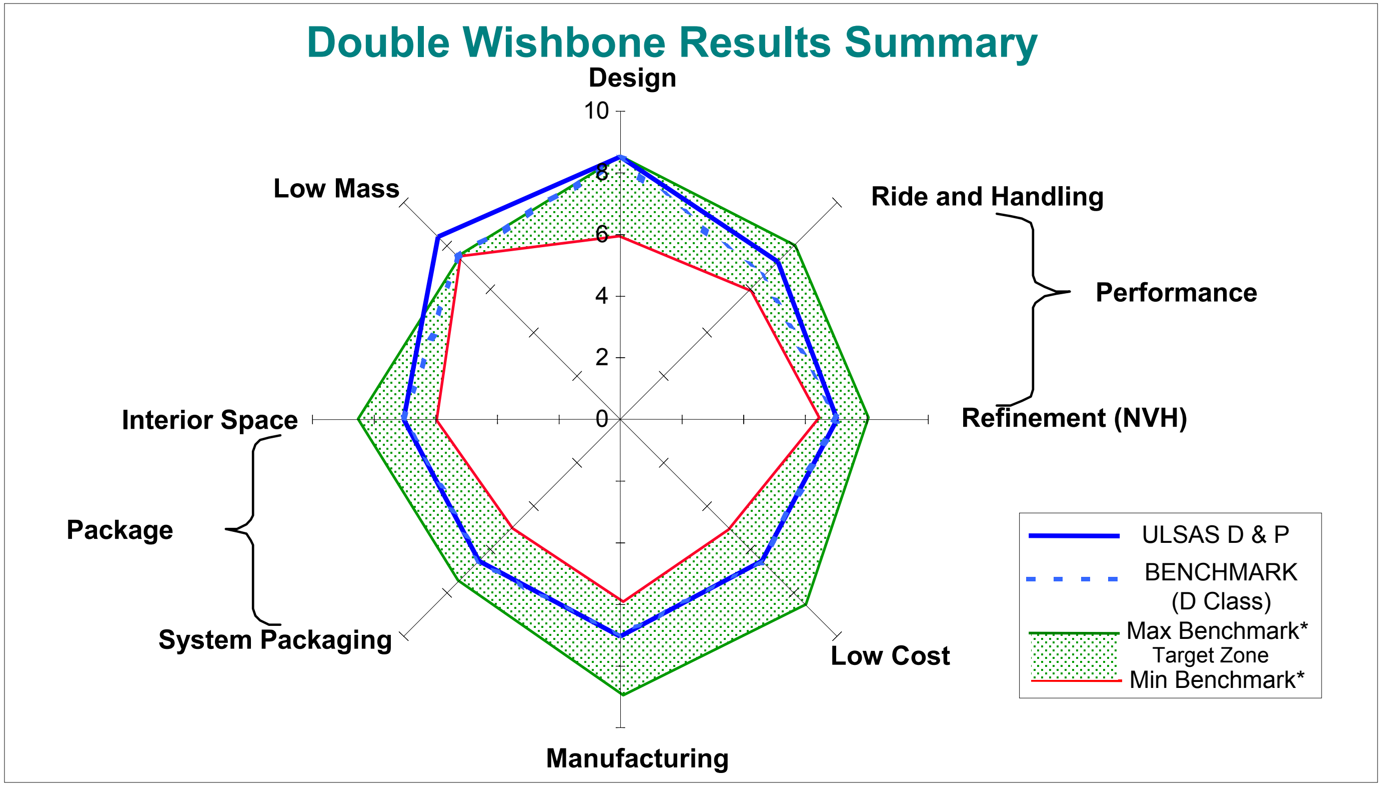
DOUBLE WISHBONE: RESULTS SUMMARY

DOUBLE WISHBONE

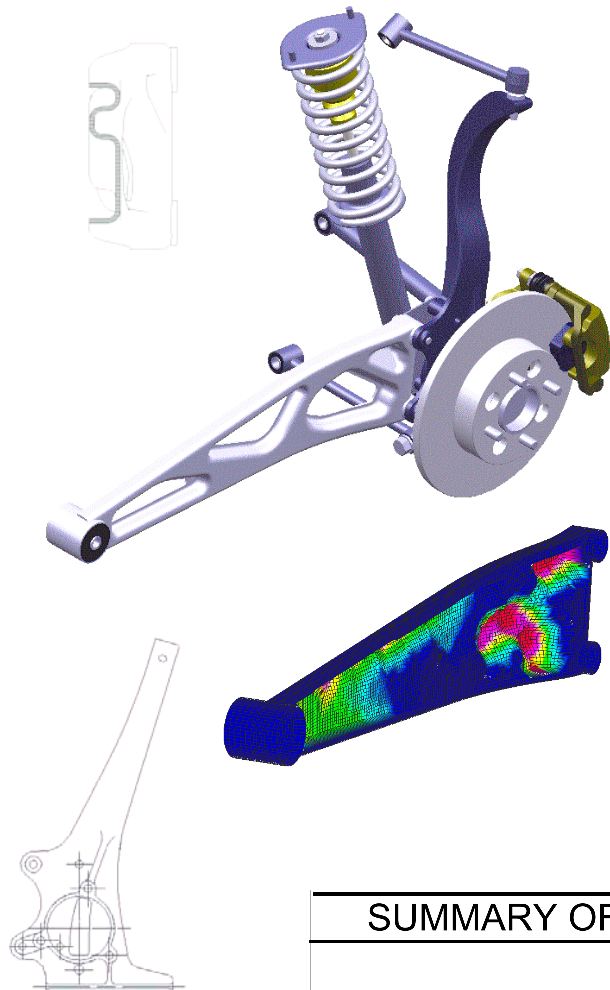


- MASS SAVINGS - NO COST PENALTY
- PERFORMANCE EXCEEDS BENCHMARK
- ALL OTHER AREAS MATCH BENCHMARK

*Maximum and minimum benchmark scores are for all the systems benchmarked

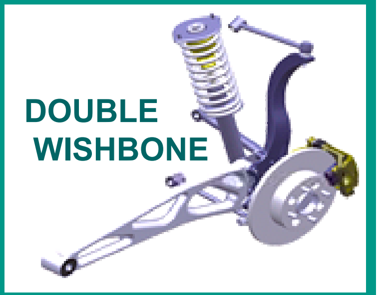
ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: DESIGN

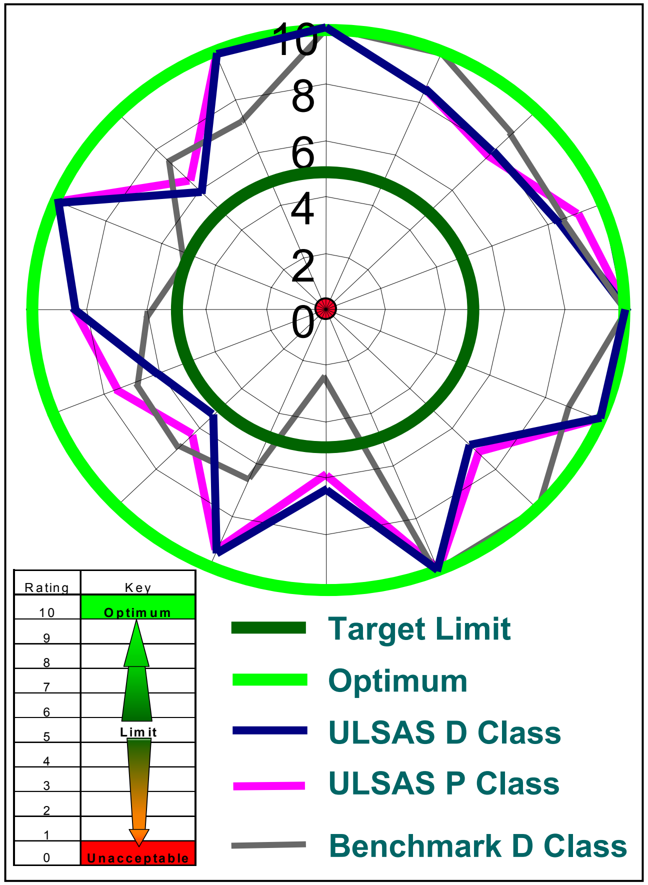


- The Double Wishbone system was evaluated against the same design criteria as in the Benchmarking Phase, including:
  - Potential for technical development
  - Potential for system/component integration
  - System image / marketability
  - Structural efficiency & elegance.
- The ULSAS solution matches the Benchmark system in all areas of design.

SUMMARY OF OVERALL SCORES & RATINGS		
	ULSAS D	BENCHMARK (D Class)
Design	8 .5	8.5



DOUBLE WISHBONE: PERFORMANCE

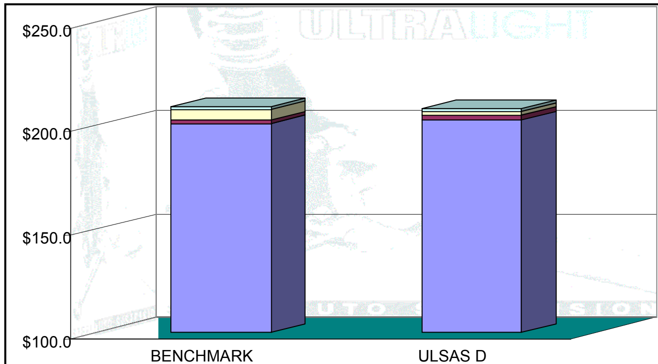


- The Double Wishbone solution demonstrates good levels of performance.
- The performance of the Double Wishbone all fall within the target acceptance limits for every criteria.
- Overall score is higher than the Benchmark for Ride & Handling and matches that of NVH.

SUMMARY OF OVERALL SCORES & RATINGS

	ULSAS D	BENCHMARK (D Class)
Ride and Handling	7.2	6.5
Refinement (NVH)	7.0	7.0

DOUBLE WISHBONE: COST



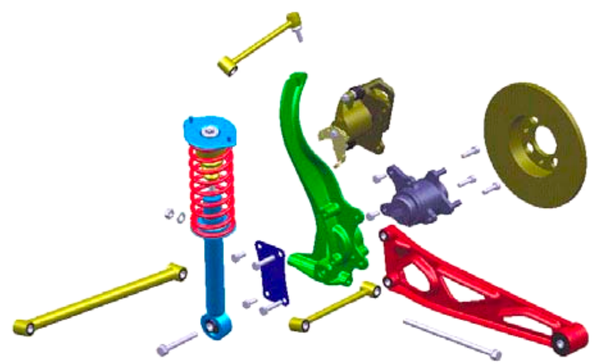
(US$)	Double Wishbone	
	Benchmark D Class	ULSAS D Class
PIECE COST	**$200.7**	**$202.5**
TOTAL TOOLING COST ($,000)	**$4,192**	**$4,340**
5 YEAR Volume (Assumptions)	2,075,000	2,000,000
TOOLING COST	$2.0	$2.2
TOTAL SYSTEM COST	$202.7	$204.7
SYSTEM ASSY		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Assembly Mins	6.59	2.87
SYSTEM ASSEMBLY COST	$4.83	$2.10
VEHICLE FITTING		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Fitting Mins	1.83	1.76
VEHICLE FITTING COST	$1.34	$1.29
Total Cost ($)	**$208.9**	**$208.1**
Cost Saving($)	$0.8	
Cost Saving %		**0%**

- The cost of the ULSAS solution compares favourably to the benchmarked suspension.
- For both the ULSAS solution and the Benchmark system, the dominant factor is the piece cost of the components and sub-assemblies.
- Reduction in assembly time is due mainly to greater levels of parts integration in the ULSAS design.
- Overall score in this area is virtually identical to the Benchmark.

SUMMARY OF OVERALL SCORES & RATINGS		
	ULSAS D	BENCHMARK (D Class)
Cost	6.5	6.5

ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: MANUFACTURING



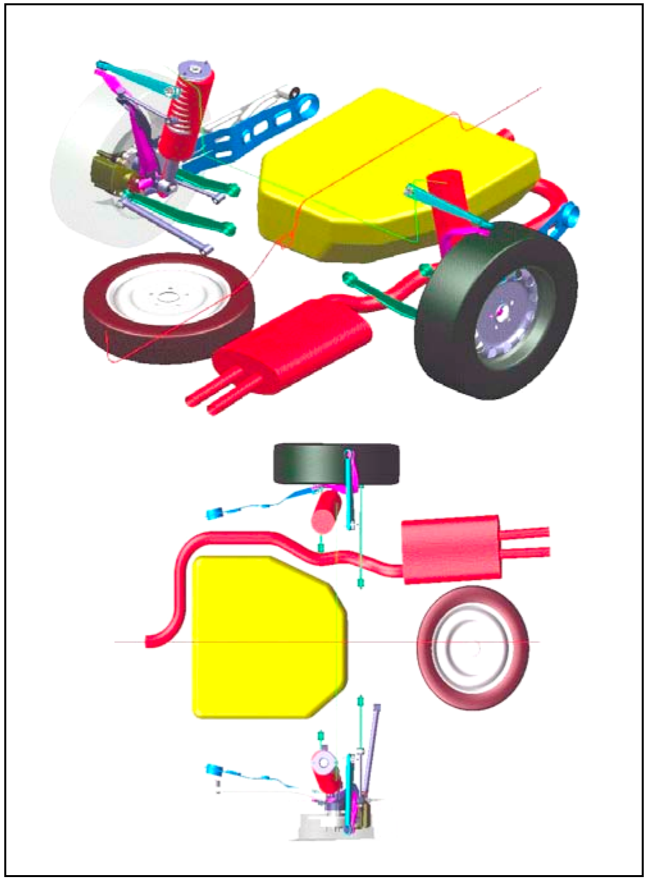
Cost of ULSAS Solutions Vs Benchmark Vehicles		
(US$)	Double Wishbone	
	Benchmark D Class	ULSAS D Class
SYSTEM ASSY		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Assembly Mins	6.59	2.87
SYSTEM ASSEMBLY COST	$4.83	$2.10
VEHICLE FITTING		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Fitting Mins	1.83	1.76
VEHICLE FITTING COST	$1.34	$1.29
Total Cost ($)	**$6.2**	**$3.4**
Cost Saving($)	$2.8	
Cost Saving %		**45%**

- The ULSAS solution compares favourably with the benchmarked system in terms of assembly and fitting times.
- Fewer parts and sub-assemblies have reduced assembly times and costs.
- An appropriate level of manufacturing feasibility has been taken into account.
- Overall score in this area surpasses the Benchmark.

SUMMARY OF OVERALL SCORES & RATINGS		
	ULSAS D	BENCHMARK **(D Class)**
Manufacturing	7.1	7.0

STEEL AUTO SUSPENSION

DOUBLE WISHBONE: PACKAGING

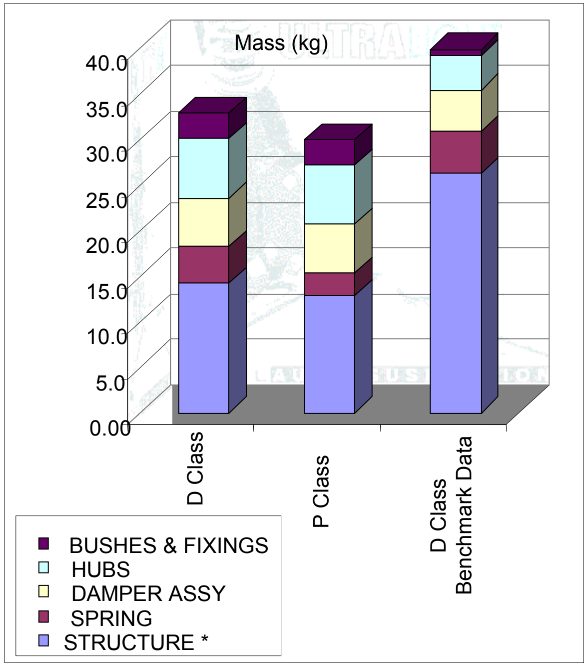


- The ULSAS solution matches the underfloor layout of the Benchmark vehicle well.
- The interior space package of the ULSAS solution is comparable with that of the Benchmarked vehicle.
- Overall score for Systems Packaging matches the Benchmark.
- The score for Interior Space matches the Benchmark.

SUMMARY OF OVERALL SCORES & RATINGS

	ULSAS D	BENCHMARK (D Class)
System Packaging	6.5	6.5
Interior Space	7.0	7.0

DOUBLE WISHBONE: MASS



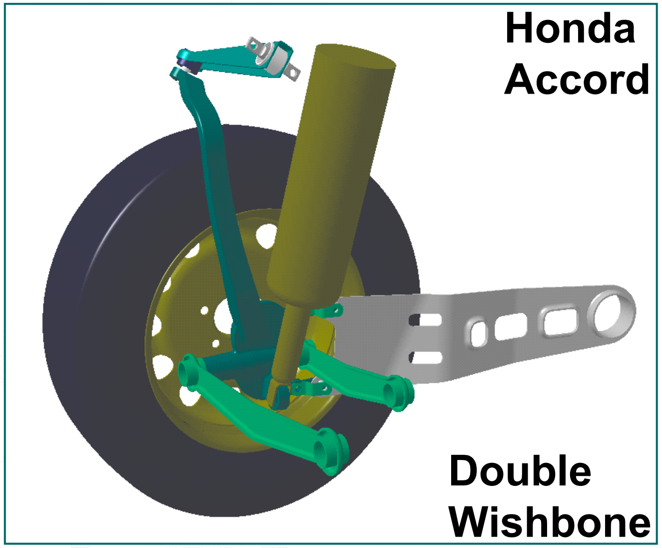
*** Structure includes knuckle and links**

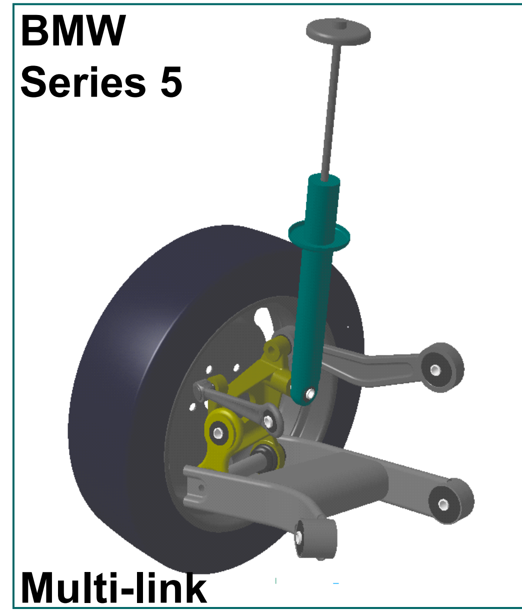
- Both the ULSAS solutions demonstrate a good mass reduction compared to the Benchmarked system.
- The mass savings of the structural elements of the system alone are even more pronounced.
- Overall score for system mass is therefore significantly higher than the Benchmark value.

Mass Of ULSAS Solutions Vs Benchmark Vehicles					
Description	**B**	**C**	**D**	**E**	**P**
Benchmark (kg)			**39.84**		
ULSAS solution (kg)			**32.88**		**31.29**
Saving vs Benchmark			**17%**		21%

SUMMARY OF OVERALL SCORES & RATINGS		
	ULSAS D	BENCHMARK (D Class)
Mass	8.4	7.5

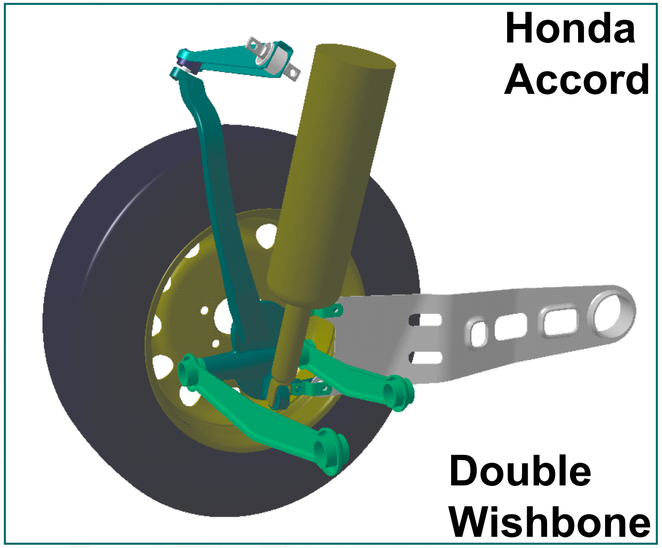
DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY

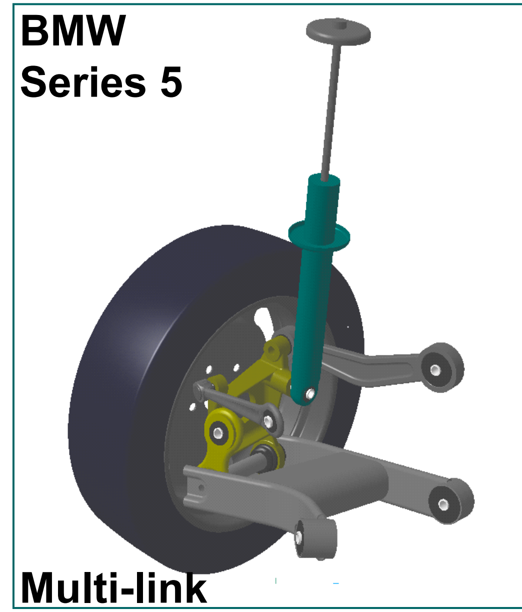




The ‘true’ multi-link suspension concept provides the greatest flexibility in the design of the static geometry and kinematic behaviour of the road wheel. The term 'multi-link system’ encompasses a wide variety of configurations. The systems fitted to the Vauxhall Vectra, Honda Accord and the BMW Series 5, can all be defined as ‘true’ multi-link systems but are very different in layout, performance and appearance. For this reason a generic description of multi-link systems is not appropriate. A review of the main criteria that are used to develop the design of such a system is of greater benefit.

