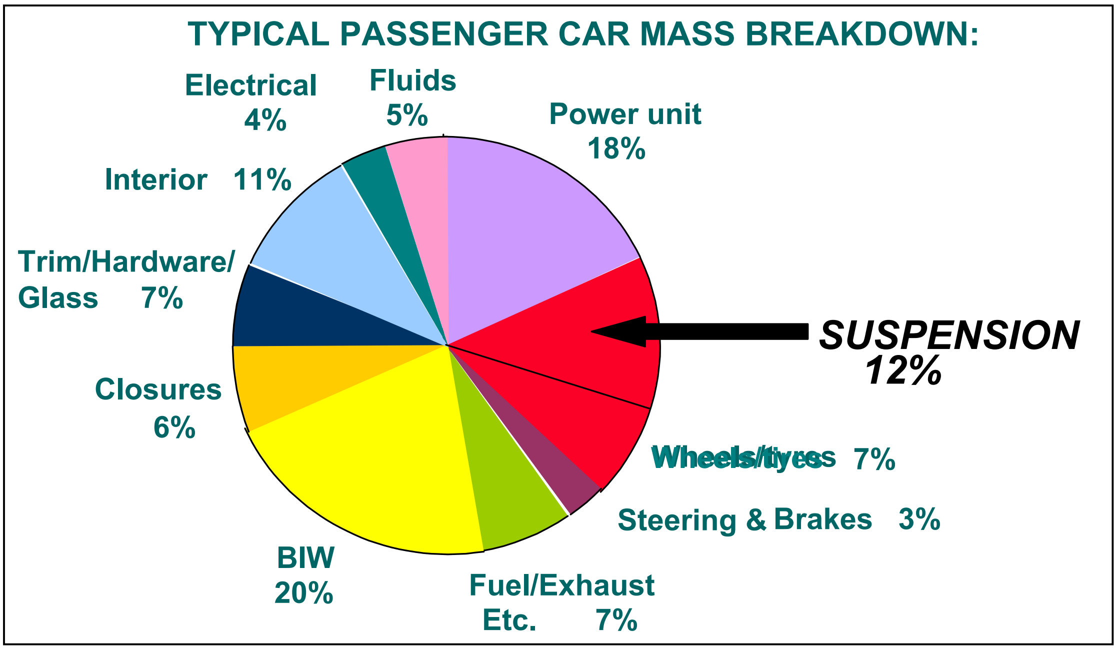
The consortium recognizes that automakers face continuing challenges to reducing mass, while remaining competitive and satisfying a variety of legislative, technical, environmental and consumer demands. The highly competitive and global nature of the automotive business increases the industry's demands for enabling technologies.

DEMANDS AND DRIVERS

The demand for lower mass is being driven by the increased environmental awareness of the vehicle consumer. Improvement in fuel efficiency is a primary objective coupled with the responsible use of natural resources and their resultant "through life" impact on the environment.

The demand for cost reduction in the automotive industry is a function of the competitive nature of the global market. It is the responsibility of the steel industry to respond to these challenges, such that vehicle producers and their supplier base can realize their objectives in a cost effective and competitive manner.

Both the customer expectations and the legislative requirements are driving the demands for higher levels of safety. The vehicle producers are now being forced to look at passive safety features to avoid accidents as well as the more traditional areas of body crash behavior. These passive safety features include such things as anti-lock braking systems (ABS), stability control systems and increasing demands for suspension systems with high levels of performance, stability and refinement. Because reduction of driver fatigue is seen by many as a fundamental requirement in improving safety, automakers are feeling more pressure to make quieter, easier-to-drive vehicles. At the same time, the end customers are also expecting ever-increasing levels comfort and space inside the vehicle, as well as better practicality for everyday use.



There are a number of suitable areas of a vehicle where mass and cost issues can be addressed. A mass breakdown of a typical volume production passenger car is illustrated in the table above. Components of vehicle mass include the body structure (20 percent), followed by the power unit (18 percent) and then the suspension systems (12 percent). From this, it is obvious that suspension systems account for a significant proportion of vehicle mass. What is of particular significance is that the unsprung mass of the suspension system directly influences vehicle dynamic performance. Therefore, weight savings identifiable in this area are of particular significance to automakers.

THE ULSAS PROJECT

The two-year ULSAS project was conducted in two phases. First Lotus engineers carried out a comprehensive benchmark study in which a variety of vehicles from North America, Europe and Asia were assessed. They tested vehicles on roads and tracks in the United States and the United Kingdom, conducted state-of-the-art evaluations and detailed design reviews, and ran weight, cost and manufacturing studies.

Then, based on the assessments, Lotus undertook a holistic review of suspension system requirements and identified opportunities for application of new steel material and process technologies. This exercise enabled engineers to establish an extensive range of targets for the design phase of the ULSAS project.

In the design process, the ULSAS study opened new avenues in suspension design, material applications and technology. While much of the technology applied in ULSAS could not be considered ground breaking by itself, the application of the technology and the mind-set for using it and advanced steels effectively are the key messages from the study. Lotus used state-of-the-art tools to do its design and analysis work, most of which are relatively common in advanced engineering departments today. Finite element analysis, both linear and non-linear, dynamic analysis using ADAMS software, and CAD (Catia) are not exceptional. However, use of analysis in the degree to which it has driven some of the designs, and particularly the mathematical modeling of sectional properties is a step forward for concept-level designs.