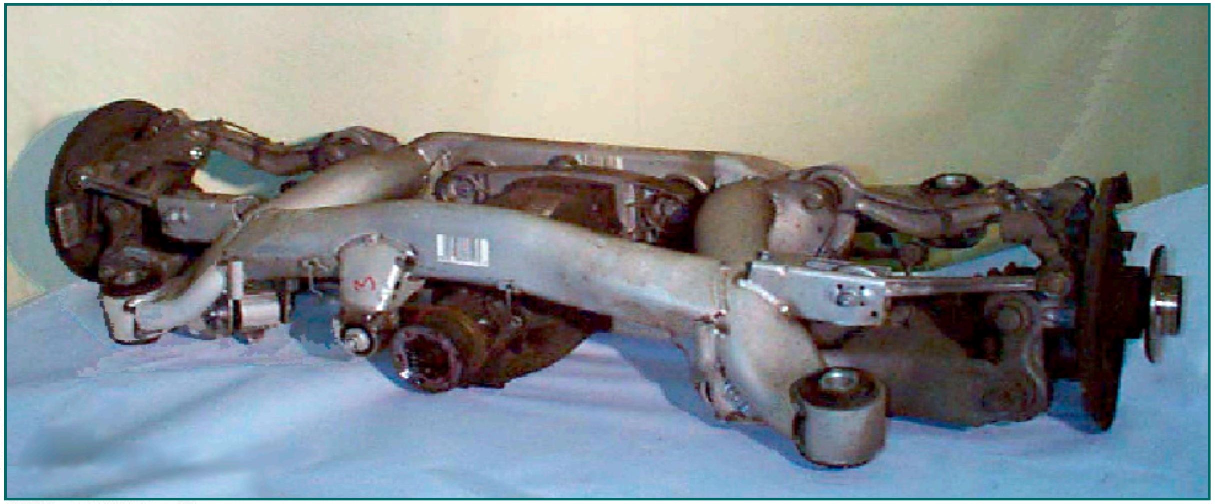
DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY





During cornering manoeuvres, the vehicle is subjected to a lateral acceleration that causes the body to roll. To ensure an effective contact between the tyre and the road surface, and therefore maximise the grip available, the tyre should be essentially vertical, with a near zero camber angle with respect to the ground. To obtain a near zero camber angle, an angle must be created between the tyre and the body as the body rolls. Viewed from the body, the top of the outer wheel should lean inwards and the top of the inner wheel should lean outwards. The angles of inclination of the wheels could be arranged such that they fully cancel the inclination due to body roll. An installation of this type would provide full (100%) camber compensation with roll. It is not appropriate to design a system with such a high level of camber compensation. The system behaviour would be sensitive to ride height and would produce large changes in camber when subjected to single wheel inputs. However a limited level of camber compensation during roll is desirable. In terms of suspension design parameters the requirements are for a camber change that produces negative camber during bump and positive camber during rebound. The priority being to produce the required camber on the outer wheel (in bump) as this wheel experiences the greater cornering force. By using a set of lateral links locating the top and bottom of the hub carrier it is possible to optimise the camber change behaviour.

DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY



Typical example of a Multi-link Rear Suspension System

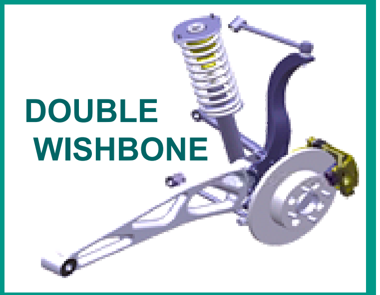
In addition to camber change considerations, the design arrangement of the lateral links influences the roll behaviour of the vehicle and ultimately the roll stability of the rear axle. The roll behaviour is a function of the lateral acceleration, the relative position of the kinematic instantaneous centre of the system (roll centre) and the vehicle centre of mass. In a suspension system with a link arrangement in which the roll centre is permitted to move upwards and outwards during cornering, a roll motion is produced which lifts the vehicle body. This is referred to as jacking. Jacking also occurs when the kinematic instantaneous centre of the system is at the mass centre. When jacking occurs the suspension mechanism on each side of the vehicle moves into rebound by the amount that the body rises. Depending on the camber characteristics the wheels can adopt a positive camber with the consequential loss of grip with the road. Pronounced jacking can result in the lifting of the inside rear wheel and the introduction of instability to the rear of the vehicle. To suppress the jacking effect it is necessary to establish a linkage geometry in which the jacking thrust is neutralised. For zero jacking the instantaneous roll centre must move towards the inside of the turn as the angle of body roll increases.

DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY

The control of the rear track of the vehicle is also a function of the design configuration of the lateral links. During single wheel vertical inputs the wheel can move laterally with respect to the body producing a lateral force at the tyre contact patch which opposes the direction of motion. This force is reacted by the body and the direction of travel of the vehicle is affected. To improve straight line stability it is necessary to minimise the track change about the system design ride height. In a suspension mechanism comprising upper and lower lateral links, the link lengths and their mounting configuration can be chosen to both optimise the camber change and minimise the track change. However the track change has a direct influence on the behaviour of the roll centre, and the two parameters cannot be tuned independently.

Example of a Double Wishbone Rear Suspension System

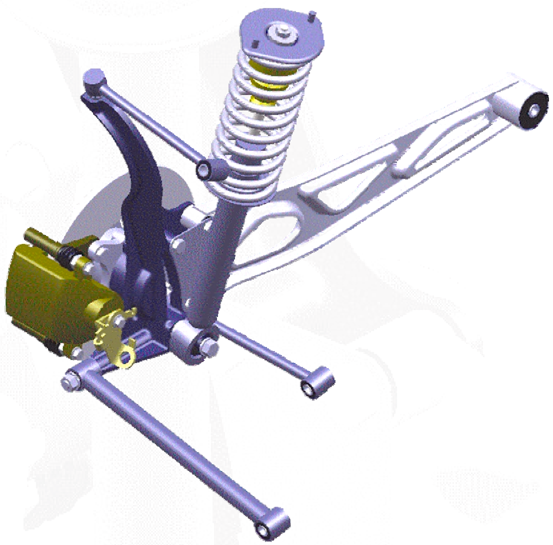
DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY



The toe change behaviour can have a similar effect on the vehicle directional stability as excessive track change. If the steer angle of the wheel changes with vertical wheel travel whilst the car is directed to travel in a straight line, the tyre will adopt a slip angle and a side force will be generated. This force will act on the body in the direction of the toe angle change, disturbing the vehicle direction of travel. However producing a toe change during cornering can be used to enhance the dynamic performance of the vehicle. A number of ways of producing a toe change can be adopted. The most common approach is to focus on obtaining the required toe change characteristic during roll, i.e. linking the toe change behaviour to the suspension wheel travel. This can produce satisfactory results, but if the toe change with wheel travel produces large amounts of steer it will have a negative effect on straight line stability and can result in an oscillatory motion. Consequently in such instances it is desirable to use some other independent means to control the toe change. It is this aspect of multi link suspension design that produces the largest variety of design solutions.

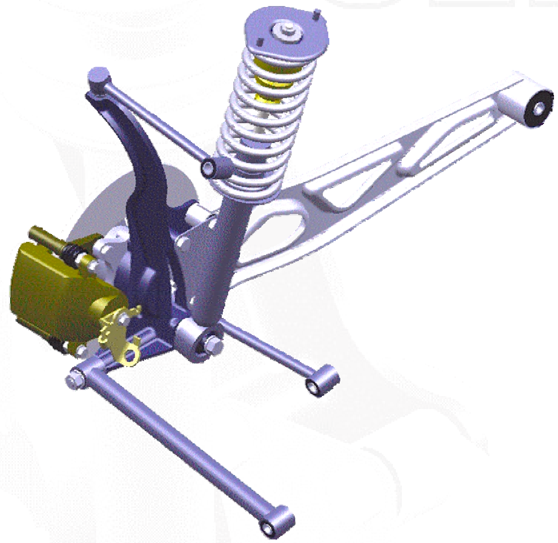
DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY

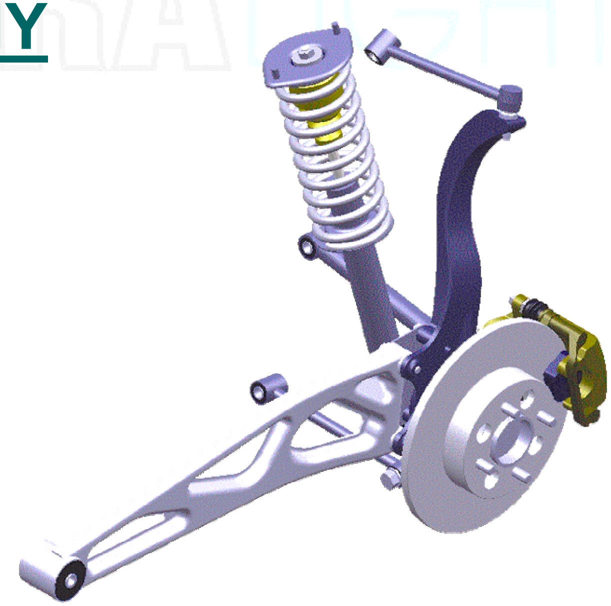
DOUBLE WISHBONE



Pitch control is another factor that must be considered in the layout of the system linkage. When a rear wheel drive car accelerates, traction forces are generated at the hub centre. As a consequence the hub moves forward and into bump with respect to the body and the rear of the vehicle can drop, i.e. squat. A converse situation arises during braking. In this instance the forces are generated at the tyre contact patch. The tyre contact patch moves rearwards and into rebound and the rear of the vehicle rises. Attitude changes due to acceleration and braking can be suppressed through the design of the suspension geometry. The positioning of the side view instantaneous pivot centre of the system can be used to minimise the pitching motion. For minimum pitch the ideal position for the centre is substantially forward and above the axle centreline at the intersection of the zero squat and zero lift lines. This position is usually within the occupant space. Consequently, packaging considerations prevent a real pivot axis to be created in this ideal position. As an alternative, a virtual pivot axis can be created by manipulating the orientation of the pivot axes of the upper and lower links to obtain the desired system pitch behaviour.

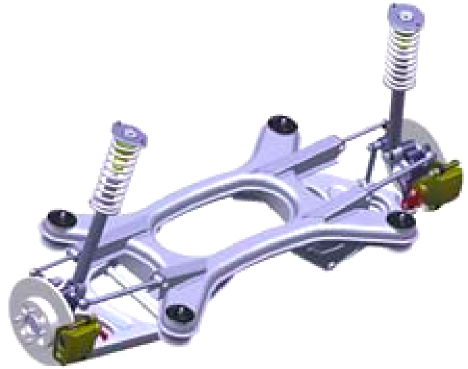
DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY

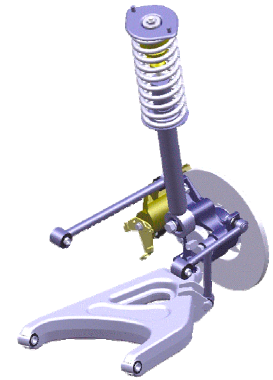




The toe control of the system is an important factor when considering the dynamic behaviour of the vehicle. The kinematic effects of toe change on straight line stability have already been discussed. The effect of forces on the system and the resulting behaviour as a result of bush deflection must also be considered. This is referred to as compliance steer. Rubber bushings are incorporated into the suspension mechanism to isolate the body from the high frequency low amplitude wheel loading that typically results from the texture of the road surface. This loading acts predominantly in the longitudinal and vertical directions. In order to accurately position the wheel with respect to the vehicle motion it is necessary to ensure that the system is stiff in the lateral direction. The basic compliance requirements of a rear suspension system are that they are supple in the longitudinal direction and stiff in the lateral direction. Obtaining the correct balance between the bush requirements, the toe change characteristics and the system dynamic behaviour is a complex problem. By introducing an additional link into the system, further opportunities can be created to tune the system characteristics. The additional link is arranged such that it guides the steer motion of the wheel in response to the direction in which the wheel loading is applied. The additional link is generally attached to the hub carrier at one end and then can be either attached to one of the existing links in the system or directly to the body structure. Kinematically the mechanism is over constrained, and it is necessary to use the compliance of the linkage system bushes to provide the required additional degrees of freedom. To achieve the optimum characteristics requires detailed design analysis supported by a development and test process during which the design can be refined.

DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY





Multi-link systems comprise a complex arrangement of components that require several points of attachment to the vehicle body. To ease the assembly process and also to maintain high standards of build consistency the systems are often fully or partially mounted to a subframe. The subframes can be rigidly or resiliently mounted to the vehicle body. The reduced number of attachment points to the body and the use of resilient mounts allows greater control over the NVH transmission paths. The behaviour of the resilient mounts also contributes to the system compliance behaviour.

The complexity of the linkages and the use of a subframe is spatially demanding. Spring media selection and the integration of the spring media within the system also have an effect on vehicle boot volume and occupant space. The use of separate spring and damper units removes the side loading concerns associated with a strut unit and can also be used to re-distribute the spring and damper load paths into the vehicle. This further enhances the opportunities to refine the system performance.

Multi-link systems can be used on both driven and non driven rear axle arrangements. It is important to identify the expected applications at the start of the design process to ensure that the effects of drivetrain torque and traction loading are considered in the development of the system design.

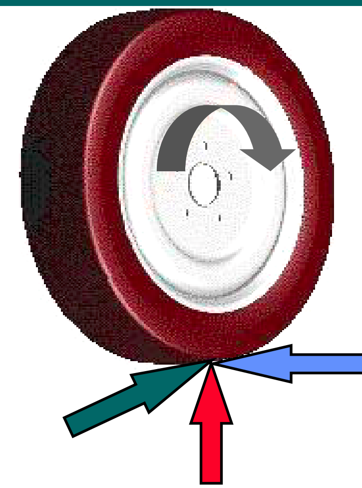
Multi-link systems are complex, and with the increased part count they can be costly. To exploit fully the potential of such a system a considerable investment is required in the system concept design during the early stages of the vehicle design process.

DOUBLE WISHBONE & MULTI-LINK SYSTEM PHILOSOPHY

Basic Forces Acting on the Suspension

3 primary forces at tyre contact patch

- **Longitudinal**
- **Lateral**
- **Vertical**



Additional Torque Loading

- **From Braking (Combined with a Longitudinal Force**

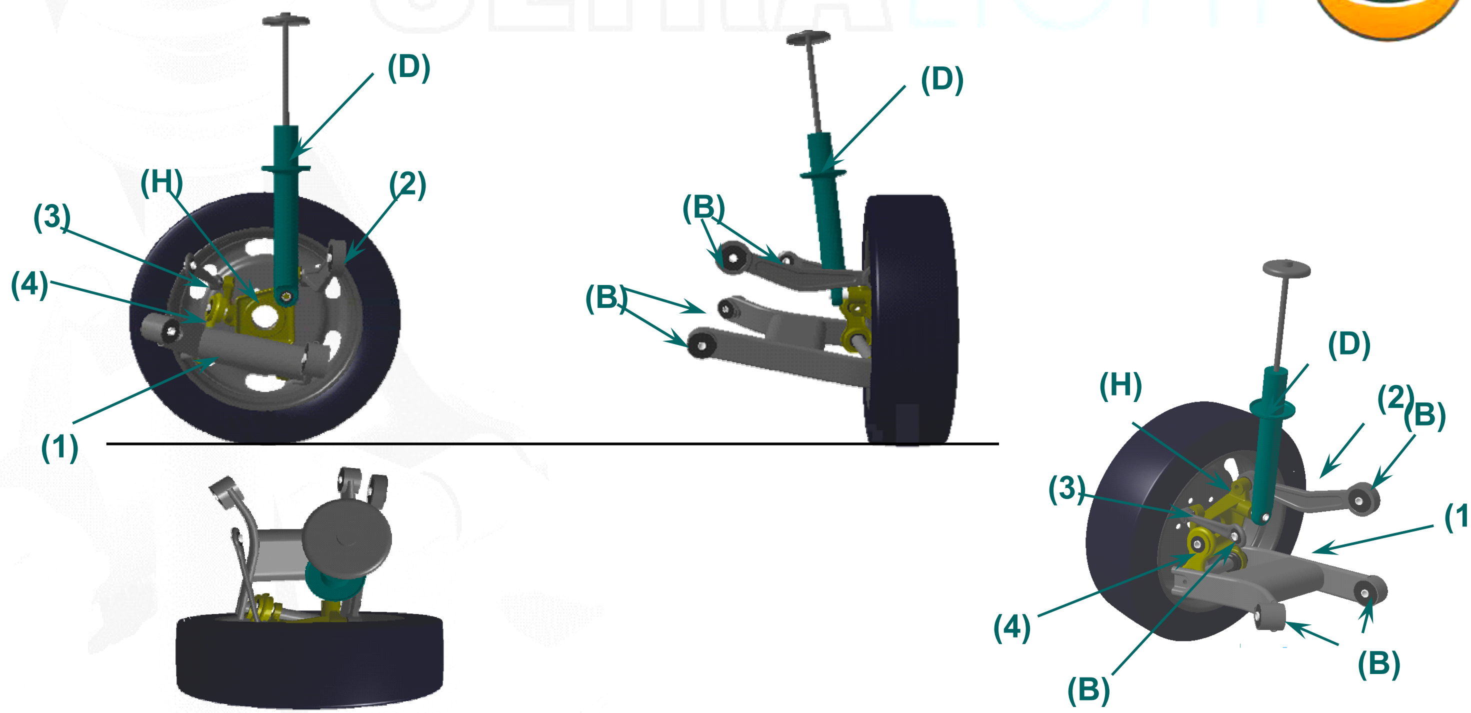
Also acceleration loadings on RWD

To better understand the complex loading in the suspension system we must first look at the fundamental forces that are generated at the tyre contact patch. These forces act in the three primary directions as shown and there is an additional torque loading from brake reaction, there are also torque's generated about the other two axes due to offset loading, trail, etc but these are of less significance. From these forces we can look at the movements in the suspension system and also examine how the forces are controlled by the suspension system.

Movements	Forces
• Longitudinal	• Longitudinal
• Lateral	• Lateral
• Ride	• Vertical
• Steer	
• Camber	• Braking/ Acceleration
• Rolling	

ULTRALIGHT STEEL AUTO SUSPENSION

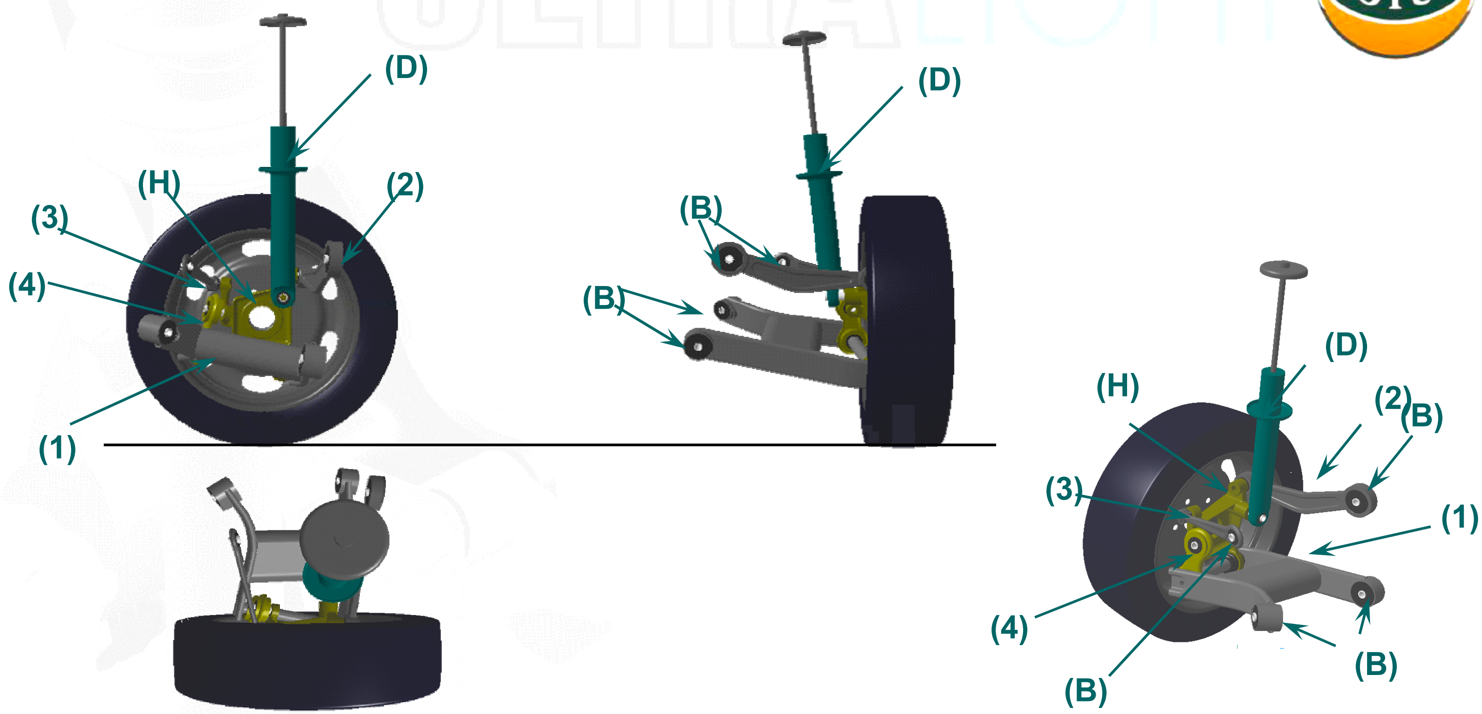
MULTI-LINK: SUSPENSION



MOVEMENTS

Longitudinal:- Deflection and articulation of bushes (B) allow fore and aft movement of the wheel.
Lateral:- Radial stiffness of bushes (B) controls track change due to lateral forces. Links (2) & (3) and arm (1) control track change during suspension travel.
Ride:- The wheel moves vertically by links (2) & (3) and arm (1) rotating about bushes (B) . and compressing the spring and damper (D).
Steer: - Steer is controlled by the interactions of links (2) (3) & (4) and arm (1) during changes in suspension travel and by bushes (B) under lateral and longitudinal forces.
Camber: - Camber is controlled by the interactions of links (2) (3) & (4) and arm (1) during changes in suspension travel and by bushes (B) under lateral forces.
Rolling:- The wheel is able to rotate on bearings in the hub carrier (H).

MULTI-LINK: SUSPENSION



FORCES

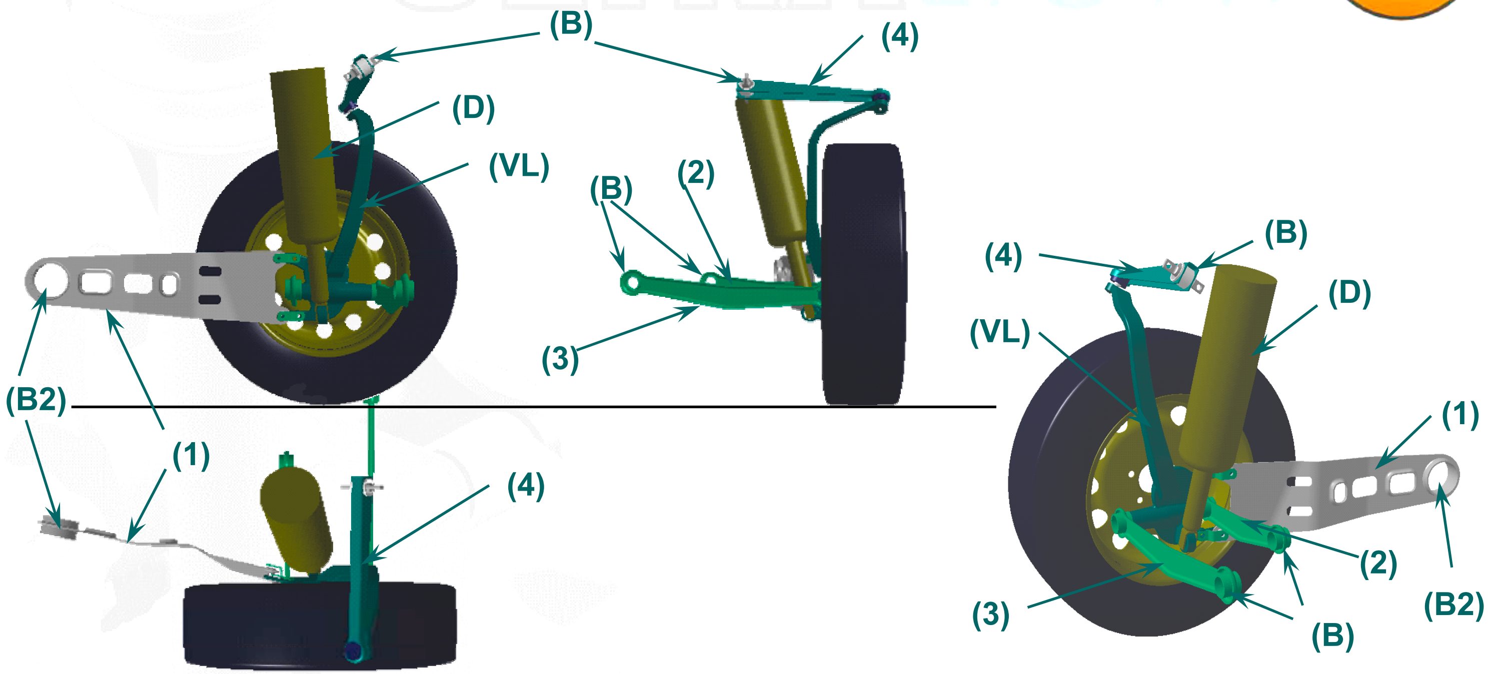
Longitudinal : Forces are resisted by tension and compression loads in links (2) (3) & (4) and . by tension, compression and bending in arm (1).