The starting point of the design phase involved the setting of objective performance targets. The purpose of this section of the design specification was to identify a range of vehicle-level targets that are independent of suspension system configuration. These targets are then, in a new vehicle development program, used to select the most appropriate suspension system characteristics based on performance capability. Due to the interactive nature of the suspension system design parameters, it is unlikely that all of the targets will be fully satisfied. However, the setting of ideal targets allow the preferred system characteristics to be selected with knowledge of the compromises that have been incurred. More over, while the engineers can understand and overcome these interactions, these characteristics are not what the customer buys. The customer is mainly interested in the subjective vehicle parameters such as how easy the car is to park, or how safe it feels, how comfortable the car is or how quietly it drives. The typical customer requirements are usually parameterized into a number of clearly defined subjective tests that can be quantified into a set of objective performance parameters.

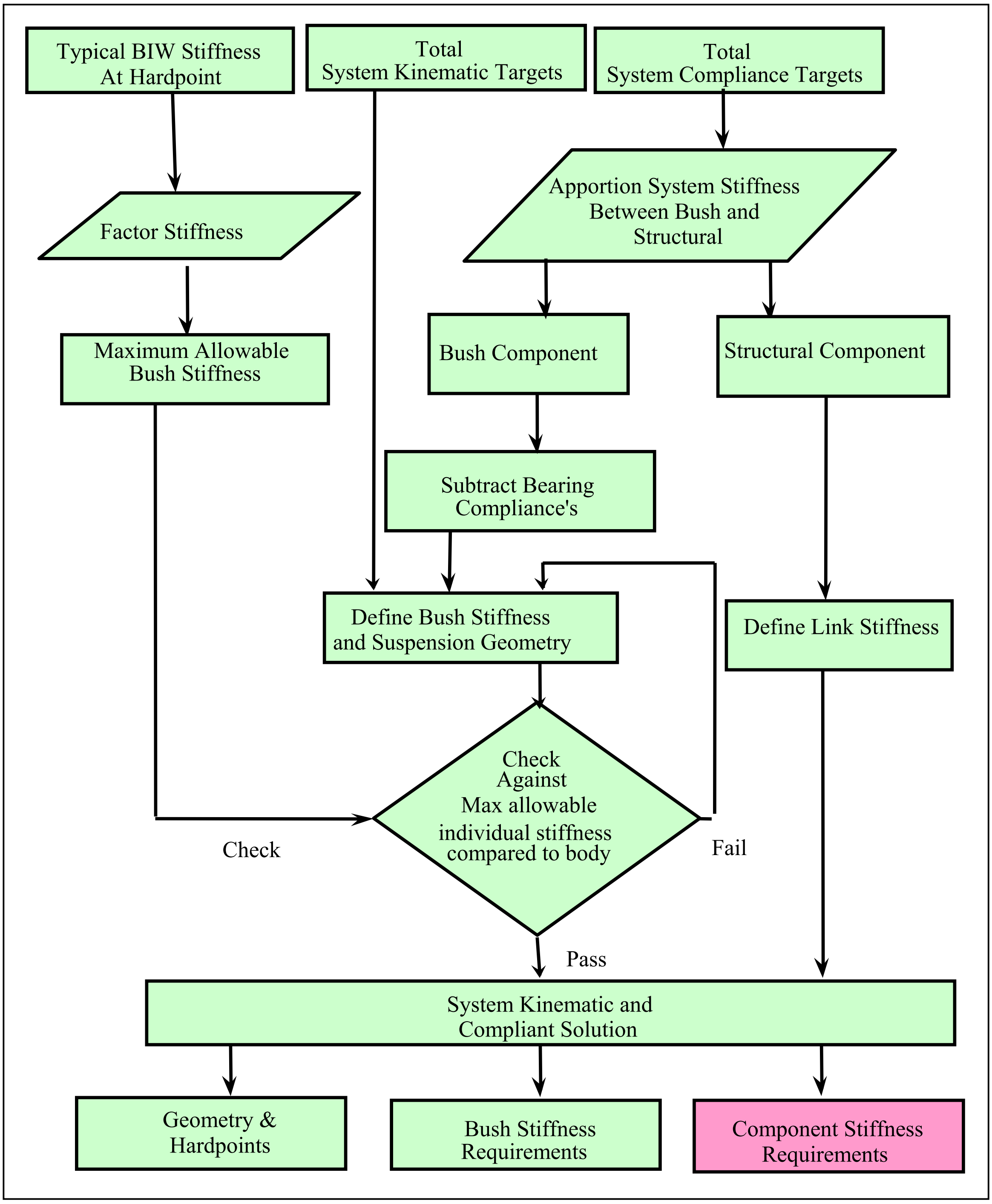
The performance of a suspension system, therefore, can be characterized by this set of objective performance parameters. In recent years, analytical techniques have been developed which simulate vehicle handling behavior based on vehicle mass properties, tire properties and objective performance parameters. This type of analysis does not require detailed definition of the suspension system configuration and allows the effect of each suspension system parameter to be studied and evaluated independently. The flexibility of the analysis method, which is not constrained by compromises associated with system configuration, enables the development of vehicle-based objective targets. These derived objective targets fall into two categories, kinematic characteristics and compliance characteristics.

The kinematic targets are largely controlled by the basic interactions of geometry and layout. These characteristics, therefore, are fairly easily modified to meet the individual tuning requirements of the vehicle manufacturer. Therefore, the kinematic targets only serve the purpose of ensuring that the layouts of the proposed concept designs are suitable for detailed development in line with each manufacturer's own customer requirements.

The compliance characteristics, however, have a more fundamental influence on basic component design targets. Detailed stiffness targets for the suspension components and bushes are established by considering the suspension compliance targets, along with body structural mounting point mobility targets.

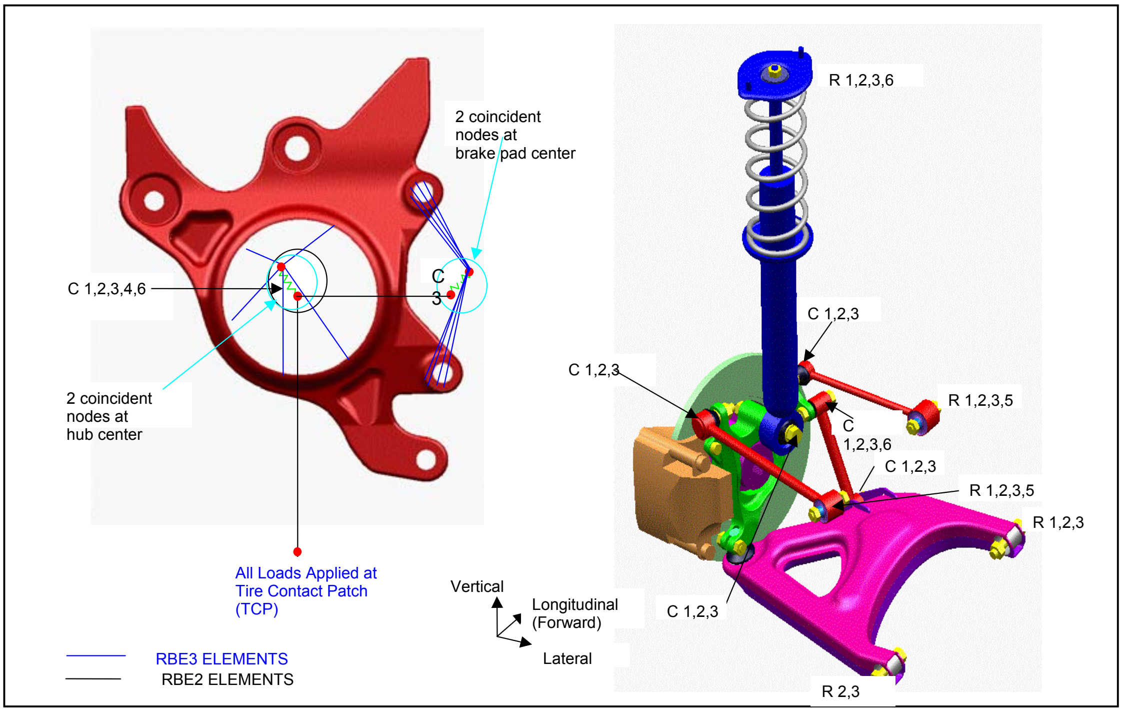
Quantifiable noise-vibration-harshness (NVH) assessment of a suspension system requires detailed knowledge of the vehicle chassis/body structure and is not possible at the concept design stage. However, control of the stiffness relationships between suspension bushes, linkage components and body mounting points will ensure that NVH performance potential is maximized. The ratio between the bush stiffness and the component stiffness is of great importance and it is vital for the NVH performance of the system that both the body mounting points and the suspension components are sufficiently stiff to allow the bushes to work correctly. Therefore, from the compliance characteristic targets and knowledge of vehicle body structures, the component stiffness targets can be established. This key fundamental requirement for component stiffness therefore provides a vital input into the design process.

Design Requirements Definition Process



To ensure the structural integrity of each of the suspension concepts, a series of design proof-load cases were derived, which are typical of industry practice. It should be noted that these are proof-load cases only, and do not include single event abuse load cases.

They allow the structural capability of each system to be assessed on a comparison basis and allow sound engineering evaluation of the alternative designs to be made and concept design refinements identified.



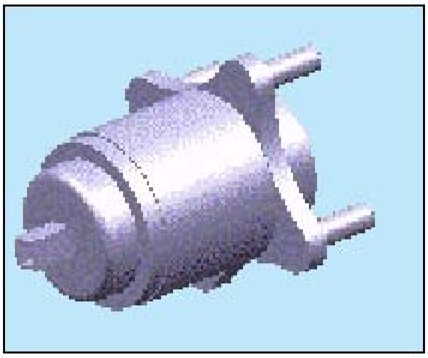
The detailed refinement and subsequent optimization of the component designs requires more detailed knowledge of the suspension system input loads and load history to enable further analysis to be conducted. In real-life situations, all structural failures in suspension components occur as a result of either crash or complex fatigue-type loading, as opposed to single load cases. It is normal practice during the concept phase of the design process to use design proof-load cases to enable initial sizing and feasibility assessments to be carried out. However, during the detail design phase, fatigue analysis is commonly used to predict the system and individual component life under a range of typical road loads, and, therefore, access the suspension's ultimate durability capacity. Occasionally, non-linear analysis follows this to examine the failure mode during single event abuse loading and will need to be in line with the particular manufacturer's strategy on safety and repairability.

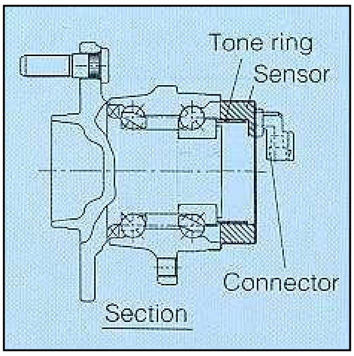
ULSAS RESULTS

The final outcome of the ULSAS program demonstrated weight savings of up to 34 percent over conventional steel designs, at no additional cost. It also clearly demonstrated that intelligent application of steel can match the mass of an aluminum system, while achieving a 30 percent cost savings over the aluminum system. These figures are for total suspension systems, but similar results were also achieved in the individual components. In achieving these impressive mass and cost objectives, ULSAS also identified and preserved a number of key vehicle performance parameters.

Two areas of interest in the ULSAS project, which were of particular significance were the use of optimized high-strength steel forgings for suspension uprights and the adoption of integrated bearing assemblies. The latest generation of integrated bearings utilize modern steel materials and technologies to help rationalize the number of parts required in the suspension uprights. The theme of optimized design and parts rationalization were paramount throughout the ULSAS program.