Lateral :-Forces are resisted by tension and compression loads in links (2) (3) & (4) and in . arm (1).

Vertical :-Forces are resisted by loads in the spring / damper unit (D) and by tension and . compression loads in links (2) (3) & (4) and in arm (1).

Braking/ :-Torque is taken by tension and compression loads in links (2) (3) & (4) and by acceleration torsion in arm (1).

DOUBLE WISHBONE: SUSPENSION



MOVEMENTS

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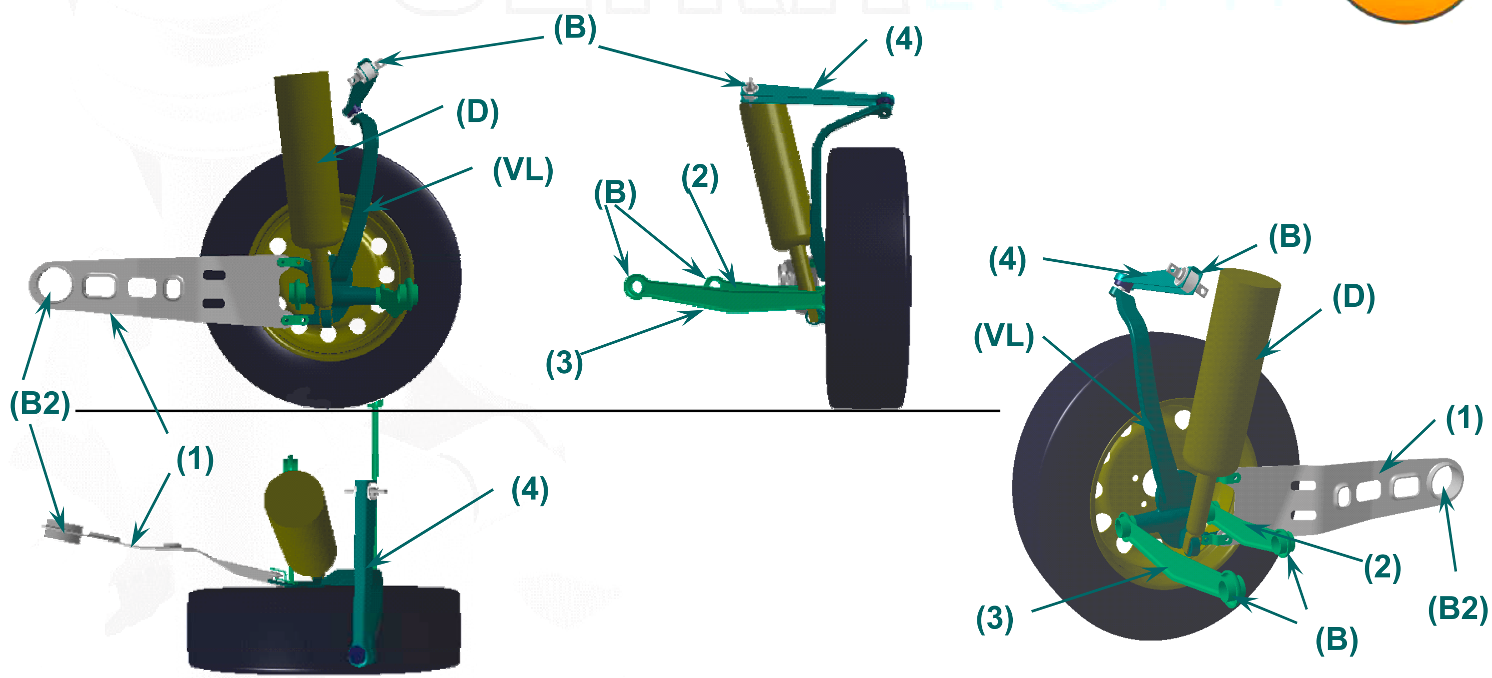
DOUBLE WISHBONE: SUSPENSION



FORCES

Longitudinal:- Forces are resisted by tension, compression and bending in arm (1) and by tension and compression loads in links (2) (3) & (4).

Lateral:- Forces are resisted by tension and compression loads in links (2) (3) & (4) and bending in the vertical link (VL).

Vertical:- Forces are resisted by loads in the spring / damper unit (D) and by tension and compression loads in links (2) (3) & (4) and bending in the vertical link (VL).

Braking:- Torque is taken by tension and bending in arm (1).

DOUBLE WISHBONE: MASS

D Class

DOUBLE WISHBONE

PARTS LIST			D Class			D Class Benchmark Data		
ITEM No.	DESCRIPTION	QTY Veh	System (kg)	Sub Assy (kg)	Parts (kg)	System (kg)	Sub Assy (kg)	Parts (kg)
1	ASSEMBLY, DOUBLE WISHBONE	1	32.88			39.84		
2	KNUCKLE ASSEMBLY, RH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
3	KNUCKLE ASSEMBLY, LH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
4	HUB BEARING UNIT	2	**6.50**	**3.250**	3.250	**3.74**		1.870
5	SHEAR PLATE	2	**0.25**	**0.126**	0.126			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
9	TRAILING ARM ASSEMBLY, LH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
10	TRAILING ARM BUSH, REAR	4			0.040			
11	TRAILING ARM BUSH, FRONT	2			0.476			
12	TRAILING ARM, RH	1			1.254			
13	TRAILING ARM, LH	1			1.254			
14	DAMPER	2	**4.20**	**2.100**		**4.56**		2.280
15	SPRING	2	**4.04**	**2.018**	2.018	**4.62**		2.310
16	MOUNT, UPR, SPRING & DAMPER	2	**1.10**	**0.550**				
17	SHORT LATERAL LINK ASSEMBLY	2	**0.31**	**0.153**	0.153	**1.85**		0.925
18	LONG LATERAL LINK ASSEMBLY	2	**1.46**	**0.729**	0.729	**2.33**		1.165
19	LINK BUSH HOUSING	8			0.034			
20	SHORT LINK	2			0.085			
21	LONG LINK	2			0.661			
22	UPPER LINK ASSEMBLY	2	**0.61**	**0.307**	0.307	**2.16**		1.080
23	BALL JOINT	2			0.140			
24	LINK	2			0.134			
25	BUSH HOUSING, UPPER LINK	2			0.033			
26	VARIOUS BUSHES AND JOINTS		**1.63**					
27	ASSORTED FIXINGS		**1.20**			**0.72**		

DOUBLE WISHBONE: MASS

P Class

DOUBLE WISHBONE

PARTS LIST			P Class			D Class Benchmark Data		
ITEM No.	DESCRIPTION	QTY Veh	System (kg)	Sub Assy (kg)	Parts (kg)	System (kg)	Sub Assy (kg)	Parts (kg)
1	ASSEMBLY, DOUBLE WISHBONE	1	**31.29**			**39.84**		
2	KNUCKLE ASSEMBLY, RH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
3	KNUCKLE ASSEMBLY, LH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
4	HUB BEARING UNIT	2	**6.50**	**3.250**	3.250	**3.74**		1.870
5	SHEAR PLATE	2	**0.25**	**0.126**	0.126			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
9	TRAILING ARM ASSEMBLY, LH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
10	TRAILING ARM BUSH, REAR	4			0.040			
11	TRAILING ARM BUSH, FRONT	2			0.476			
12	TRAILING ARM, RH	1			1.254			
13	TRAILING ARM, LH	1			1.254			
14	DAMPER	2	**4.20**	**2.100**		**4.56**		2.280
15	SPRING	2	**2.45**	**1.226**	1.226	**4.62**		2.310
16	MOUNT, UPR, SPRING & DAMPER	2	**1.10**	**0.550**				
17	SHORT LATERAL LINK ASSEMBLY	2	**0.31**	**0.153**	0.153	**1.85**		0.925
18	LONG LATERAL LINK ASSEMBLY	2	**1.46**	**0.729**	0.729	**2.33**		1.165
19	LINK BUSH HOUSING	8			0.034			
20	SHORT LINK	2			0.085			
21	LONG LINK	2			0.661			
22	UPPER LINK ASSEMBLY	2	**0.61**	**0.307**	0.307	**2.16**		1.080
23	BALL JOINT	2			0.140			
24	LINK	2			0.134			
25	BUSH HOUSING, UPPER LINK	2			0.033			
26	VARIOUS BUSHES AND JOINTS		**1.63**					
27	ASSORTED FIXINGS		**1.20**			**0.72**		

DOUBLE WISHBONE: COST

D & P Class

N.B. All Costs in US $ Tooling in US$(,000)

DOUBLE WISHBONE

PARTS LIST			D & P Class			Benchmark D Class		
ITEM No.	DESCRIPTION	QTY Veh	PART COST	SYSTEM COST	TOOLING COST	PART COST	SYSTEM COST	TOOLING COST
1	ASSEMBLY, DOUBLE WISHBONE	1		202.50	4340.00		200.70	4192.00
2	KNUCKLE ASSEMBLY, RH	1	$24.0	$24.0	$600	$17.3	$17.3	$578
3	KNUCKLE ASSEMBLY, LH	1	$24.0	$24.0	$600	$17.3	$17.3	
4	HUB BEARING UNIT	2	$19.0	$38.0	$0	$8.3	$16.6	$149
5	SHEAR PLATE	2	$1.1	$1.1	$30			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	$12.0	$12.0	$1,100	$17.3	$34.6	$990
9	TRAILING ARM ASSEMBLY, LH	1	$12.0	$12.0	$1,100			
10	TRAILING ARM BUSH, REAR	4						
11	TRAILING ARM BUSH, FRONT	2						
12	TRAILING ARM, RH	1						
13	TRAILING ARM, LH	1						
14	DAMPER	2	$16.0	$32.0	$360	$23.1	$46.2	$495
15	SPRING	2	$5.5	$11.0	$0			
16	MOUNT, UPR, SPRING & DAMPER	2	$1.6	$3.2	$250			
17	SHORT LATERAL LINK ASSEMBLY	2	$3.6	$7.2	$100	$6.6	$13.2	$660
18	LONG LATERAL LINK ASSEMBLY	2	$4.5	$9.0	$100	$9.6	$19.2	$660
19	LINK BUSH HOUSING	8						
20	SHORT LINK	2						
21	LONG LINK	2						
22	UPPER LINK ASSEMBLY	2	$7.0	$14.0	$100	$8.4	$16.8	$660
23	BALL JOINT	2						
24	LINK	2						
25	BUSH HOUSING, UPPER LINK	2						
26	VARIOUS BUSHES AND JOINTS		$13.0	$13.0			$17.8	
27	ASSORTED FIXINGS		$2.0	$2.0			$1.7	

DOUBLE WISHBONE: MATERIAL

D Class

DOUBLE WISHBONE

PARTS LIST				MATERIAL	
ITEM No.	DESCRIPTION	QTY Veh	REMARKS	Gauge (mm)	Grade (MPa)
1	ASSEMBLY, DOUBLE WISHBONE	1	FULL SUSPENSION ASSEMBLY		
2	KNUCKLE ASSEMBLY, RH	1	FORGED PART	na	600
3	KNUCKLE ASSEMBLY, LH	1	FORGED PART	na	600
4	HUB BEARING UNIT	2	GEN 3 WITH ACTIVE ABS SENSOR		
5	SHEAR PLATE	2	BLANK & PIERCE	2	500
6	DISC, BRAKE	2	SOLID, CAST IRON		
7	CALIPER, BRAKE	2	INTEGRATED HANDBRAKE MECHANISM		
8	TRAILING ARM ASSEMBLY, RH	1	FABRICATION (ITEMS:- 10,11,12)		
9	TRAILING ARM ASSEMBLY, LH	1	FABRICATION (ITEMS:- 10,11,13)		
10	TRAILING ARM BUSH, REAR	4	TUBE	3	500
11	TRAILING ARM BUSH, FRONT	2	TUBE	3	500
12	TRAILING ARM, RH	1	PRESSING	3	500
13	TRAILING ARM, LH	1	PRESSING	3	500
14	DAMPER ASSEMBLY	2	INCL SPRING SEAT & BUMP RUBBER	See note	
15	SPRING	2	SHEAR STRESS 1300MPa	Ø 10.91	1300
16	MOUNT, UPR, SPRING & DAMPER	2	2 BOLT FIXING TO BIW.		
17	SHORT LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,20)		
18	LONG LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,21)		
19	LINK BUSH HOUSING	8	TUBE	3	250
20	SHORT LINK	2	TUBE	Ø 14 x 1.5	250
21	LONG LINK	2	TUBE	Ø 25 x 3	250
22	UPPER LINK ASSEMBLY	2	WELD AND PRESS FIT (ITEMS:- 23,24,25)		
23	BALL JOINT	2			
24	LINK	2	TUBE	Ø 13 x 1.5	250
25	BUSH HOUSING, UPPER LINK	2	TUBE	1.5	250
26	VARIOUS BUSHES AND JOINTS		RUBBER BUSHES & SPHERICAL JOINTS		
27	ASSORTED FIXINGS		NUTS, BOLTS & WASHERS ETC		

Note : Damper Assembly Consists of 4 Main Components

Damper Body:	350 MPa Material
Damper Rod:	Dia 13mm x 3mm tube
Spring Pan:	350 Mpa Material
Bump Stop Rubber:	Polyurethane Material

DOUBLE WISHBONE: MATERIAL

P Class

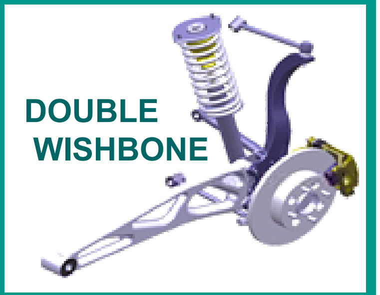
DOUBLE WISHBONE

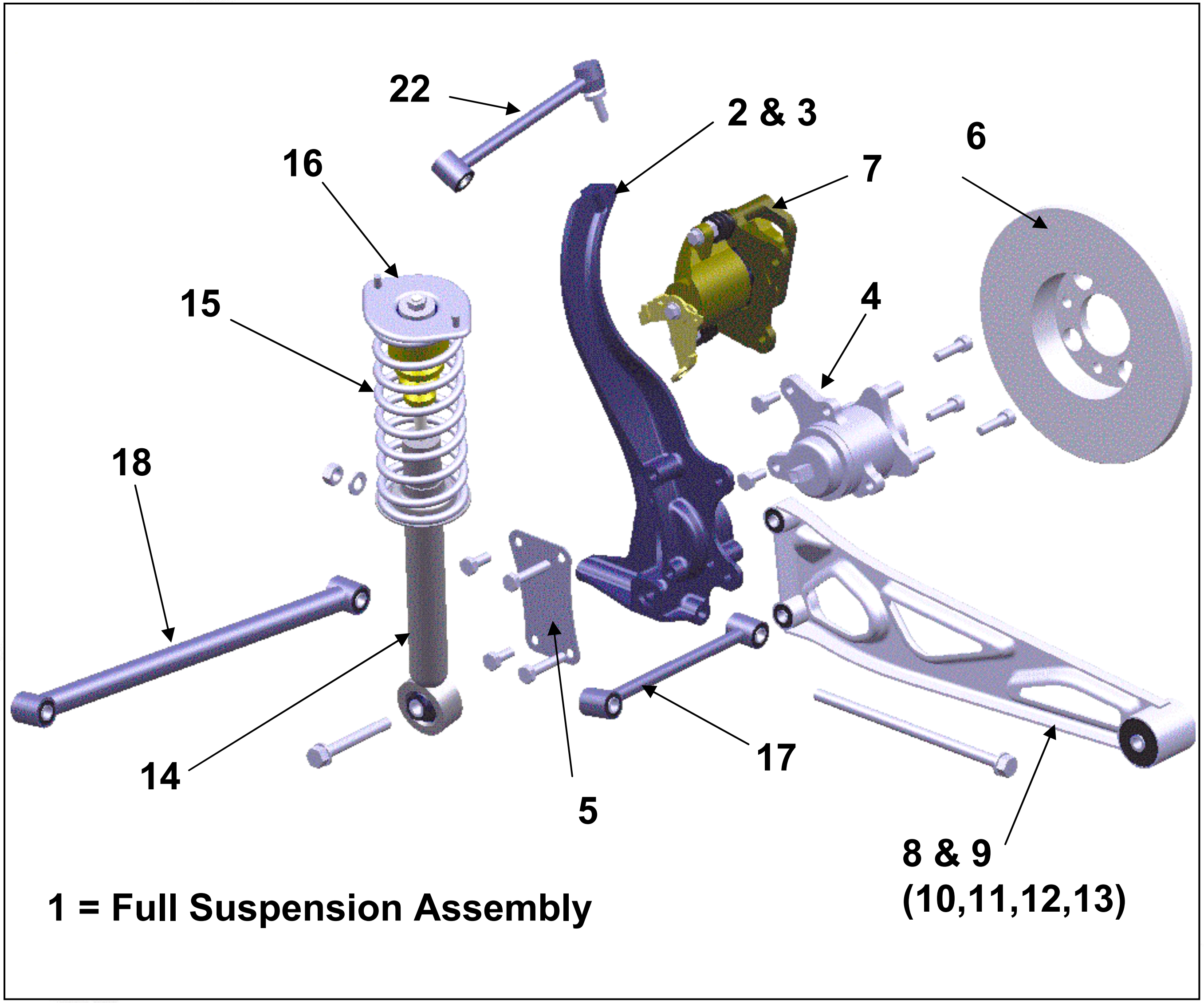
PARTS LIST				MATERIAL	
ITEM No.	DESCRIPTION	QTY Veh	**REMARKS**	Gauge (mm)	Grade (MPa)
1	ASSEMBLY, DOUBLE WISHBONE	1	FULL SUSPENSION ASSEMBLY		
2	KNUCKLE ASSEMBLY, RH	1	FORGED PART	na	600
3	KNUCKLE ASSEMBLY, LH	1	FORGED PART	na	600
4	HUB BEARING UNIT	2	GEN 3 WITH ACTIVE ABS SENSOR		
5	SHEAR PLATE	2	BLANK & PIERCE	2	500
6	DISC, BRAKE	2	SOLID, CAST IRON		
7	CALIPER, BRAKE	2	INTEGRATED HANDBRAKE MECHANISM		
8	TRAILING ARM ASSEMBLY, RH	1	FABRICATION (ITEMS:- 10,11,12)		
9	TRAILING ARM ASSEMBLY, LH	1	FABRICATION (ITEMS:- 10,11,13)		
10	TRAILING ARM BUSH, REAR	4	TUBE	3	500
11	TRAILING ARM BUSH, FRONT	2	TUBE	3	500
12	TRAILING ARM, RH	1	PRESSING	3	500
13	TRAILING ARM, LH	1	PRESSING	3	500
14	DAMPER ASSEMBLY	2	INCL SPRING SEAT & BUMP RUBBER	See note	
15	SPRING	2	SHEAR STRESS 1300MPa	Ø 9.08	1300
16	MOUNT, UPR, SPRING & DAMPER	2	2 BOLT FIXING TO BIW.		
17	SHORT LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,20)		
18	LONG LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,21)		
19	LINK BUSH HOUSING	8	TUBE	3	250
20	SHORT LINK	2	TUBE	Ø 14 x 1.5	250
21	LONG LINK	2	TUBE	Ø 25 x 3	250
22	UPPER LINK ASSEMBLY	2	WELD AND PRESS FIT (ITEMS:- 23,24,25)		
23	BALL JOINT	2			
24	LINK	2	TUBE	Ø 13 x 1.5	250
25	BUSH HOUSING, UPPER LINK	2	TUBE	1.5	250
26	VARIOUS BUSHES AND JOINTS		RUBBER BUSHES & SPHERICAL JOINTS		
27	ASSORTED FIXINGS		NUTS, BOLTS & WASHERS ETC		

Note : Damper Assembly Consists of 4 Main Components

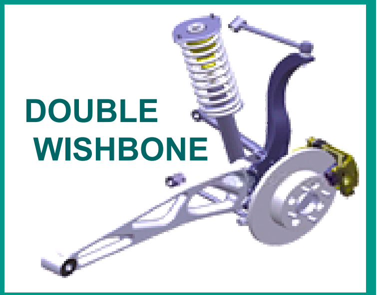
Damper Body:	350 MPa Material
Damper Rod:	Dia 13mm x 3mm tube
Spring Pan:	350 Mpa Material
Bump Stop Rubber:	Polyurethane Material