Two of the systems studied in the ULSAS program that featured both optimized forgings and integrated bearings were the Double Wishbone system and the Multi-Link system. The integrated bearings featured optimized profile wheel flanges, internal speed

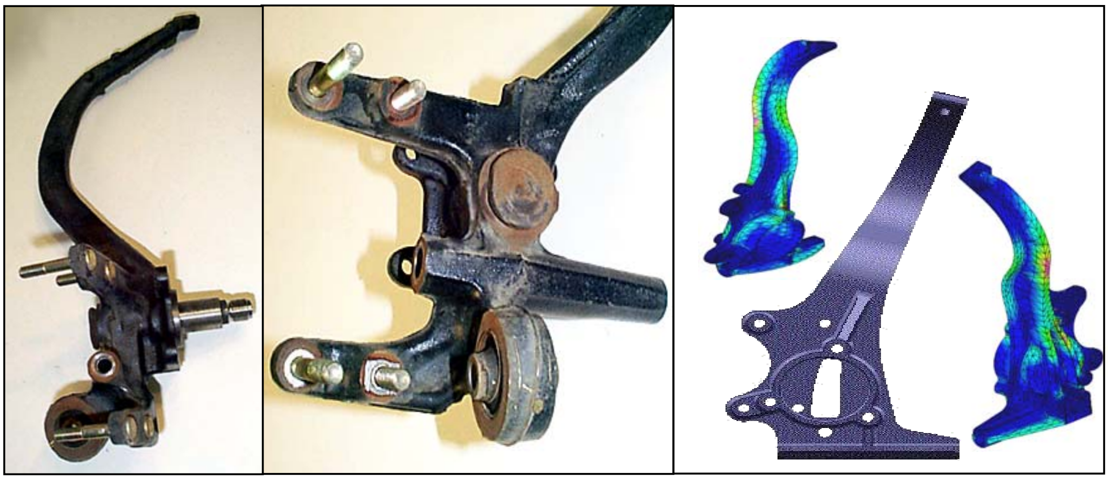




sensors (for anti-lock brake systems, etc.) and direct attachment to the upright or circliped into place in the upright.

The two benchmarked uprights were of very different designs. The double wishbone system had a long swan neck design made of cast iron, whereas the Multi-Link system used a compact design in forged aluminum. In each case the ULSAS optimized steel design maintained the basic fundamental design principals of the benchmark system.

DOUBLE WISHBONE

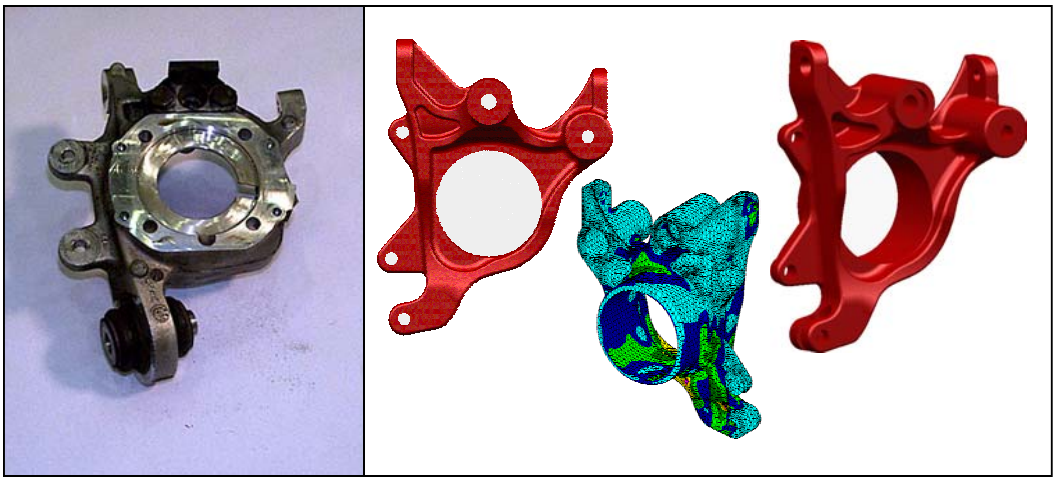


Benchmark Cast Iron Upright ULSAS Forged Steel Upright.

	Benchmark system	ULSAS Design	% Change
Mass (Kg)	7.4	4.0	46% Reduction
Cost ($)	17.5	24.0	37% Increase

The Double Wishbone upright demonstrated considerable mass savings of 46 percent but carried a 37 percent cost penalty. However, the performance of the part was considerably improved in terms of stiffness, which enhances overall vehicle dynamic performance.

MULTI-LINK



Benchmark Aluminum Upright ULSAS Forged Steel Upright

	Benchmark system	ULSAS Design	% Change
Mass (Kg)	2.7	3.0	11% Increase
Cost ($)	30.0	21.0	30% Reduction

The Multi-Link forged steel upright achieved a mass within 11 percent of the aluminum-benchmarked component, while yielding a substantial 30 percent reduction in cost. The part was comparable to the original in terms of package, performance and stiffness.

The results of the ULSAS program showed affordable mass savings can be achieved, compared with conventional steel-based designs, and that considerable cost savings can be achieved with no mass penalty, compared to aluminum benchmarked systems. In demonstrating what can be achieved with the latest steels and technologies, Lotus Engineering has adjusted its own perception of the mass, cost and performance advantages available. This adjustment has been to such an extent that Lotus has redesigned the suspension uprights on its renowned Elise model from aluminum to steel.