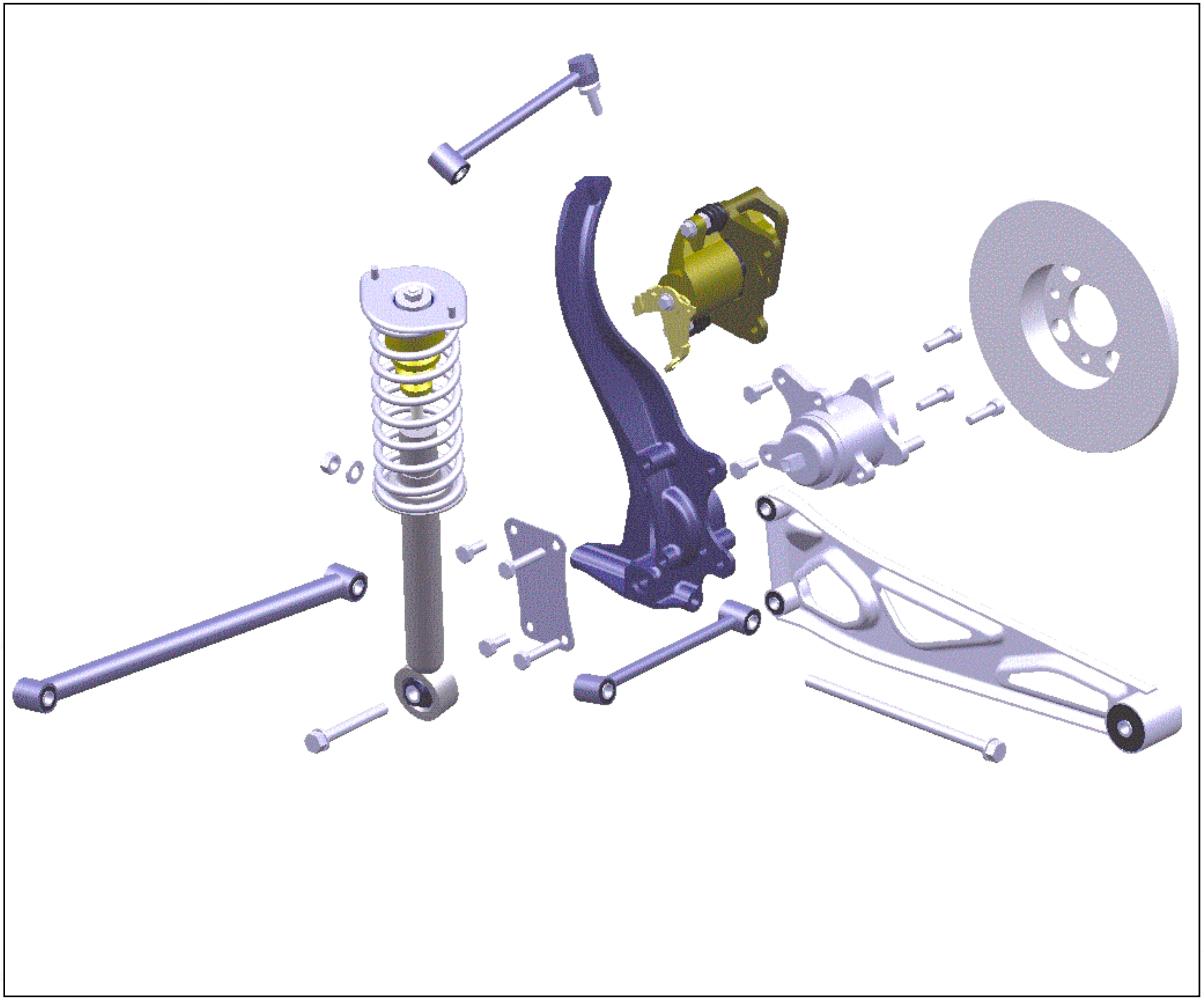
DOUBLE WISHBONE: EXPLODED VIEW





DOUBLE WISHBONE: DESIGN

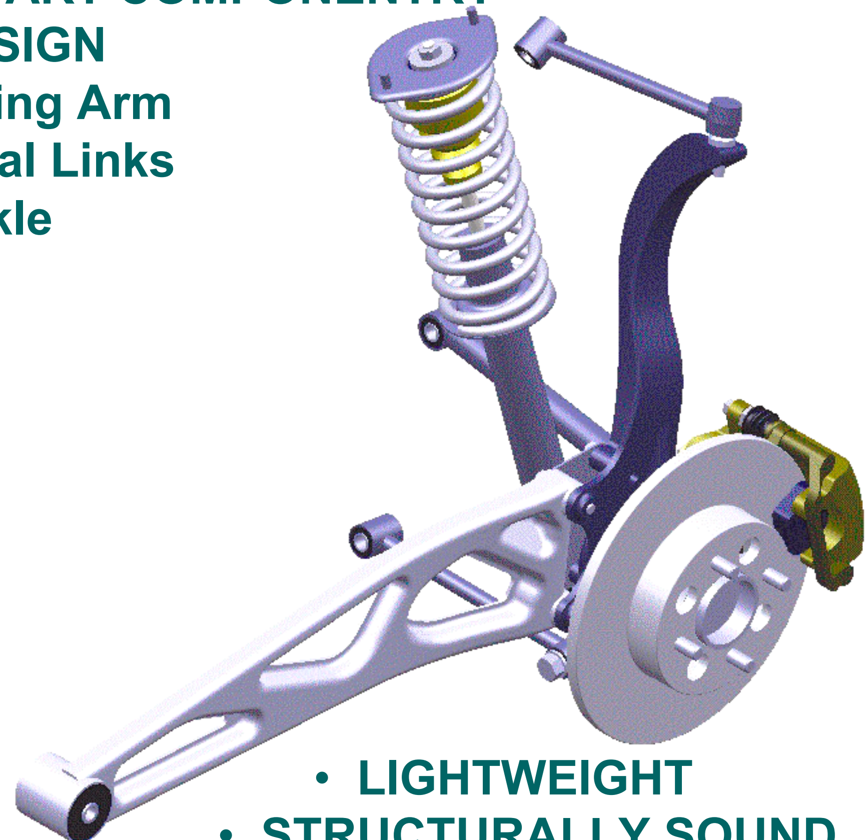




DOUBLE WISHBONE: DESIGN

Overview

- BASED ON BENCHMARK PRINCIPLES
- STATE OF THE ART COMPONENTRY
- OPTIMISED DESIGN
  - Pressed Trailing Arm
  - Tubular Lateral Links
  - Forged Knuckle

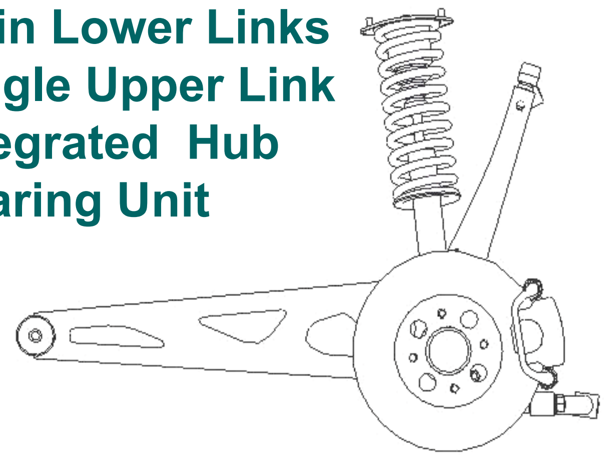


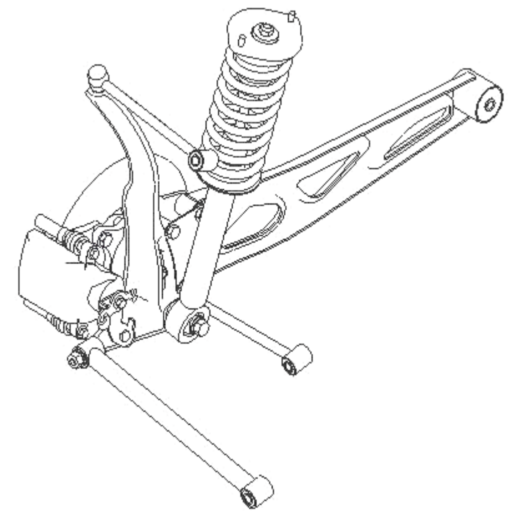
- LIGHTWEIGHT
- STRUCTURALLY SOUND
- GOOD PERFORMANCE
- MANUFACTURABLE
- AFFORDABLE

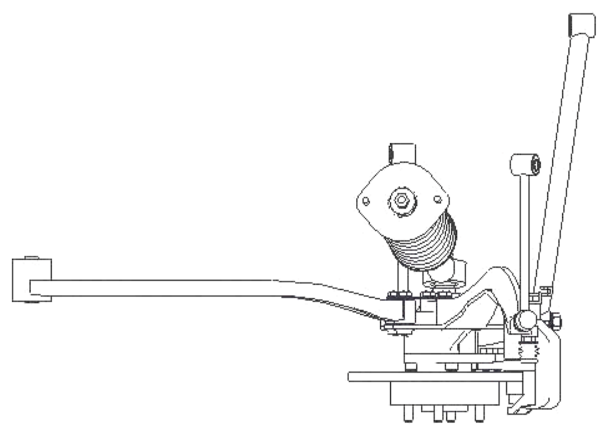
DOUBLE WISHBONE: DESIGN

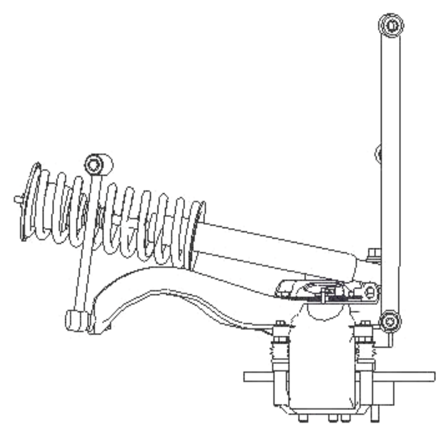
Overview

- Co-axial Spring Damper
- Single Trailing Arm
- Twin Lower Links
- Single Upper Link
- Integrated Hub Bearing Unit









DOUBLE WISHBONE: DESIGN

Approach

- **The initial package layout was created with 3D models developed in the CAD system. These were based upon sections and shape that exhibit appropriate properties.**

- **The designs were refined by close collaboration between CAD & CAE to develop these initial concepts through a series of evolutions and optimisations to the final concept proposal.**

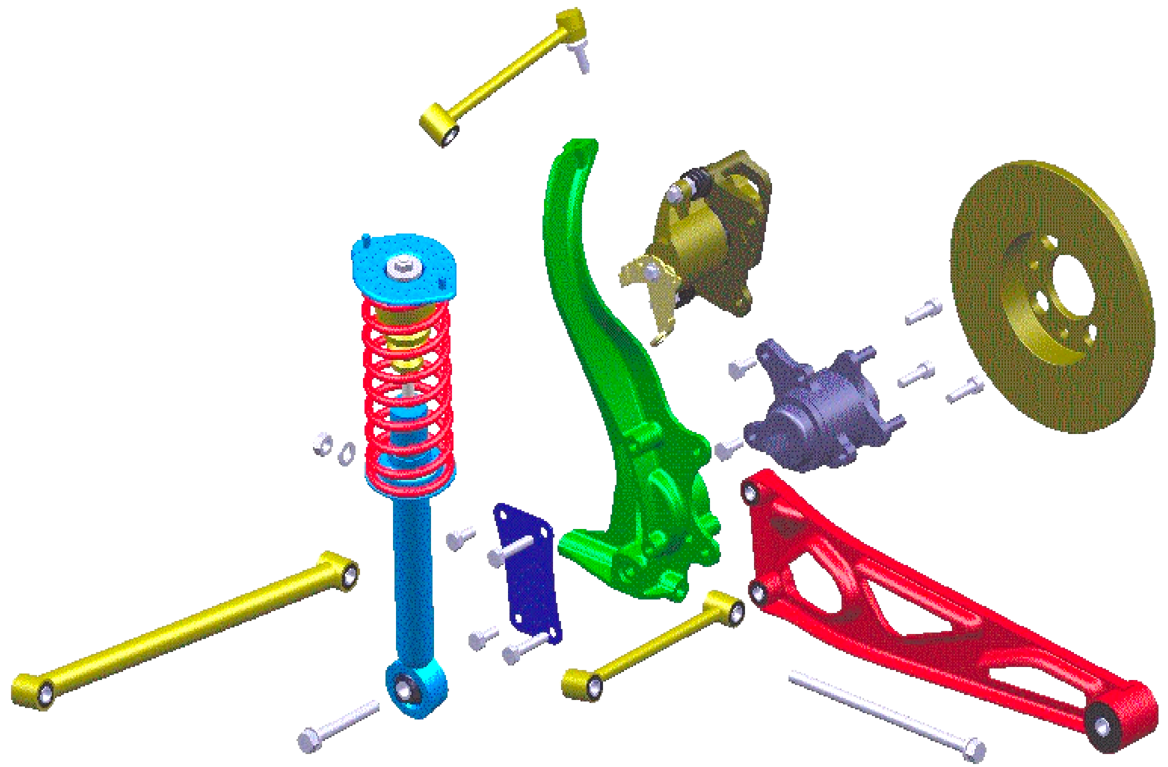
- **Structural Analysis optimisation techniques were utilised to establish material gauges and grades for each part of the main structural component, so as to meet both the stiffness and structural targets.**

- **Further, more detailed analysis (including non-linear in selected areas) was carried out to validate the design. In some cases, even detail design features were fully investigated and validated.**

DOUBLE WISHBONE: DESIGN

Parts Review

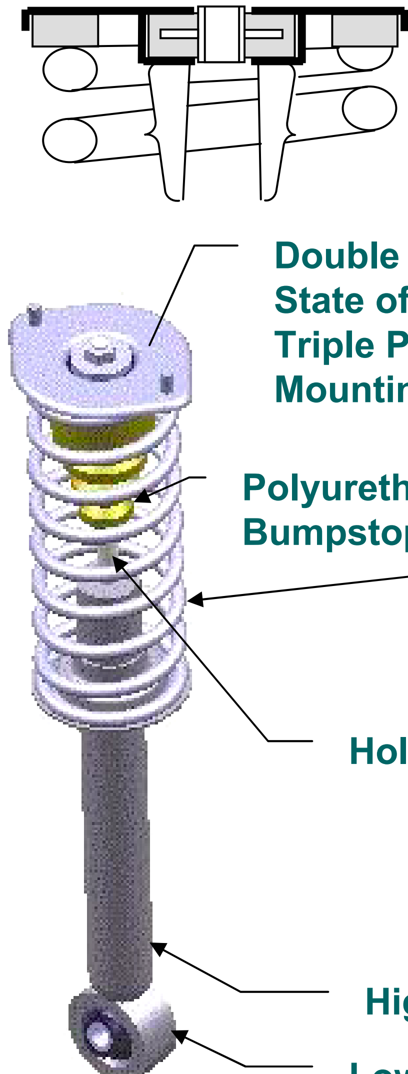
DOUBLE WISHBONE

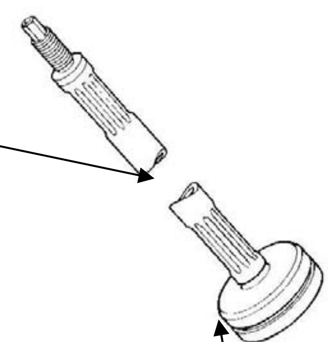


DOUBLE WISHBONE: DESIGN

Spring Damper

			D Class	P Class
Outer Diameter	Do	mm	92.01	90.19
Inner diameter	Di	mm	70.20	72.03
Design length	Ld	mm	234.23	234.23
Bump length	Lb	mm	134.23	142.23
Rebound length	Lr	mm	318.23	322.23
Load at Design length	Pd	N	4068.08	2636.44
Number of working coils	n	-	9.25	7.91
Total number of coils	N		10.75	9.41
Maximum Allowable Stress		N/mm^2	1300	1300
Mean coil diameter	D	mm	81.11	81.11
Wire diameter	d	mm	10.91	9.08
Spring rate	**S**	**N/mm**	**28.13**	**15.78**
Wire length	Lw	mm	2752.26	2413.62
Spring mass	m	kg	**2.02**	**1.23**





DOUBLE WISHBONE: DESIGN

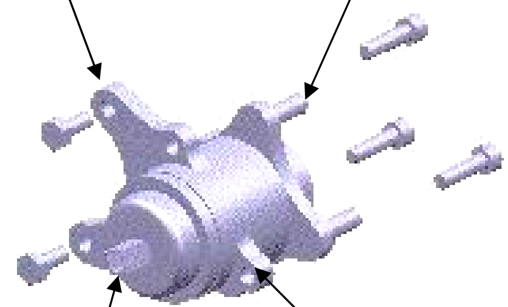
Hub & Bearing Unit

DOUBLE WISHBONE

GENERATION 3 TYPE HUB & BEARING UNIT

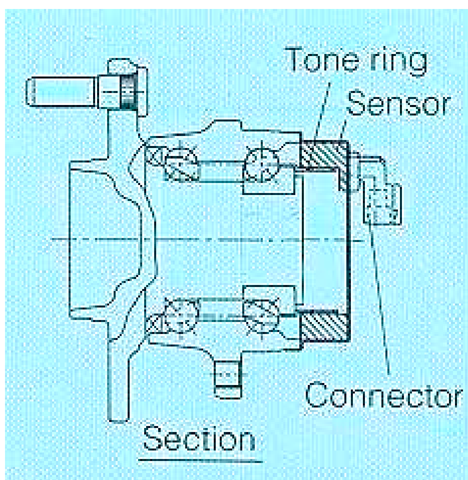
Integral Brake Caliper Mountings

Integrated Wheel Hub Flange



Integral ABS Sensor (Anti-Lock Brake System)

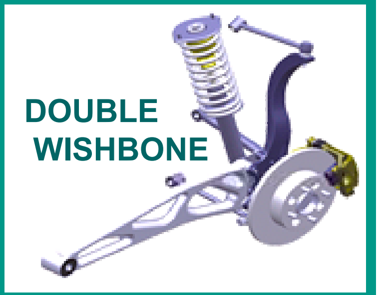
Flange to Bolt Bearing Unit to knuckle

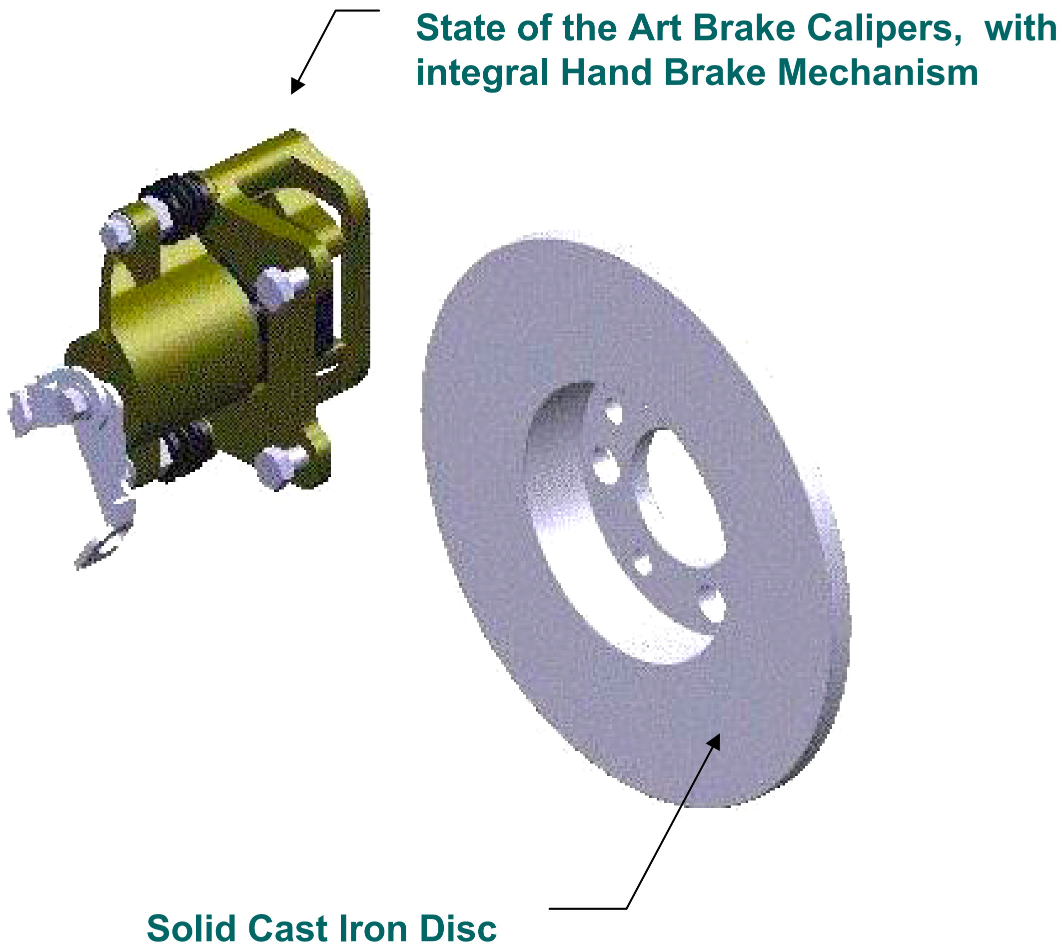


Typical Cross Section of Bearing

DOUBLE WISHBONE: DESIGN

Brakes & Bushes





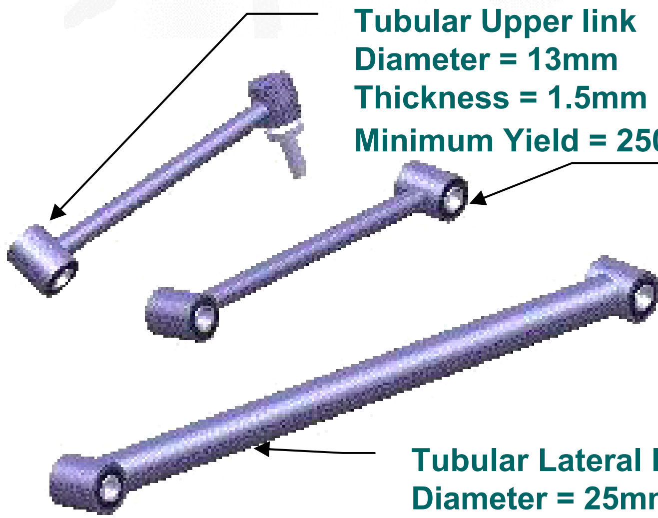
DOUBLE WISHBONE: DESIGN

Lateral Links

Analysis demonstrated that a ‘cigar’ shaped member holds a marginal structural advantage over a parallel thin walled tube.

However, the manufacturing cost penalty of adopting such a configuration is significant. Therefore the links employed throughout the ULSAS programme are all parallel thin walled tubes.

Nevertheless, a variety of compatible end fittings have been considered & employed in the design solutions, examples of which are depicted.

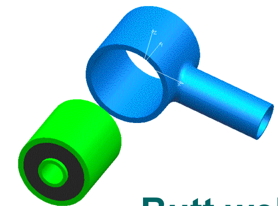


Tubular Upper link
Diameter = 13mm
Thickness = 1.5mm
Minimum Yield = 250 MPa

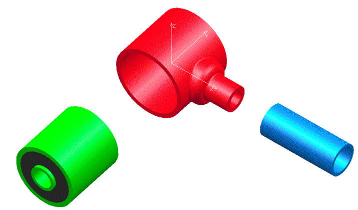
Tubular Lateral link
Diameter = 14mm
Thickness = 1.5mm
Minimum Yield 250 MPa

Tubular Lateral link
Diameter = 25mm
Thickness = 3.0mm
Minimum Yield = 250 MPa

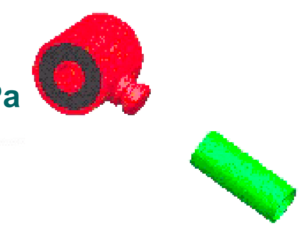
Alternative End Fixings



Butt welded



Hydro-formed T Piece clinched or welded

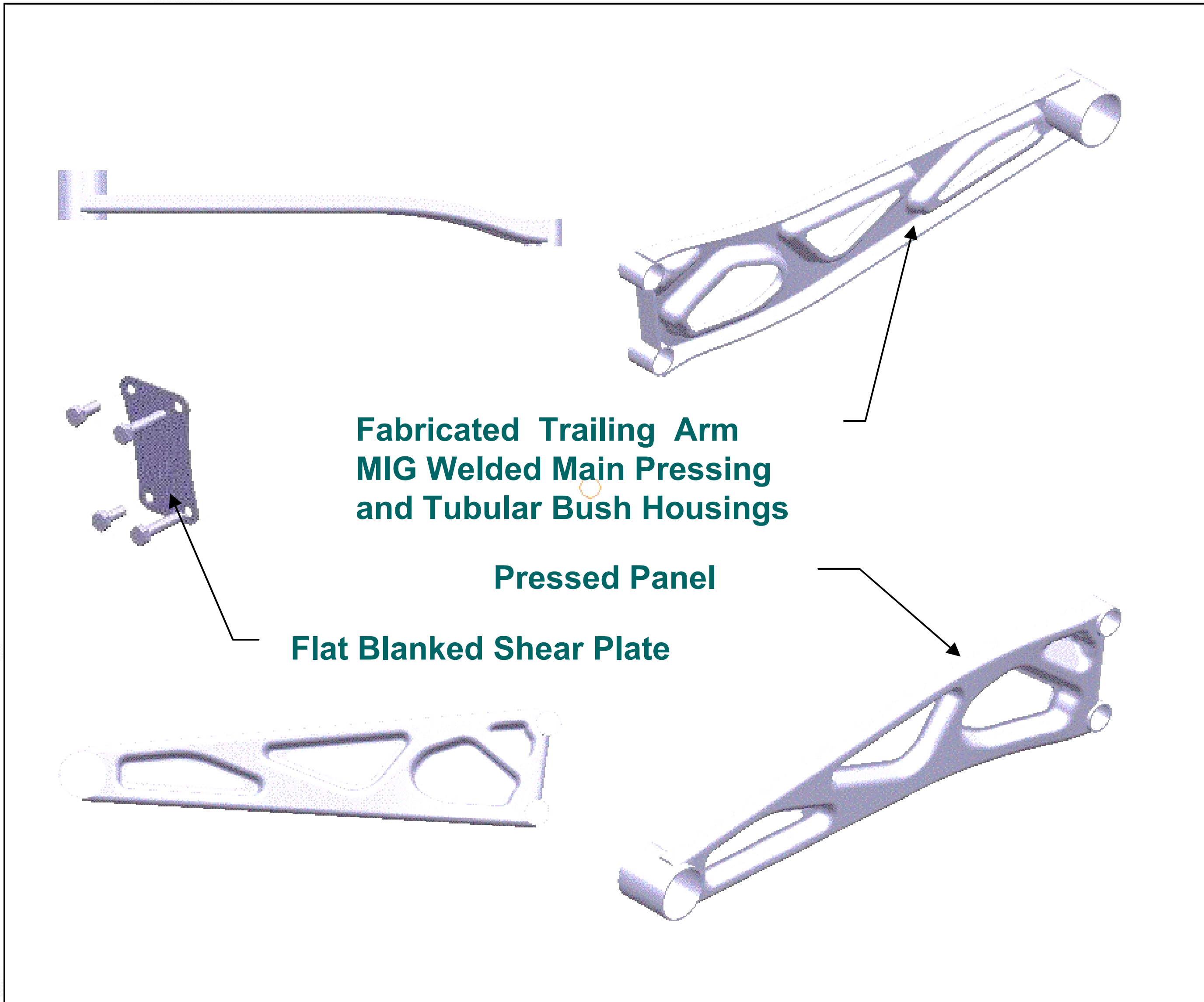


Cold rotary swage

ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: DESIGN

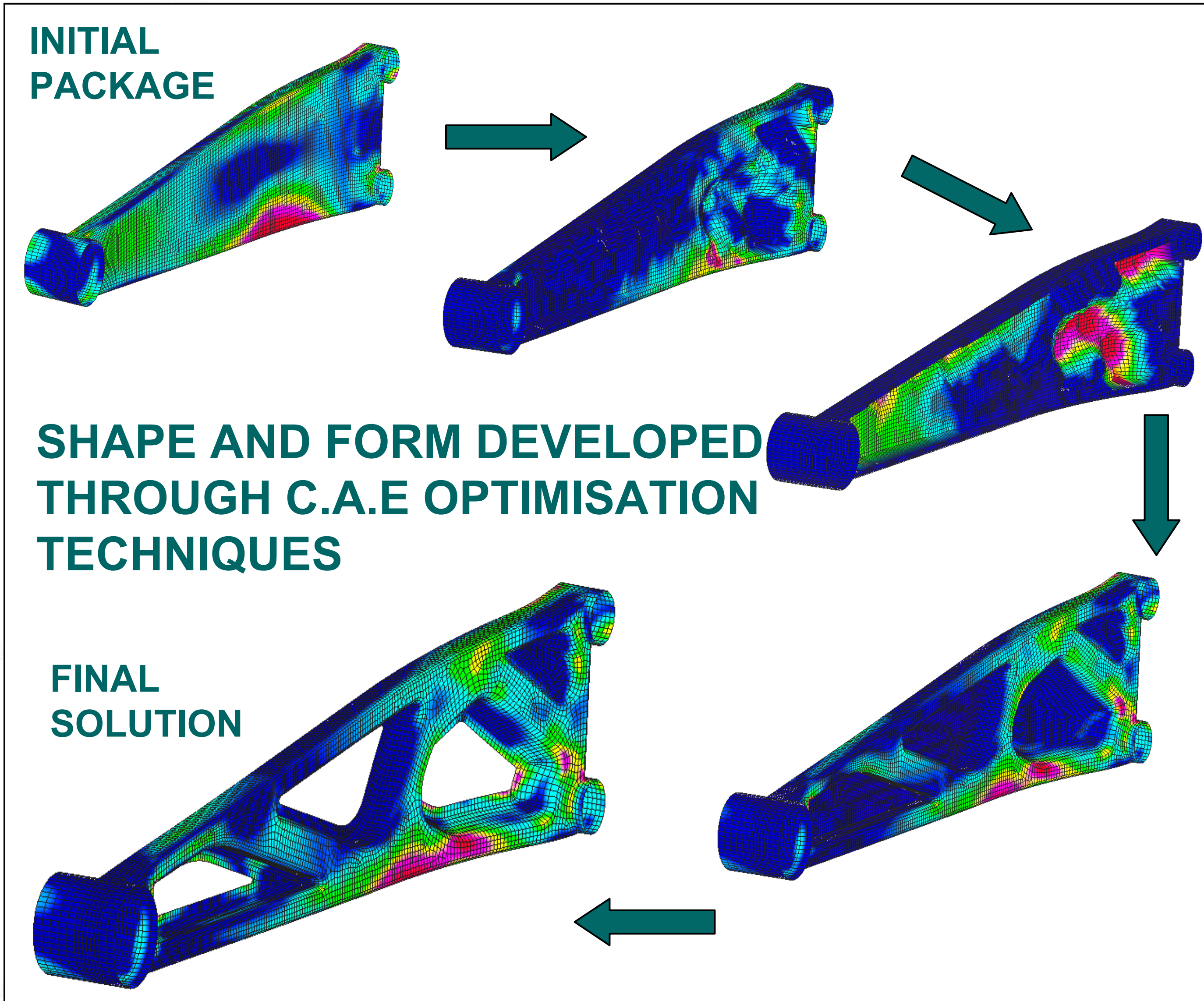
Trailing Arm



DOUBLE WISHBONE: DESIGN

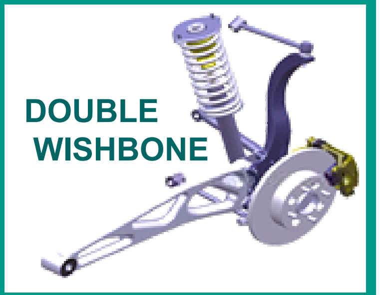
Trailing Arm

ULTRALIGHT STEEL AUTO SUSPENSION

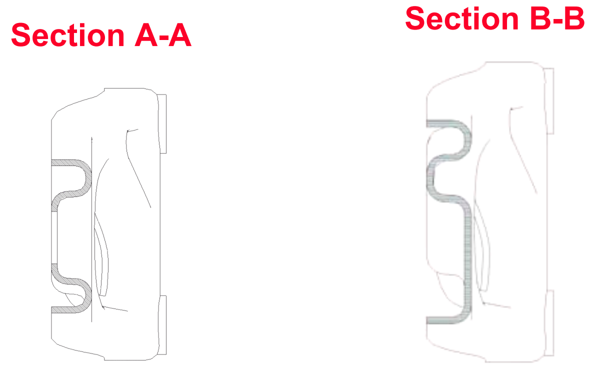


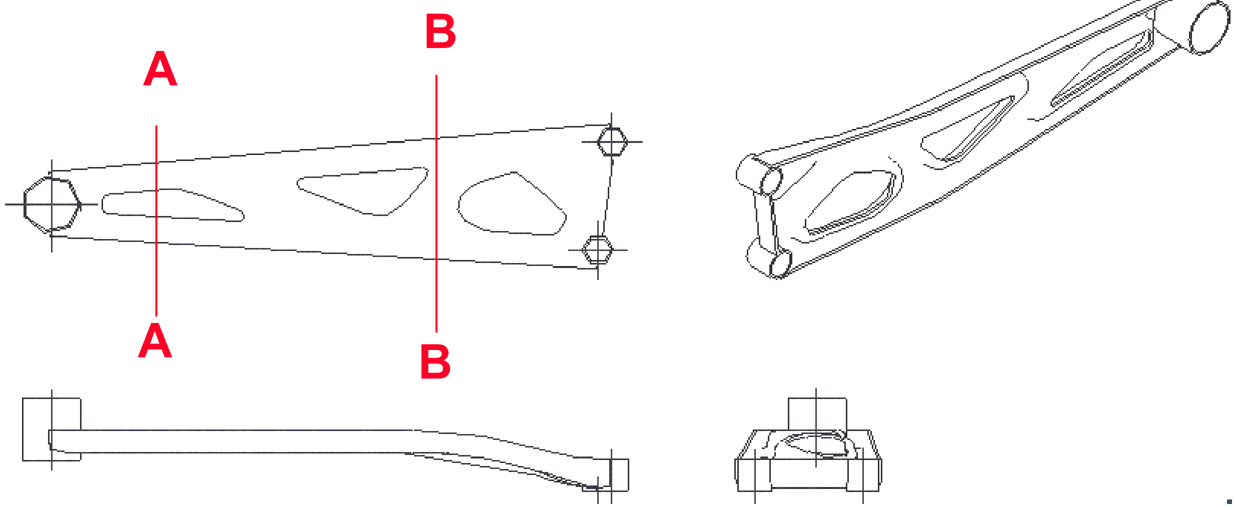
DOUBLE WISHBONE: DESIGN

Trailing Arm



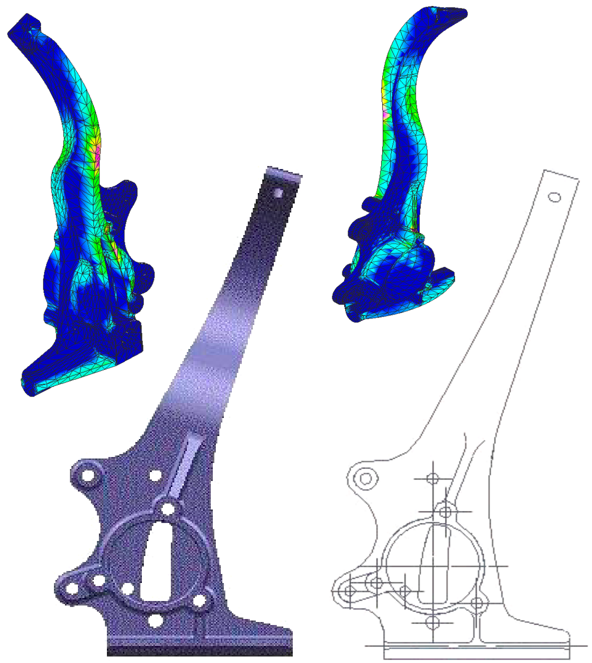
Part	Trailing Arm	
Process	Pressing	
	D	P
Material Gauge (mm)	3	3
Material Grade (Mpa)	500	500
Mass (kg)	1.81	1.81



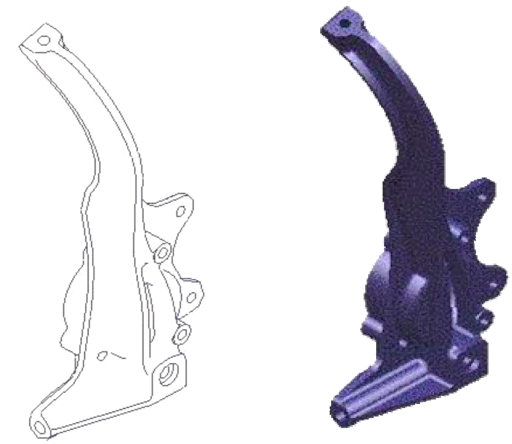


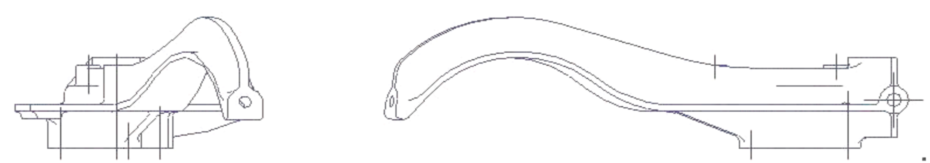
DOUBLE WISHBONE: DESIGN

Knuckle



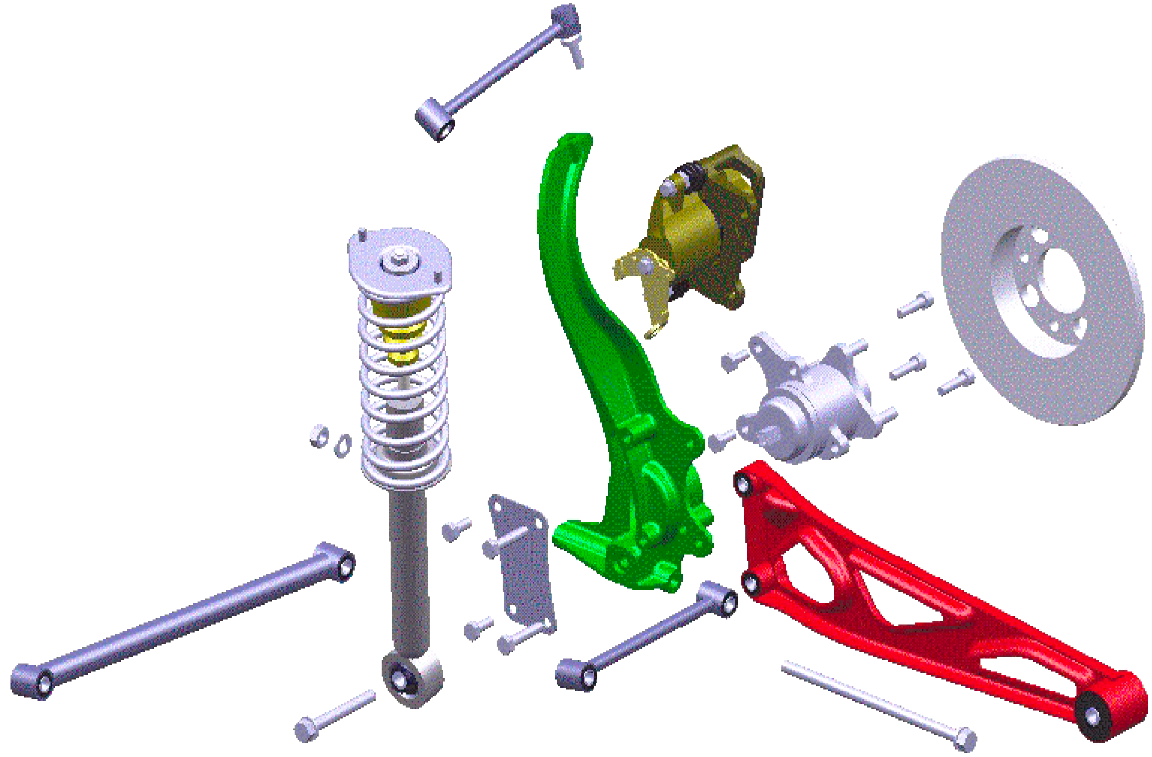
Part	Knuckle	
Process	Forging	
Class	D	P
Material Gauge (mm)	na	na
Material Grade (Mpa)	600	600
Mass (kg)	3.98	3.98





High Strength Forged Steel Knuckle was Designed and Developed in Conjunction With C.A.E Optimisation Techniques

DOUBLE WISHBONE
Finite Element Analysis



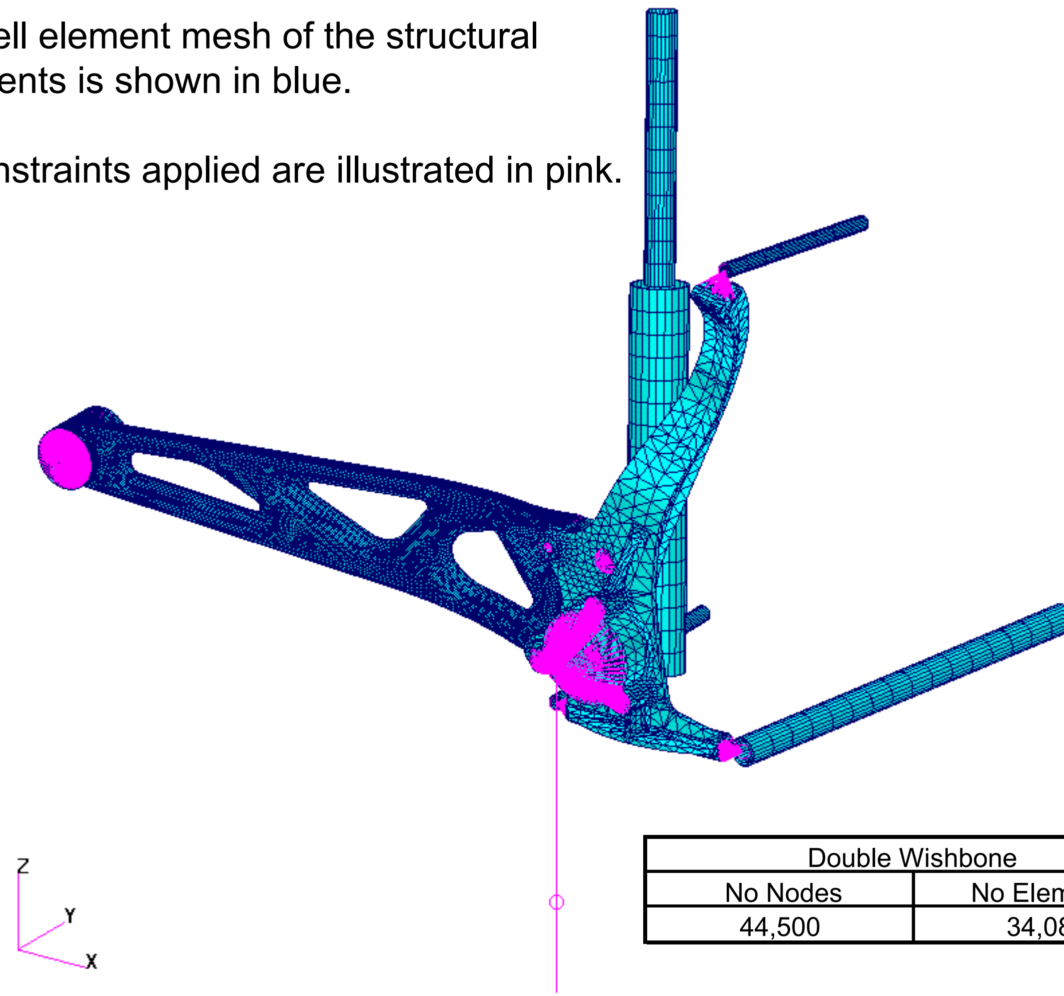
DOUBLE WISHBONE

Finite Element Analysis

Finite Element Model of Double Wishbone System:

•The shell element mesh of the structural components is shown in blue.

•The constraints applied are illustrated in pink.