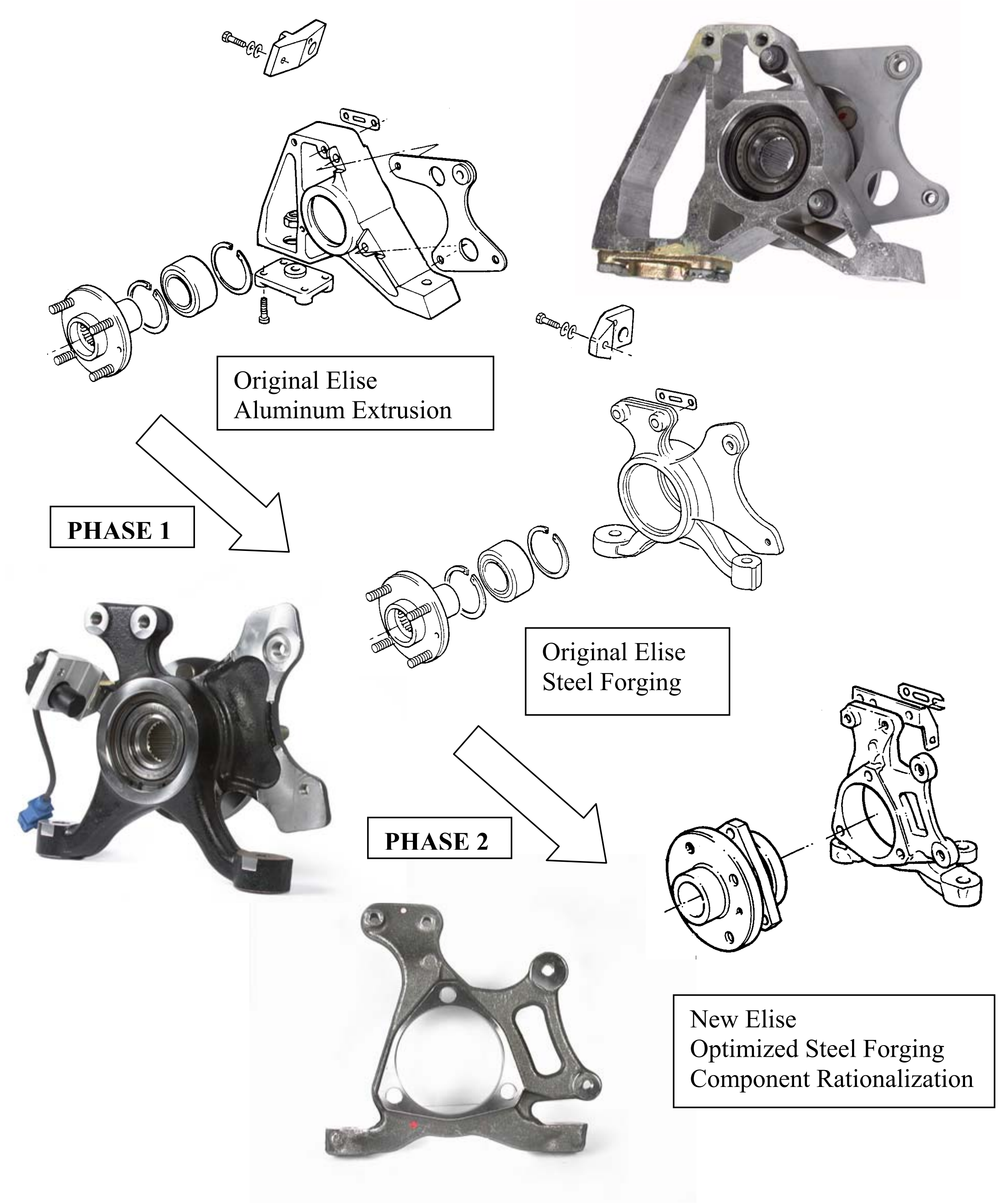
<u>THE LOTUS ELISE</u>

For more than five years the Lotus Elise has been the undisputed sportscar king. Winning countless awards for its technical innovation, handling prowess and fun-to-drive purity, its fan base includes anyone who has ever sat behind its steering wheel.

Some champions quit while they're ahead, not Lotus. It's raising its game to meet new challenges. And now the Elise looks like it is hanging on to its title as `the world's best handling sportscar' for years to come. An all-encompassing evolution of the previous car, the Elise has fresh styling inside and out with improved aerodynamics for greater high-speed stability. Newly designed chassis systems provide superior ride and handling, with higher levels of roadholding, sharper steering, more powerful brakes, quicker throttle response and overall greater functionality. In addition, with new manufacturing processes, the car gets an all-round upgrade in quality. It's a more mature car, yet it has lost none of its "Lotus-ness", nor any of the magic associated with the name Elise - light, fast, agile, and above all, more fun than ever.

THE ELISE UPRIGHT REDESIGN

The lessons learned and the philosophies developed during the ULSAS program were applied to the redesign of the Elise suspension uprights. This was carried out in two phases, first on the original Elise where the upright was changed to forged steel from an aluminum extrusion. Then, for the introduction of the new Elise, a further redesign was carried out to further develop the design and rationalize the number of components.



The new Elise forged uprights were developed with a process that iterated between the design and analysis functions. The geometric hard points (mounting points) of the suspension were linked together within the package envelope for the suspension corner assembly (wishbones, wheel, brake disc and calliper). The design was done using CATIA software. The output from CATIA was a solid model, which was exported to the analysis software, via CATXPRES.

Elise Rear Suspension Upright

The analysis of the upright was based on vehicle's durability requirements. The mathematical simulation took the loads from a Belgium Block Pave element of the whole durability cycle. One lap of pave load data was collected from the test circuit. Vehicle Load Sensors (VELOS) wheel load collection instrumentation was used to measure wheel center loads. The VELOS accurately measures longitudinal, lateral vertical forces, as well as the respective moments introduced into the rolling wheel under operational conditions. Six loads are given, X, Y and Z forces together with X, Y and Z moments. The data was collected in ASCII format. Following data processing and de-multiplexing, these six-time histories were converted into nCODE binary CAD files.

The CATIA CAD data were meshed in MSC/Patran and second order tetrahedral elements were used. The boundary conditions were applied directly to the geometry. The model was restrained to ground via the three ball joints;

Ball Joint	Element Type	Degrees Of Freedom
Lower	RBE2	123
Upper	RBE2	12
Steering Arm (TCA)	RBE2	2

Internal multi-point constraints, MPC's, were written to transfer the applied loads from the wheel center to the upright.

Connection	Element Type	Degrees Of Freedom
Wheel Centre to bearing	RBE3	123
Wheel Centre to brake	RBE3	123

Static unit loads were applied at the wheel center.

Direction	Load Type	Magnitude	Load Path
X	Force	1000 N	Bearing
Y	Force	1000 N	Bearing
Z	Force	1000 N	Bearing
About X	Moment	1000 Nmm	Bearing
About Y	Moment	1000 Nmm	Brake Calliper
About Z	Moment	1000 Nmm	Bearing

The solution code was MSC/Nastran. A linear static analysis was performed.

MATERIAL DATA

Historically, forgings for suspension parts have been made from heat-treated carbon and low alloy steels. Recent developments have lead to the introduction of microalloy-as-forged-steels with improved strength and fatigue properties, enhanced machinability and greater uniformity of properties. These new materials have greatly helped the automotive designers by allowing them to specify parts that are near-net shape, reducing machining costs and reducing component mass. As a result microalloy and Air-Cooled Forged Steels (ACFSs) are steadily increasing in their use for suspension components.

The new generations of engineering steels, ACFSs, have provided better product consistency, with uniform grain size and microstructure. These steels give a more repeatable product and eliminate the need for heat treatment, which gives a further reduction in costs. The chemical composition of these ACFSs was developed to provide additional precipitation strengthening during controlled air cooling after forging. Subsequently, the compositions have been systematically modified to determine optimum mechanical properties. The intent was to replace traditional forging grades with new simple carbon steels, but without heat treatment and with mechanical properties similar to heat-treated steels. A series of ACFSs were developed and grouped together and then included in a European Standard, EN 10267.

<u>Material Properties</u>

Grade	Rp N/mm^2	Rm N/mm^2	Elongation %	Reduction in Area %
19MnVS6 DIN EN 10267	>500	650-800	>15	>40
30MnVS6 DIN EN 10267	>550	750-900	>12	>30
38MnVS6 DIN EN 10267	>580	850-1000	>12	>30
46MnVS6 DIN EN 10267	>480	800-900	>8	>20
SAE 1046 HT	600	800-900	>14	>50

Besides replacing heat treatment, the ACFSs have further benefits, in contrast to the quenched and tempered steel. These typically include:

- No hardness drop from case to core
- Homogenous ferrite-perlite microstructure over the whole section
- Consistent machinability due to microstructure
- No additional annealing for stress relieving due to controlled slow air-cooling

In addition to this interest in basic mechanical properties, automotive designers are primarily concerned with material fatigue properties so as to optimize critical components for lightweighting and lower cost. Performance of the newer generations of ACFSs under cyclic loading conditions is greatly enhanced compared to the traditional forging grades. Test results comparing 38Mn VS6 DIN EN 10267 with AISI 1548-HT showed considerable benefits in fatigue life. The average fatigue-loading limit for infinite life was around 10-20 percent higher for the 38Mn VS6 DIN EN 10267.

In general, there are three sources of material cyclic properties. These are:

- Sample testing
- Derived from empirically defined rules
- From an existing database

The material cyclic properties for the Elise upright were both derived and taken from the MSC/Patran database.

A method of predicting material cyclic properties is based on monotonic properties and more than 1500 fatigue tests (Baumel, Jr. and Seeger) and introduces the ductility factor, α.

Material Monotonic Properties

Grade	Rp N/mm^2	Rm N/mm^2	E N/mm^2	Ductility factor α = 1 when Rm/E <= 0.003
19MnVS6 DIN EN 10267	>500	650-800	210000	1
30MnVS6 DIN EN 10267	>550	750-900	210000	1
38MnVS6 DIN EN 10267	>580	850-1000	210000	1
46MnVS6 DIN EN 10267	>480	800-900	210000	1
SAE 1046 HT	600	800-900	210000	1