Double Wishbone	
No Nodes	No Elements
44,500	34,086

DOUBLE WISHBONE: STRESS RESULTS

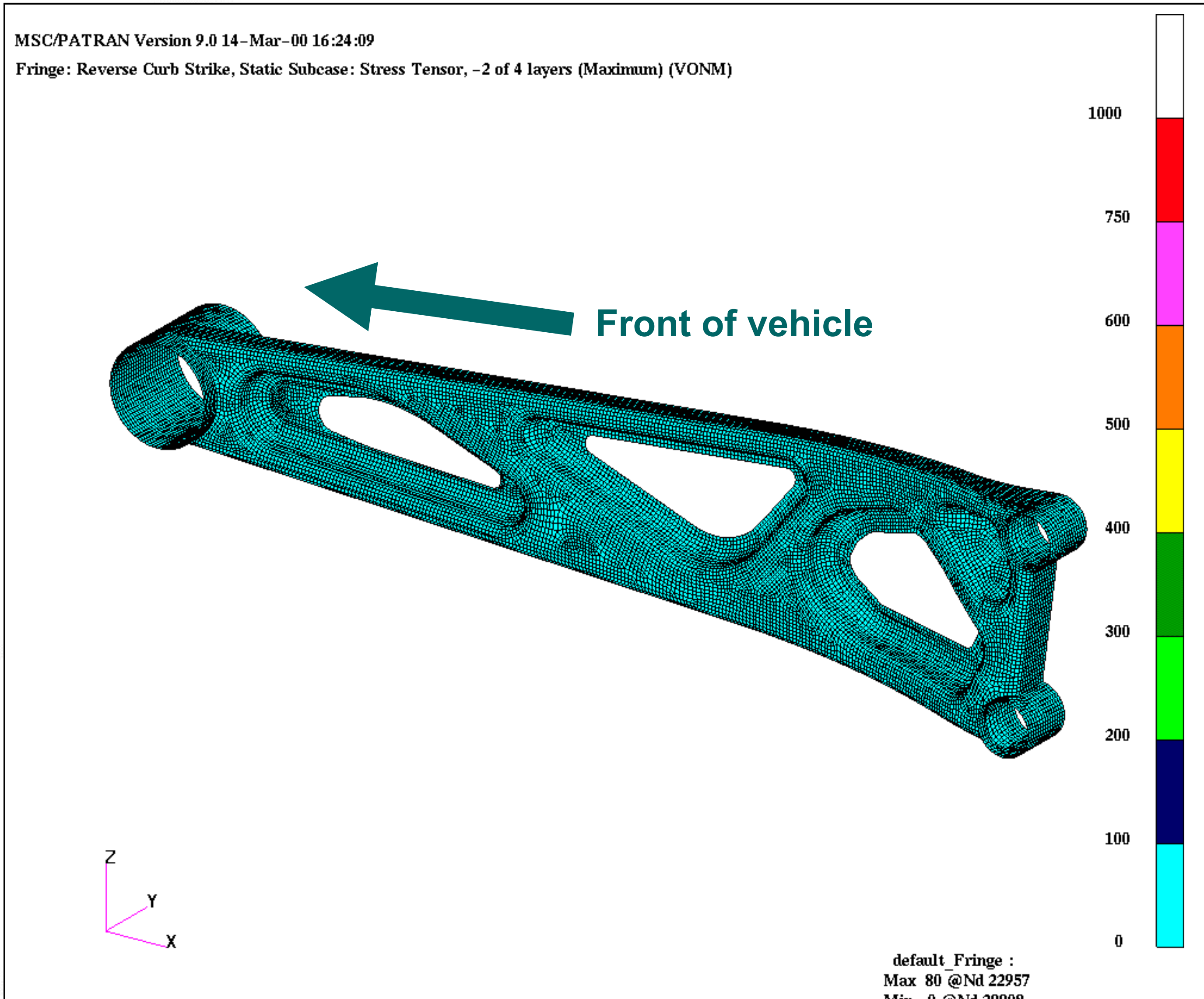
D Class

Load Case	Max stress (Von Mises) Knuckle	Max stress (Von Mises) Trailing Arm
Reverse Curb Strike (TCP)	468 MPa	80 MPa
Lateral Curb Strike 1 with load transfer	392 MPa	13 MPa
Lateral Curb Strike 2 with no load transfer	360 MPa	40 MPa
Vertical Bump (TCP)	557 MPa	166 MPa
Forward Braking with ABS (TCP)	345 MPa	633 MPa
Combined Bump and Cornering (TCP)	557 MPa	591 MPa
Pothole Brake (TCP)	513 MPa	593 MPa
	Knuckle	**Trailing Arm**

Click on result to view details

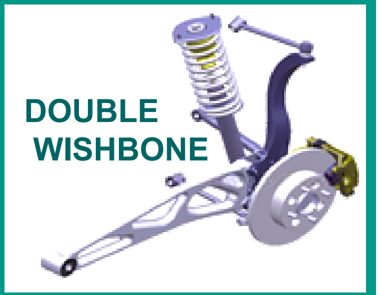
DOUBLE WISHBONE: TRAILING ARM

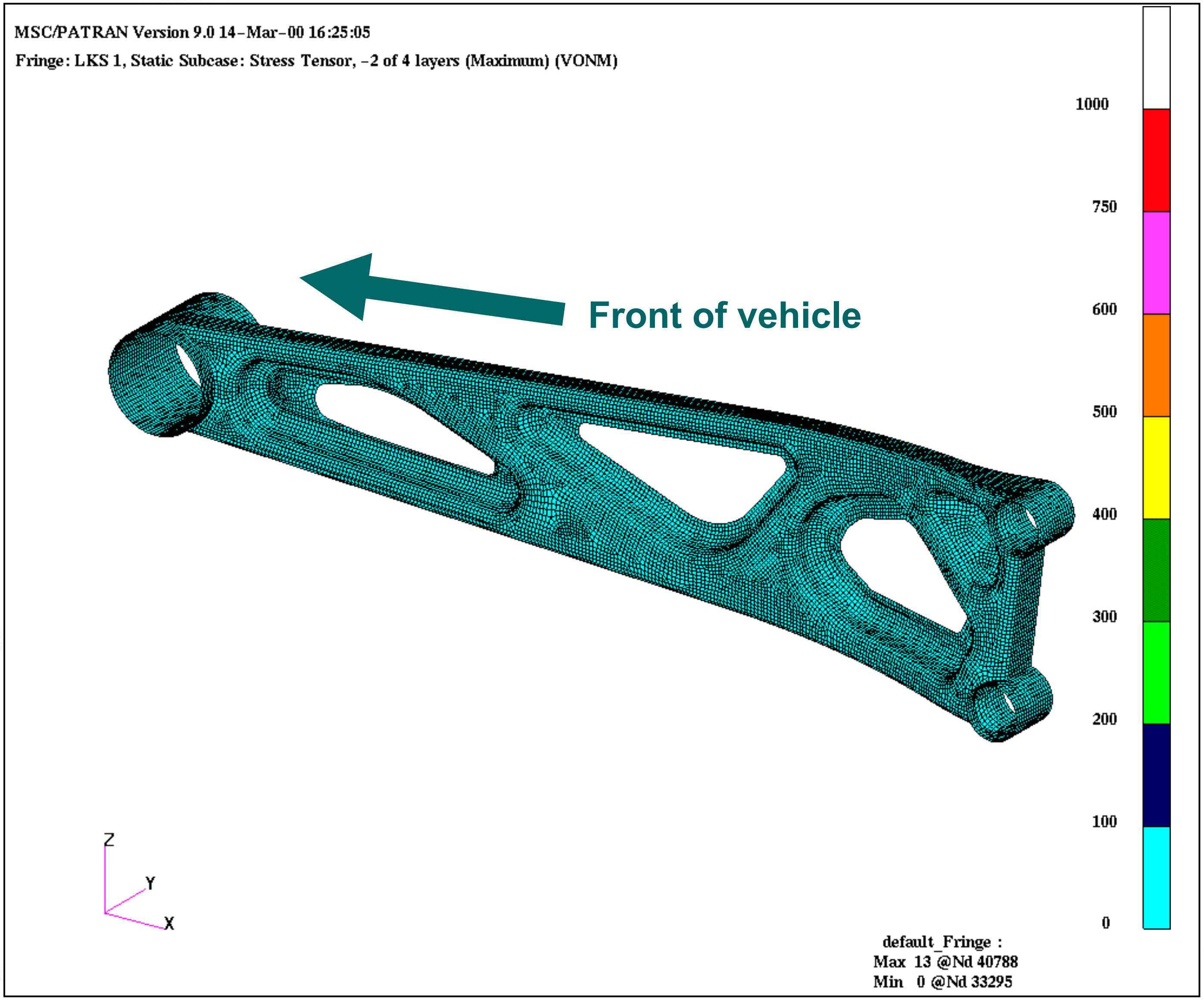
Reverse Curb Strike, D Class



DOUBLE WISHBONE: TRAILING ARM

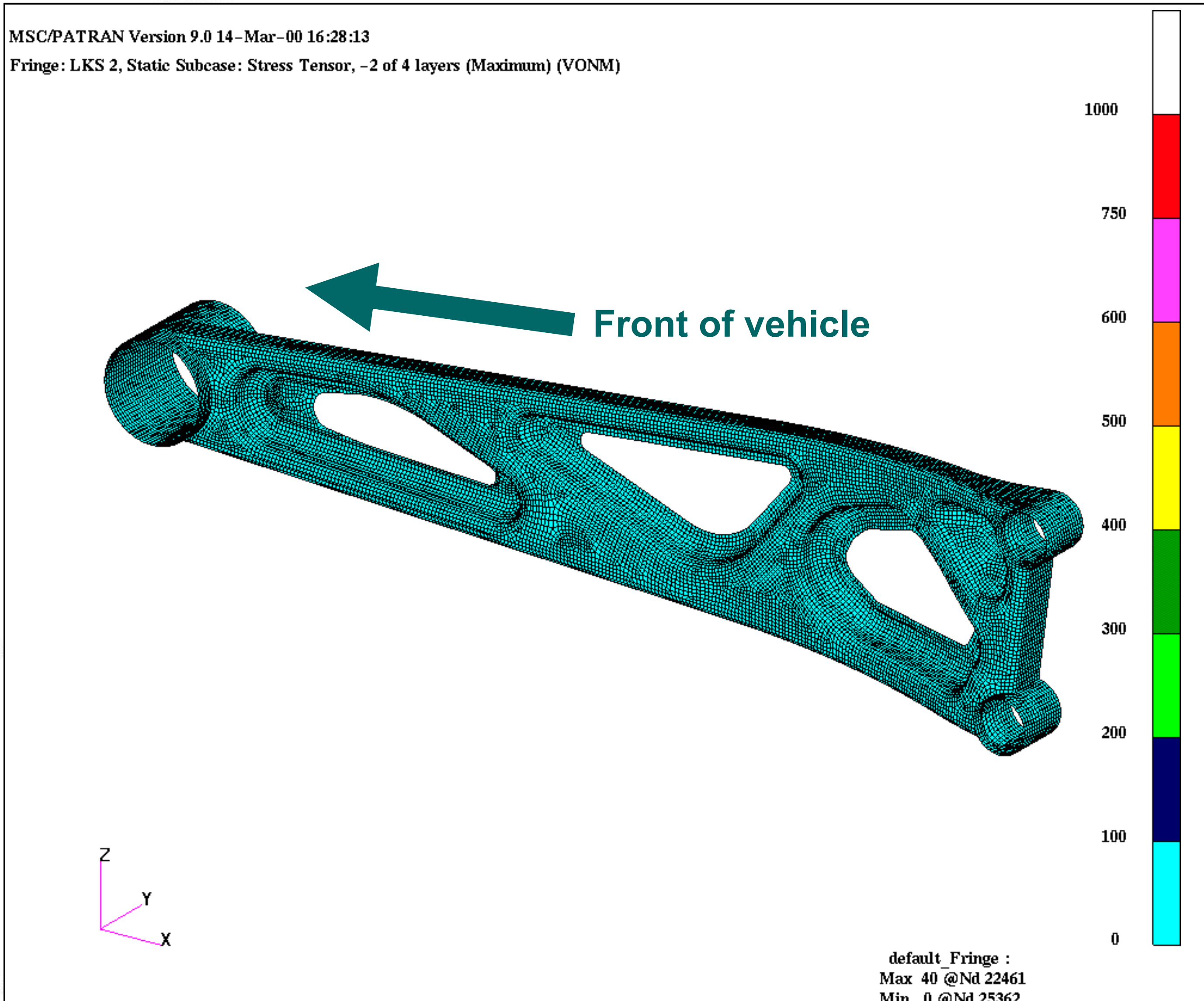
Lateral Curb Strike 1, D Class





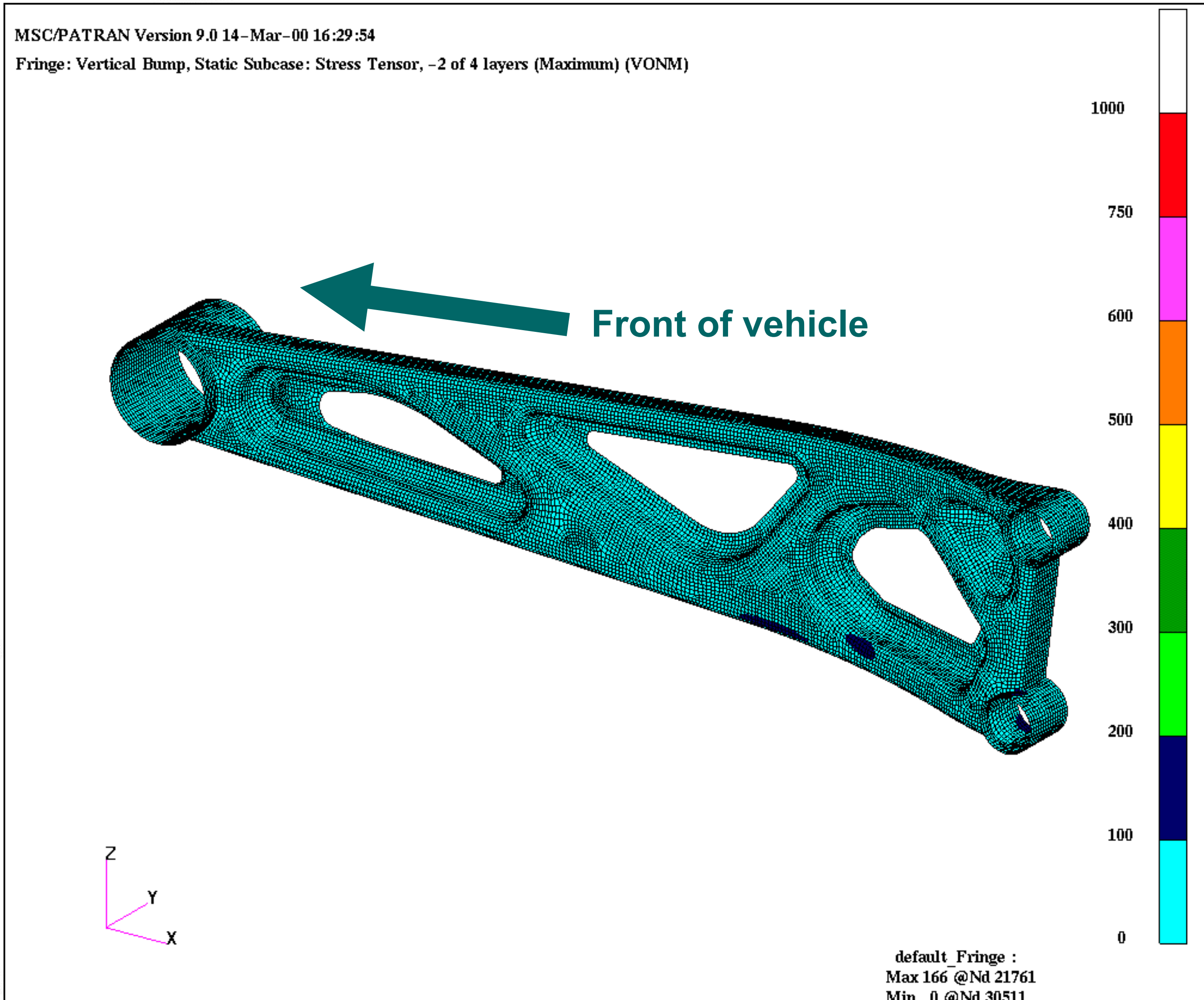
DOUBLE WISHBONE: TRAILING ARM

Lateral Curb Strike 2, D Class

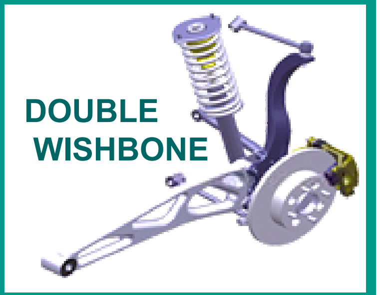


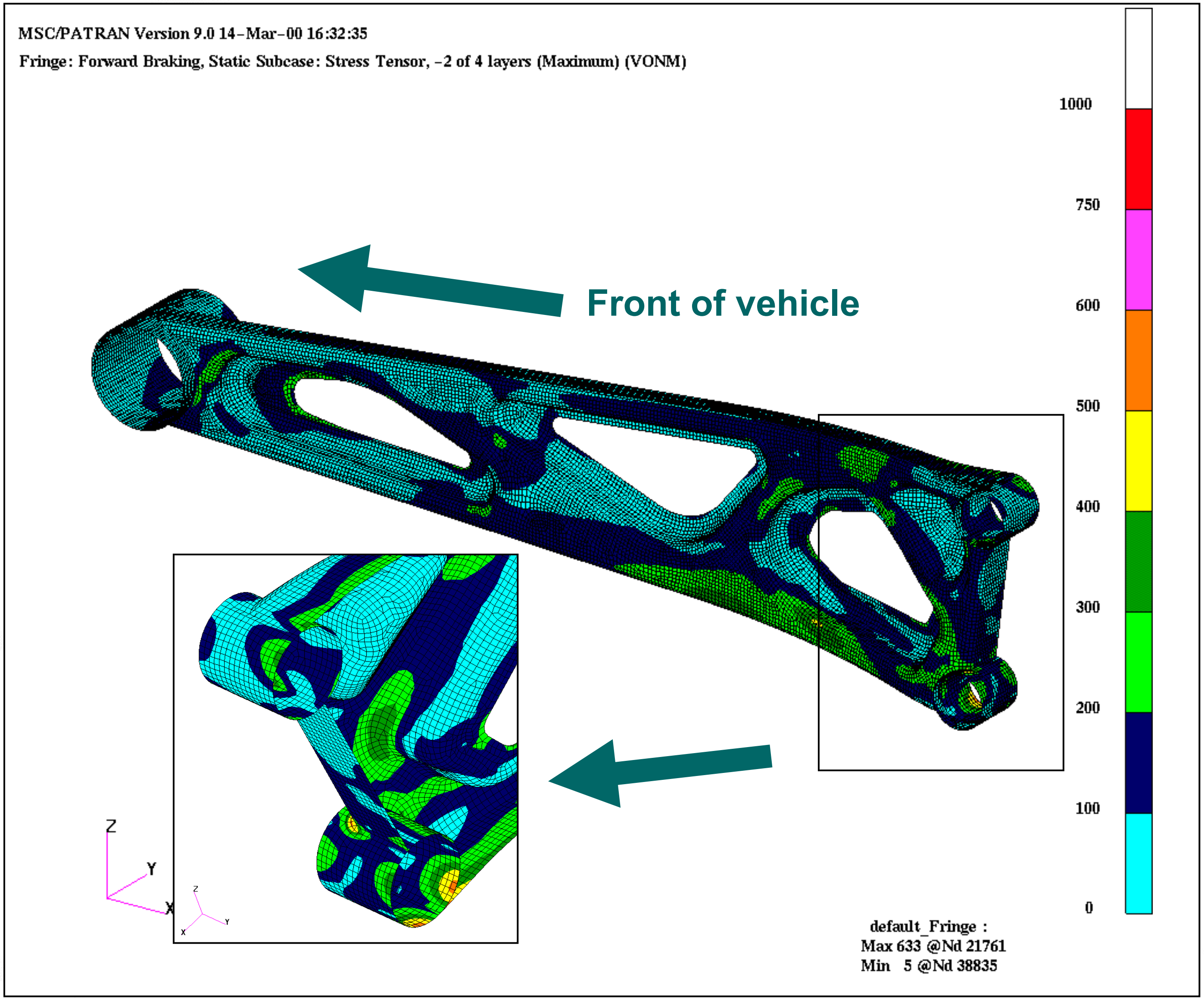
DOUBLE WISHBONE: TRAILING ARM

Vertical Bump, D Class



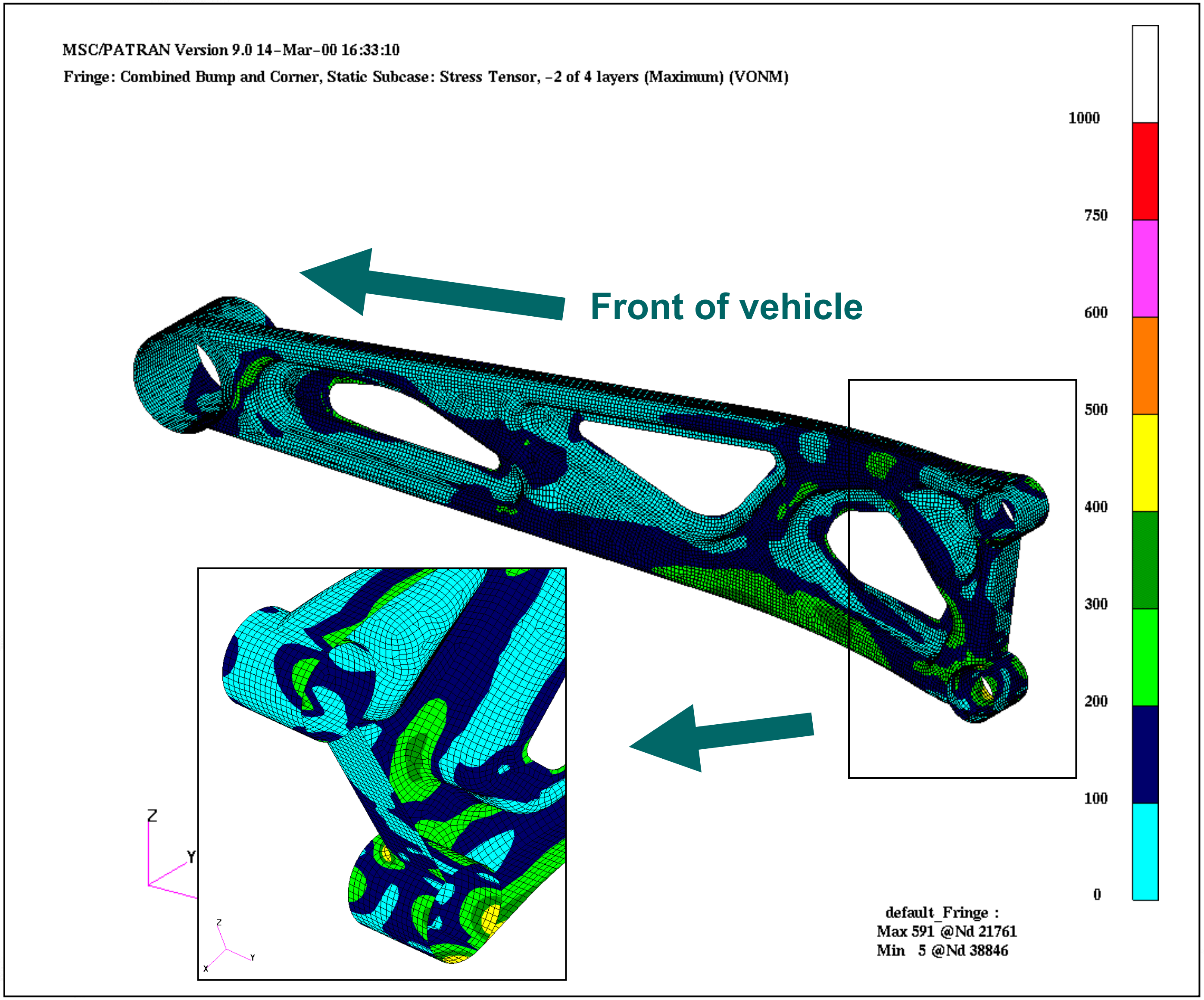
DOUBLE WISHBONE: TRAILING ARM
Forward Braking, D Class