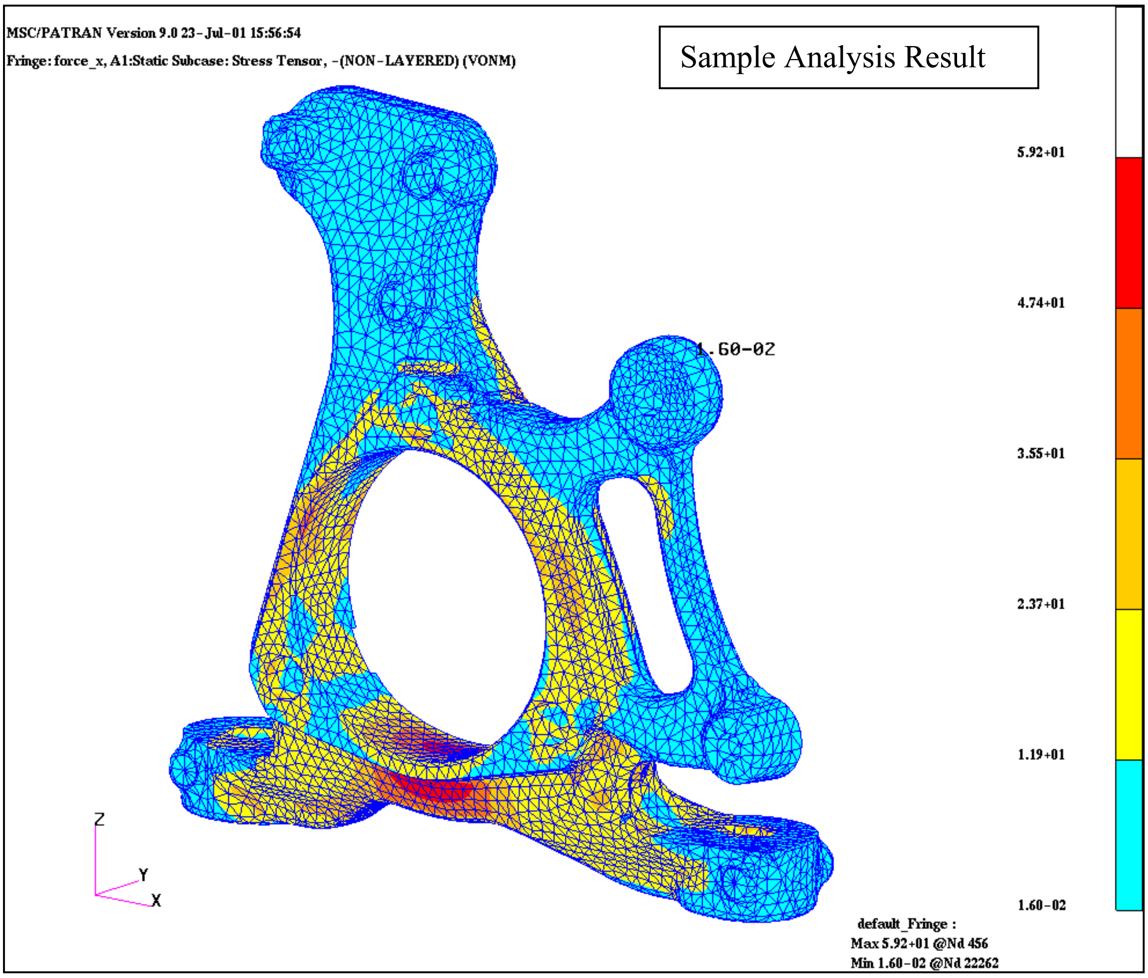
Estimated from UTS from the MSC/FATIGUE user's manual theory section 7.5.

Parameter		Uniform Material Law for Low alloy steels
Fatigue strength coefficient,	sf'	1.5 Rm
Fatigue strength exponent,	b	-0.087
Fatigue ductility exponent,	c	-0.58
Fatigue ductility coefficient,	ef'	0.59α
Cyclic strain-hardening exponent,	n'	0.15
Cyclic strength coefficient,	K'	1.65 Rm

Material cyclic properties used for analysis

Material	sf'	B	c	ef'	n'	K'
19MnVS6 DIN EN 10267	975	-0.087	-0.58	0.59	0.15	1072
30MnVS6 DIN EN 10267	1125	-0.087	-0.58	0.59	0.15	1237
38MnVS6 DIN EN 10267	1275	-0.087	-0.58	0.59	0.15	1402
46MnVS6 DIN EN 10267	1200	-0.087	-0.58	0.59	0.15	1320
SAE 1046 HT	1200	-0.087	-0.58	0.59	0.15	1320

Fatigue analysis requires the three main inputs described above to be of high quality to give reliable fatigue life predictions. The analysis type chosen was crack initiation (EN) for the parent material. The six load cases were combined and biaxiality calcuations made. Neuber plasticity correction was used. The design and analysis inputs were iterated, and the manufacturing requirements applied, until an optimized design was achieved. The resulting design met rigorous structural stiffness and durability criteria, as well as the manufacturing requirement of near-net shape forging for minimum machining.



Following the analysis, the final production material was selected in conjunction with the forging supplier Carl Dan. Peddinghaus (CDP) GmbH.

Material: 38MnVS6 DIN EN 10267 (microalloyed steel; needs no heat treatment)

Chemical composition:

C	0,34 - 0,41 %
Si	0,15 - 0,80 %
Mn	1,20 - 1,60 %
P	max. 0,025 %
S	0,020 - 0,060 %
Cr	max. 0,3 %
Mo	max. 0,08 %
N	0,01 - 0,02 %
V	0,080 - 0,20 %

Mechanical properties:

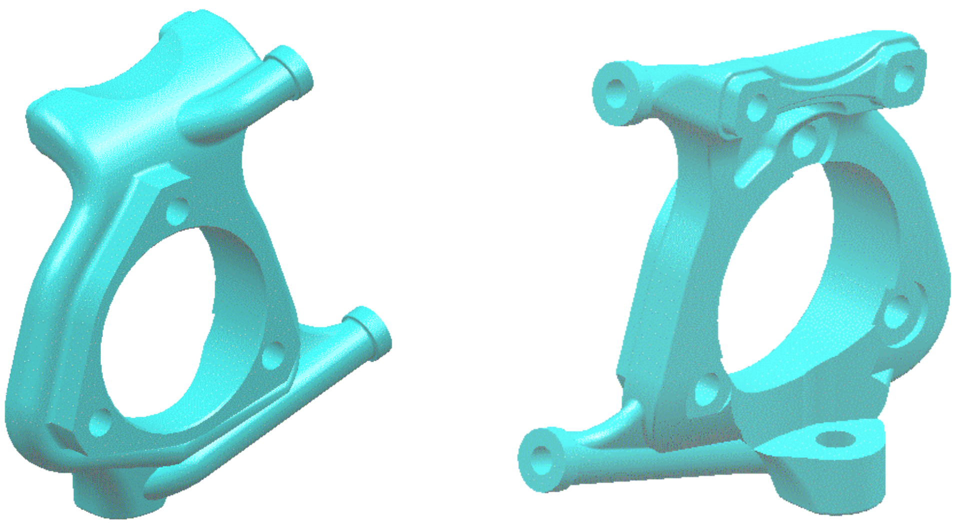
Hardness (surface/ core) :	242 - 302 HB
Rp0,2 (yield strength) :	min. 560 N/mm2
Rm (tensile strength) :	min. 820 N/mm2
A5 (elongation) :	min 10 %
Z (reduction of area) :	min 20 %