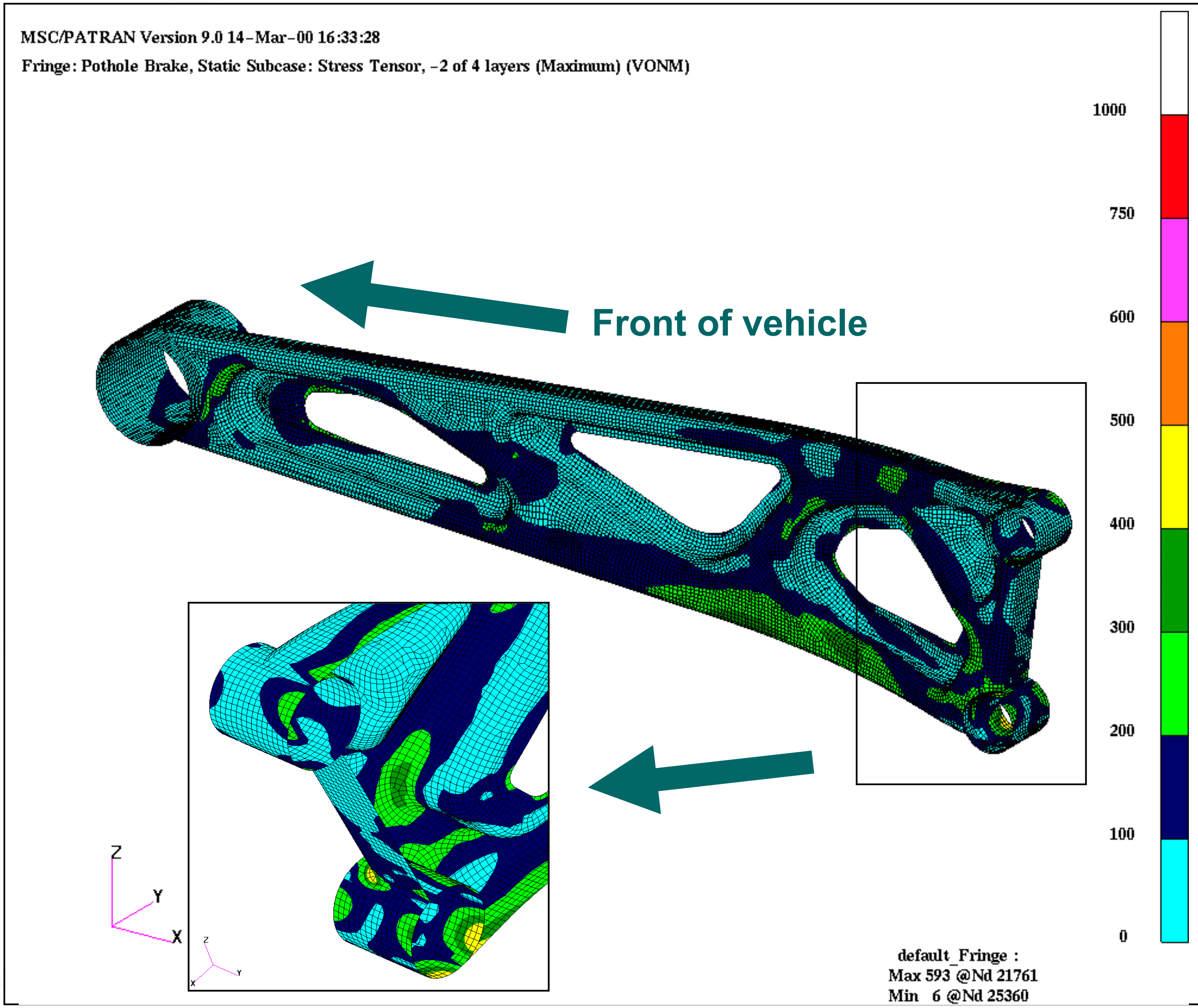
DOUBLE WISHBONE: TRAILING ARM

Combined Bump & Corner, D Class



DOUBLE WISHBONE: TRAILING ARM

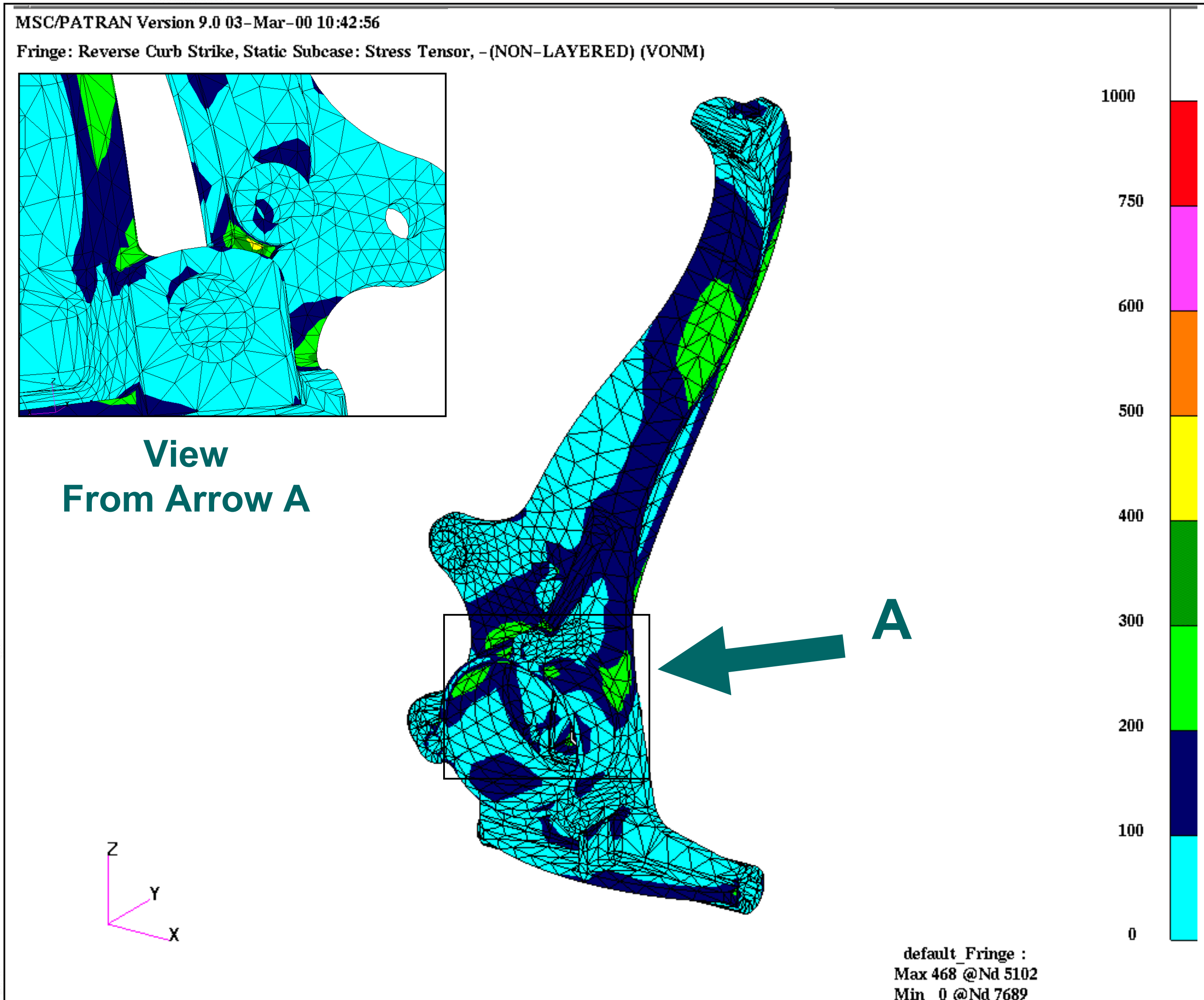
Pothole Brake, D Class



ULTRALIGHT STEEL AUTO SUSPENSION

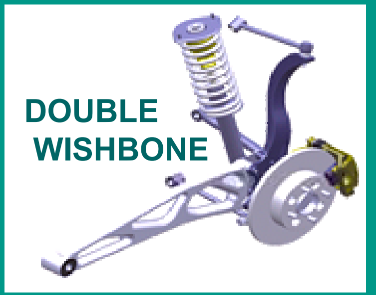
DOUBLE WISHBONE: KNUCKLE

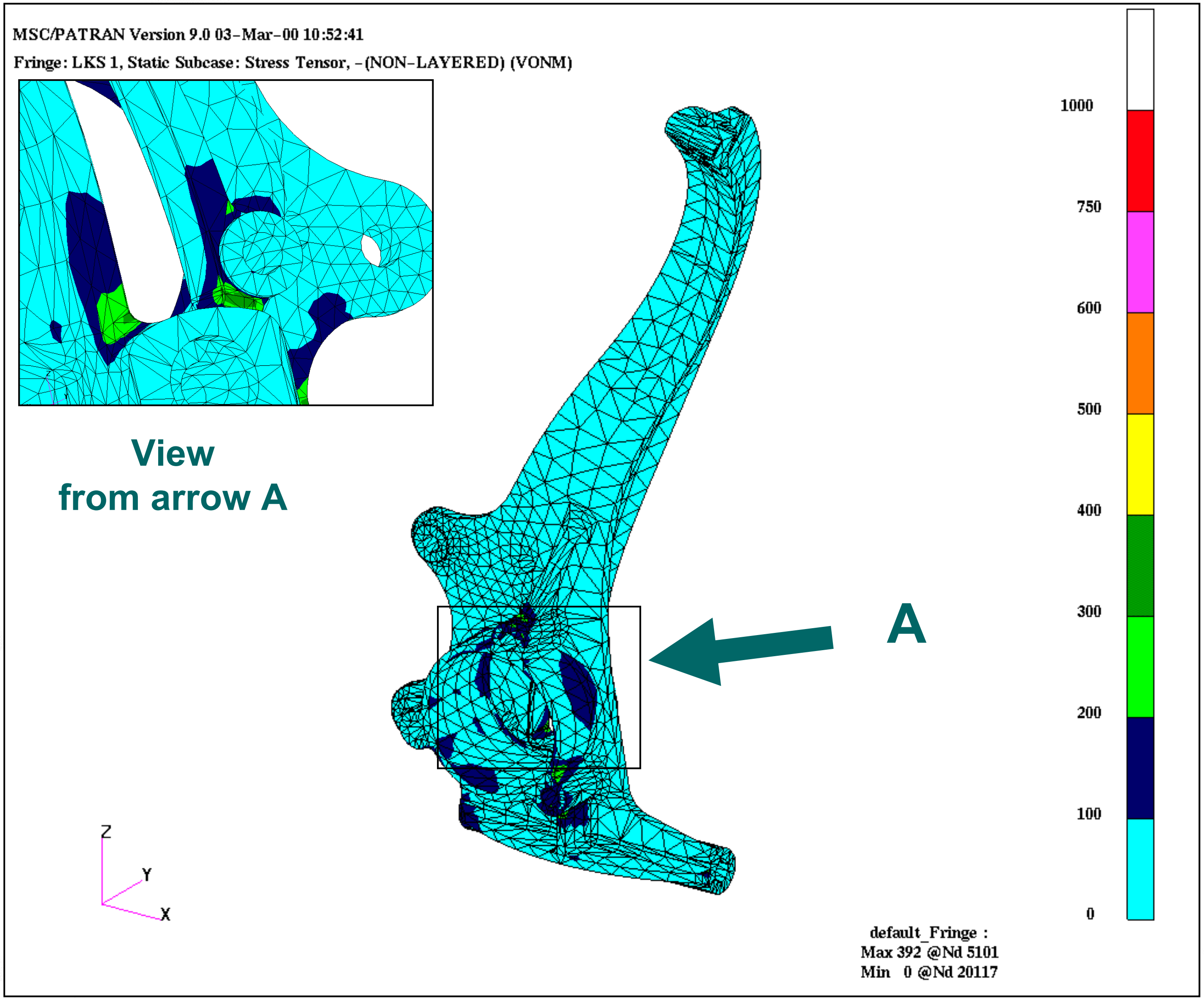
Reverse Curb Strike, D Class



DOUBLE WISHBONE: KNUCKLE

Lateral Curb Strike 1, D Class

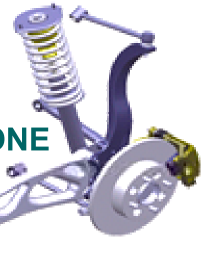


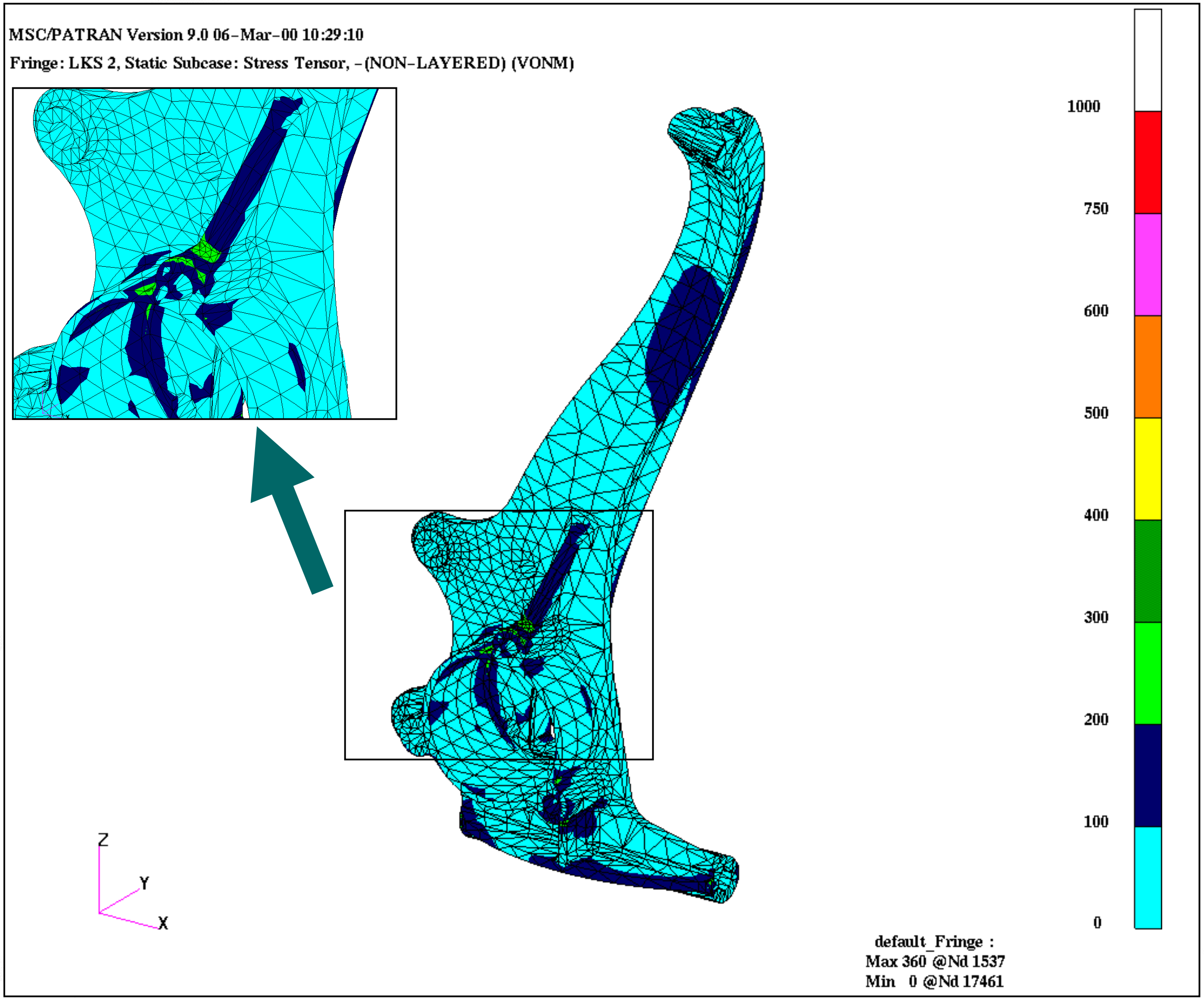


DOUBLE WISHBONE: KNUCKLE

Lateral Curb Strike 2, D Class

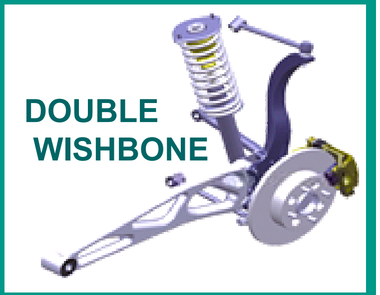
DOUBLE WISHBONE

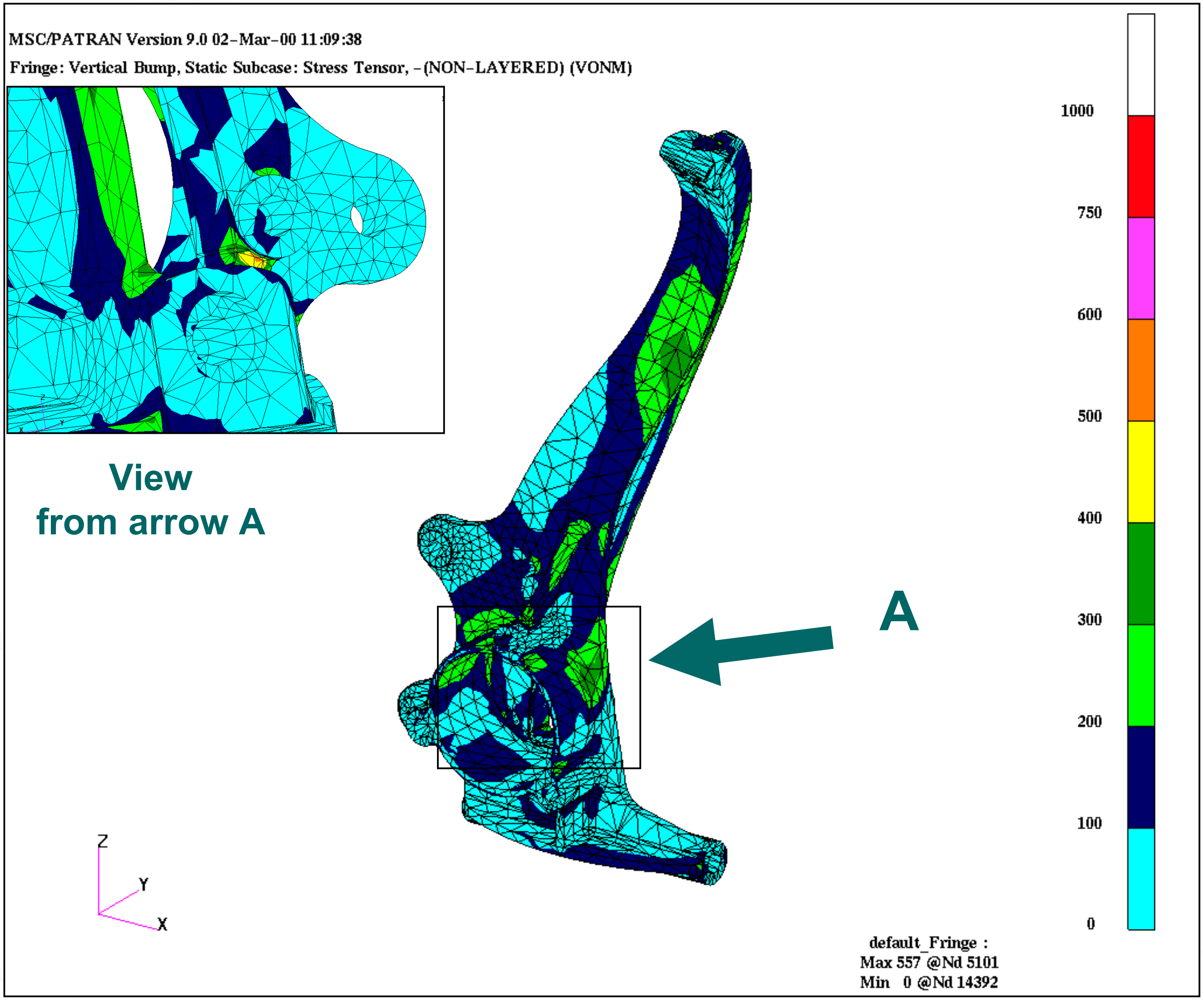




DOUBLE WISHBONE: KNUCKLE

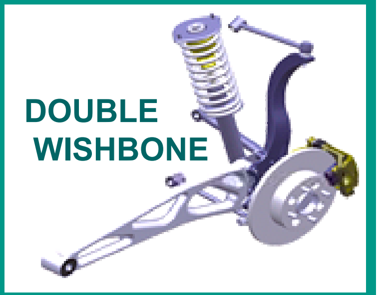
Vertical Bump, D Class

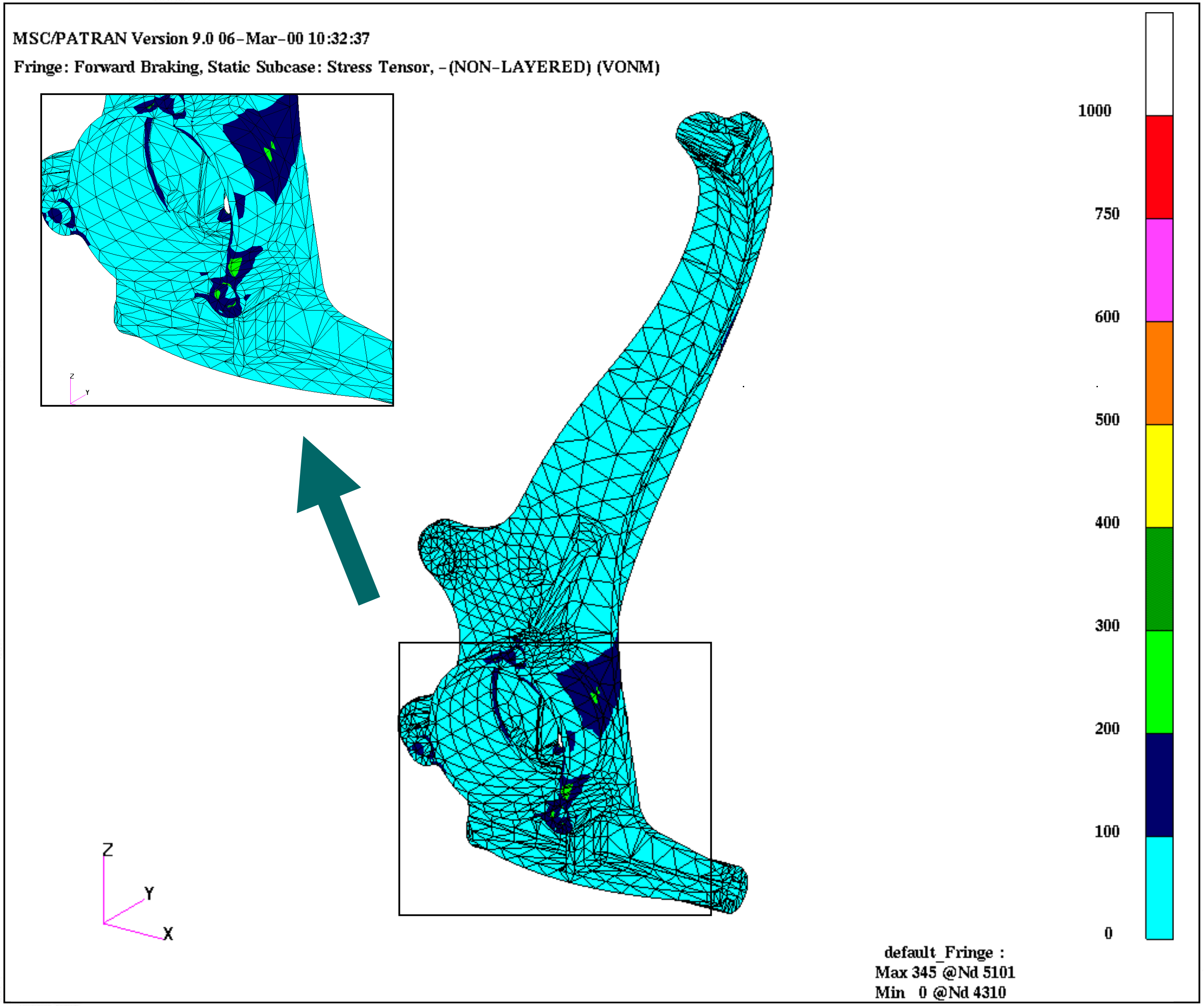




DOUBLE WISHBONE: KNUCKLE

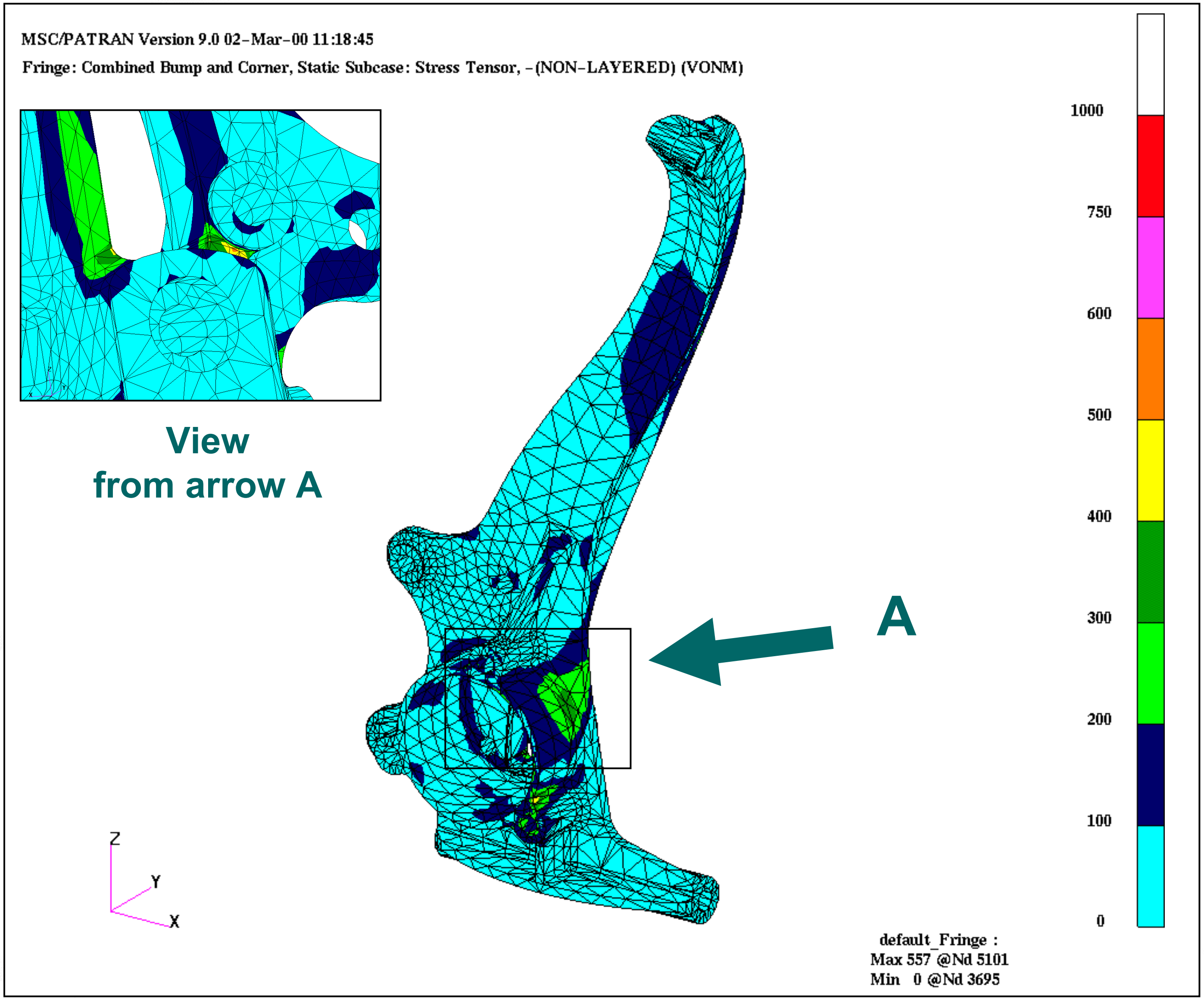