Concurrent with the design and analysis phase, production engineers from Lotus and CDP worked on manufacturing feasibility issues and cost estimates. This work examined tooling and machining requirements to ensure that the optimum design was achieved from all respects. The conclusion of this phase showed there was a clear business case to develop the project further. A component was designed that meets or exceeds all functional requirements, improves stiffness and more than doubles durability. The predicted mass of the component was only a 10-20 percent increase, with an estimated total cost decrease of less than five percent, compared with the original design.

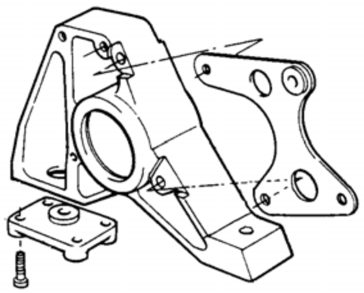
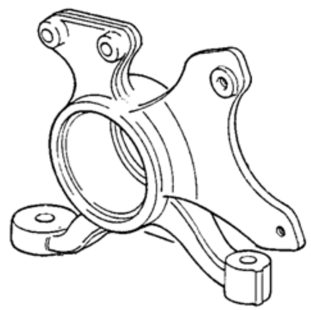
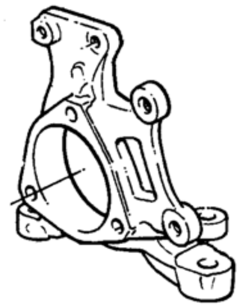
On the evidence of the concept phase, tooling was commissioned for the first phase design. These parts were manufactured and successfully tested and proved. The part was then introduced as a permanent change onto the Lotus Elise (Series 1). These parts achieved a massive £34.36 (67%) cost saving, with a 0.58kg (28%) weight increase, per upright.

The design then went into a second phase for the Lotus Elise Series 2 where the part was further optimized and parts rationalized. The optimized parts achieved a slightly lower reduction in cost, due to increased complexity in the forging. Although this cost was still a considerable £32.50 (64%) saving compared with the original design. The mass increase was limited to 0.388 kg per upright. In this phase the front upright was also changed to a steel forging with similar benefits in terms of cost and performance.

<u>Elise Front Suspension Upright</u>



Lotus Elise Rear Hub Uprights
Comparative Mass and Cost Data

Part number	Description	Illustration	Material	Application	Upright Mass (kg)	Upright Cost (£)
C111D0047F C111D0048F	Upright Rear-LH Upright Rear-RH		Aluminum Extrusion Steel Brkt Steel Bush Housing	Elise (Series 1)	2.105 2.105	£50.99 £50.99
A111D0143K A111D0142K	Hub Carrier, LH Hub Carrier, RH		Forged Steel	Elise (Series 1)	2.685 (+28%) 2.685 (+28%)	£16.63 (-67%) £16.63 (-67%)
A116D0001F A116D0002F	Upright, LH Upright, RH		Forged Steel	Elise (Series 2)	2.493 (+18%) 2.493 (+18%)	£18.49 (-64%) £18.49 (-64%)

Lotus Elise Rear Upright Assemblies

Components contributing to Mass and Cost analysis

	Group A Included			Group B Not-Included		
Application	**Part Number**	**Description**	**Qty**	**Part Number**	**Description**	Qty
Elise (Series 1 – Early)	C111D0047F	Upright Rear-LH	1	A111C6001F	Hub Assembly	1
	B111D0049F	Carrier – Ball Joint RR LWR	1	A111C6002F	Bearing – Double Taper Roller	1
	A111W1158F	Screw M10 x 30	4	A111C6016F	Circlip – Int Dia 68mm	2
	C111J0007H	Adapter Plate RR Caliper LH	1	B111D0024F	Bracket – Speed Sensor Mounting	1
	A111W7160F	Bolt – M10x45	1	A075W4035Z	Washer – Spring M6	1
	A111W7161F	Bolt – M10x60	1	A075W4013Z	Washer - Flat M6	1
	A089W3082F	Nut M10x1.5	2	A075W1029Z	Set-screw M6x25	1
	A111J0005H	Bush – Adapter Plate RR Caliper	1			
Elise (Series 1 - Late)	A111D0143K	Hub Carrier, Forged Steel, LH	1	A111C6001F	Hub Assembly	1
				A111C6002F	Bearing – Double Taper Roller	1
				A111C6016F	Circlip – Int Dia 68mm	2
				A111D0148F	Bracket – Speed Sensor Mounting	1
				A075W4035Z	Washer – Spring M6	1
				A075W4013Z	Washer - Flat M6	1
				A075W1029Z	Setscrew M6x25	1
Elise (Series 2)	A116D0001F	Upright, m/c Forging, Rear, LH	1	A117D6005F	Hub Assembly + ABS Sensor	1
				A116W1170F	Bolt	3

CONCLUSION

The experience of Lotus has validated the theoretical advantages identified in the ULSAS project. Lotus has shown that with appropriate application of steel products and technologies, real life vehicle improvements are obtainable. Considerable cost savings of over 60 percent were achieved with a mass penalty of under 0.4 kg. From a total vehicle standpoint, this translates into a massive saving of over £100 with only a 1.5 kg weight increase from changing all four uprights. In addition, the steel optimized designs delivered significant performance benefits with greater stiffness, superior durability and improved customer satisfaction.

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