Forward Braking, D Class





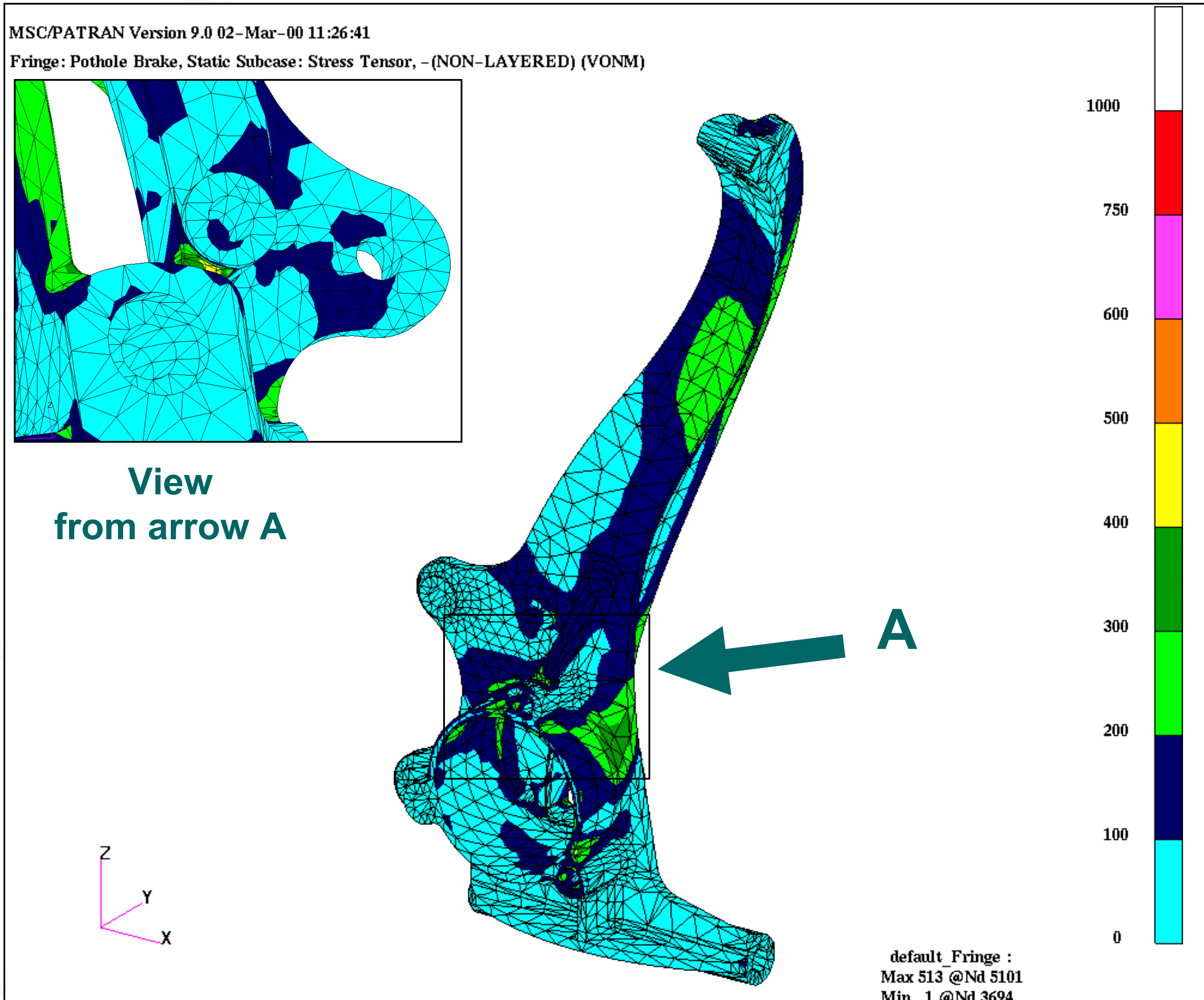
DOUBLE WISHBONE: KNUCKLE

Combined Bump & Corner, D Class

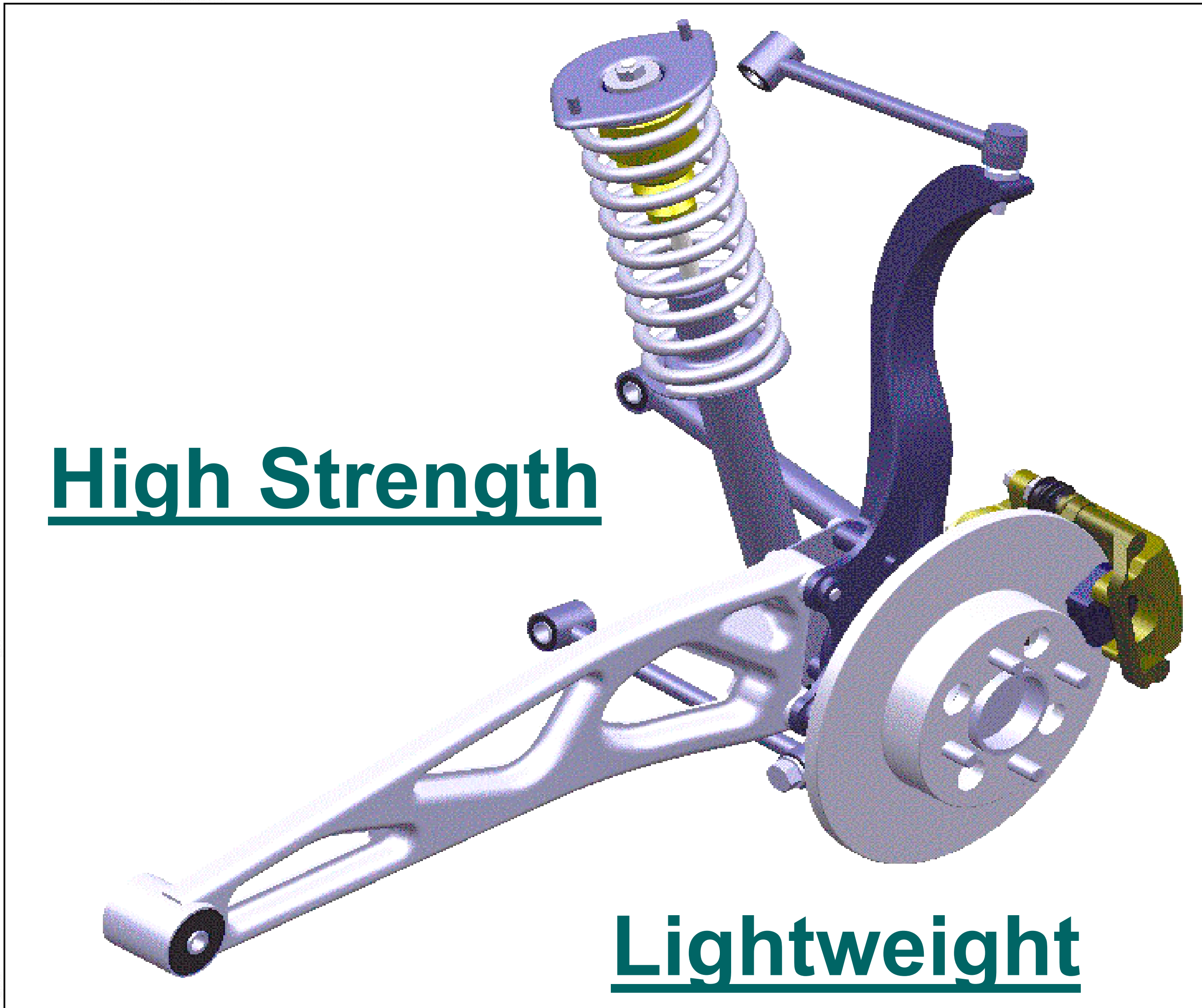


DOUBLE WISHBONE: KNUCKLE

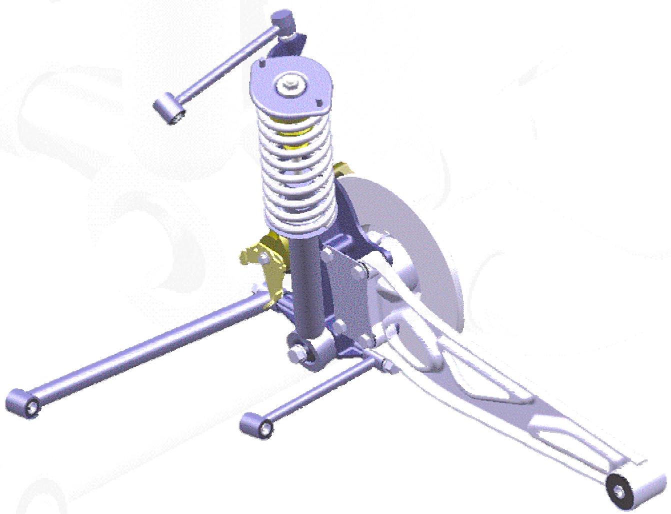
Pothole Brake, D Class



DOUBLE WISHBONE: DESIGN & FEA



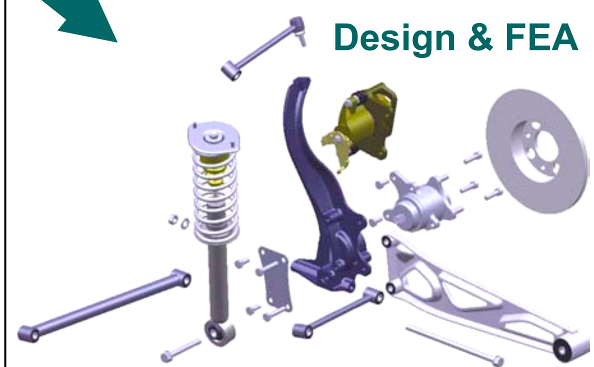
DOUBLE WISHBONE: DESIGN & FEA



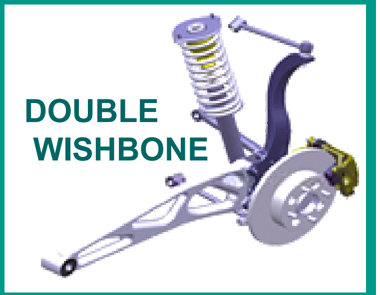
Mass, Cost and Material

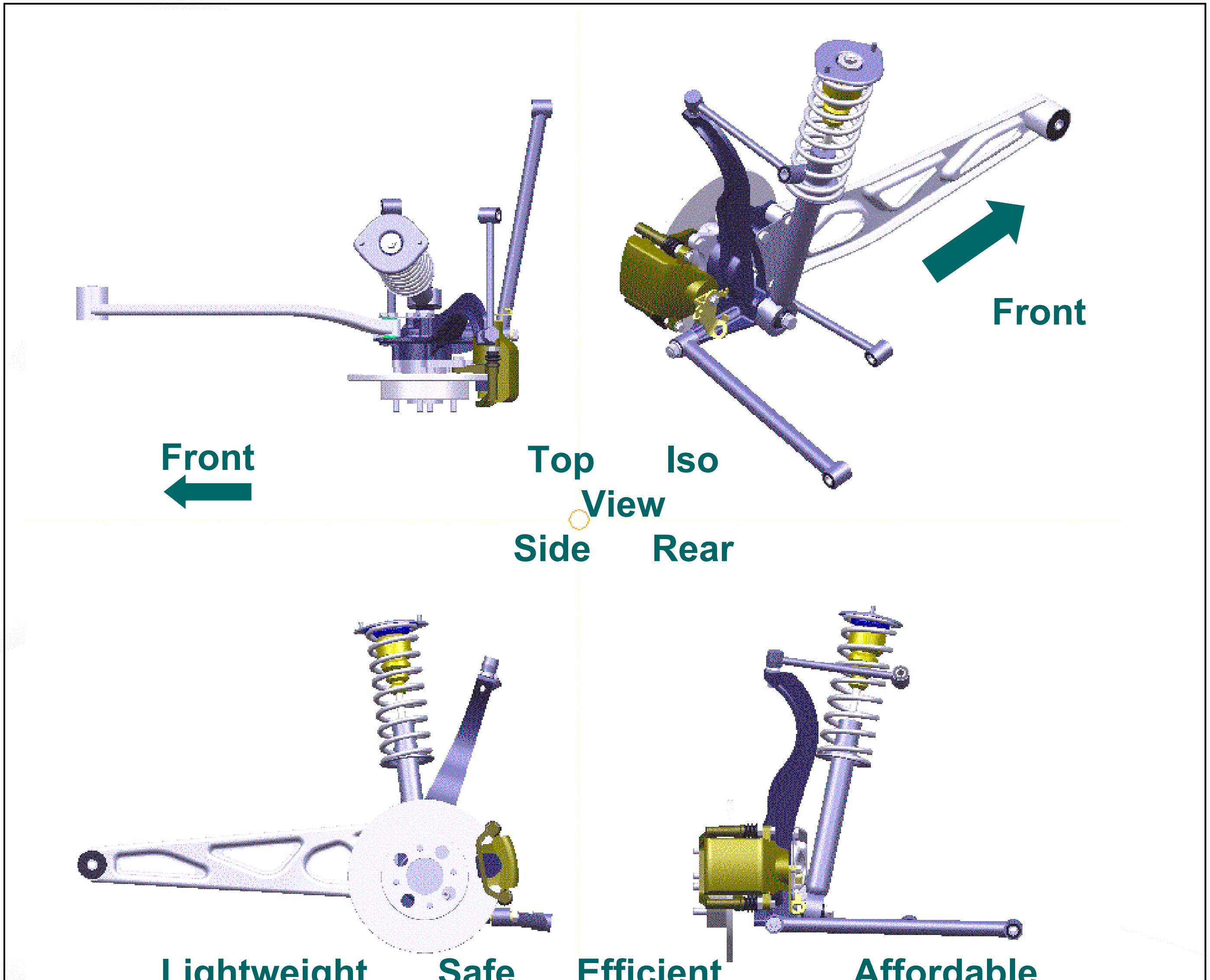
PARTS LIST		
ITEM No.	DESCRIPTION	QTY Veh
1	ASSEMBLY, DOUBLE WISHBONE	1
2	KNUCKLE ASSEMBLY, RH	1
3	KNUCKLE ASSEMBLY, LH	1
4	HUB BEARING UNIT	2
5	SHEAR PLATE	2
6	DISC, BRAKE	2
7	CALIPER, BRAKE	2

Design & FEA



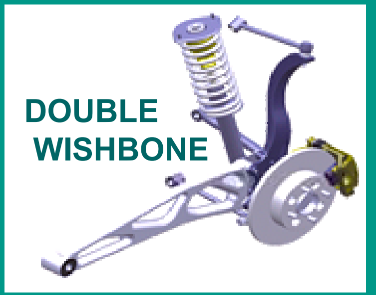
DOUBLE WISHBONE: DESIGN & FEA

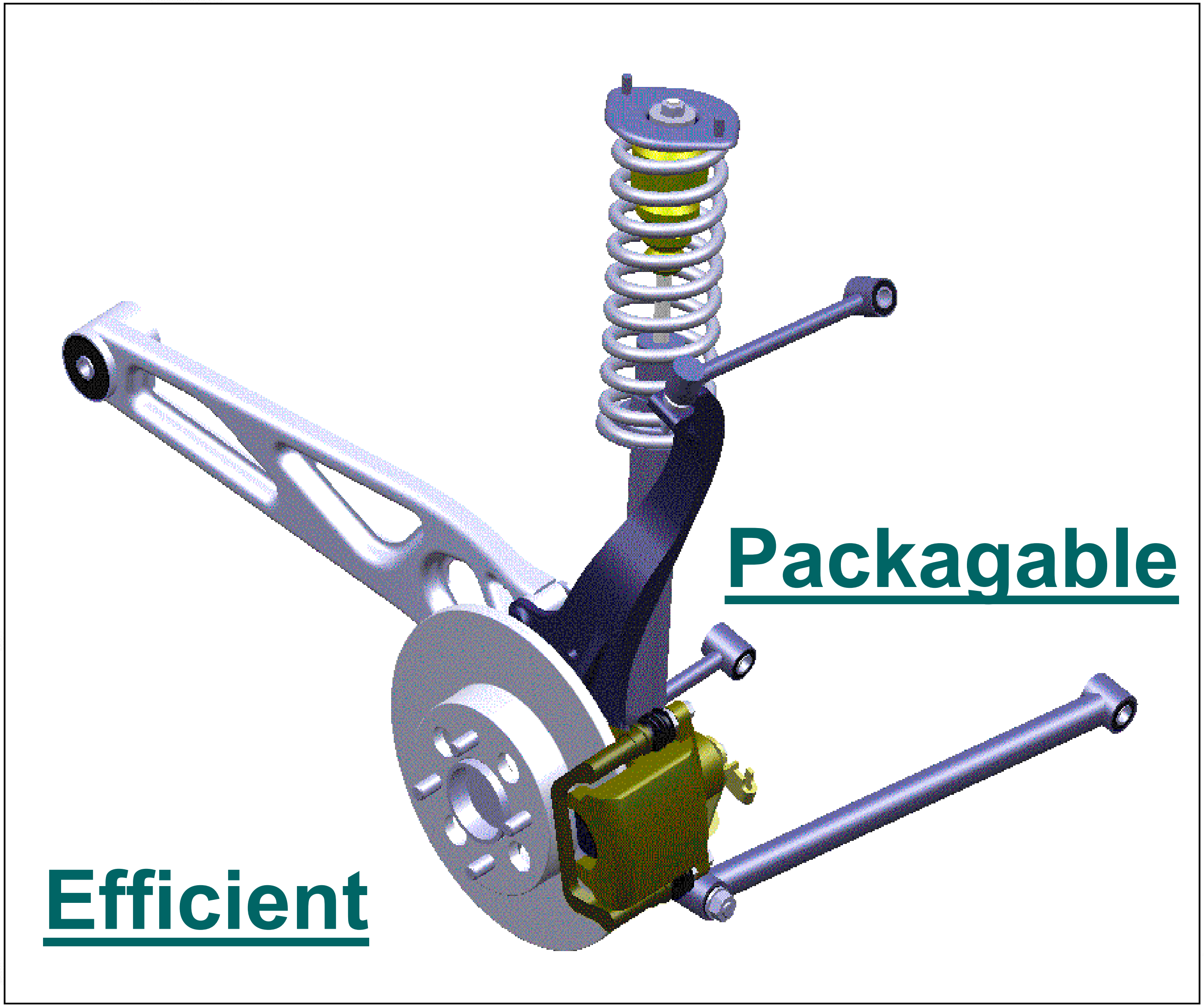




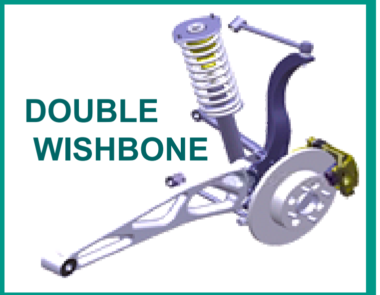
Lightweight Safe Efficient Affordable

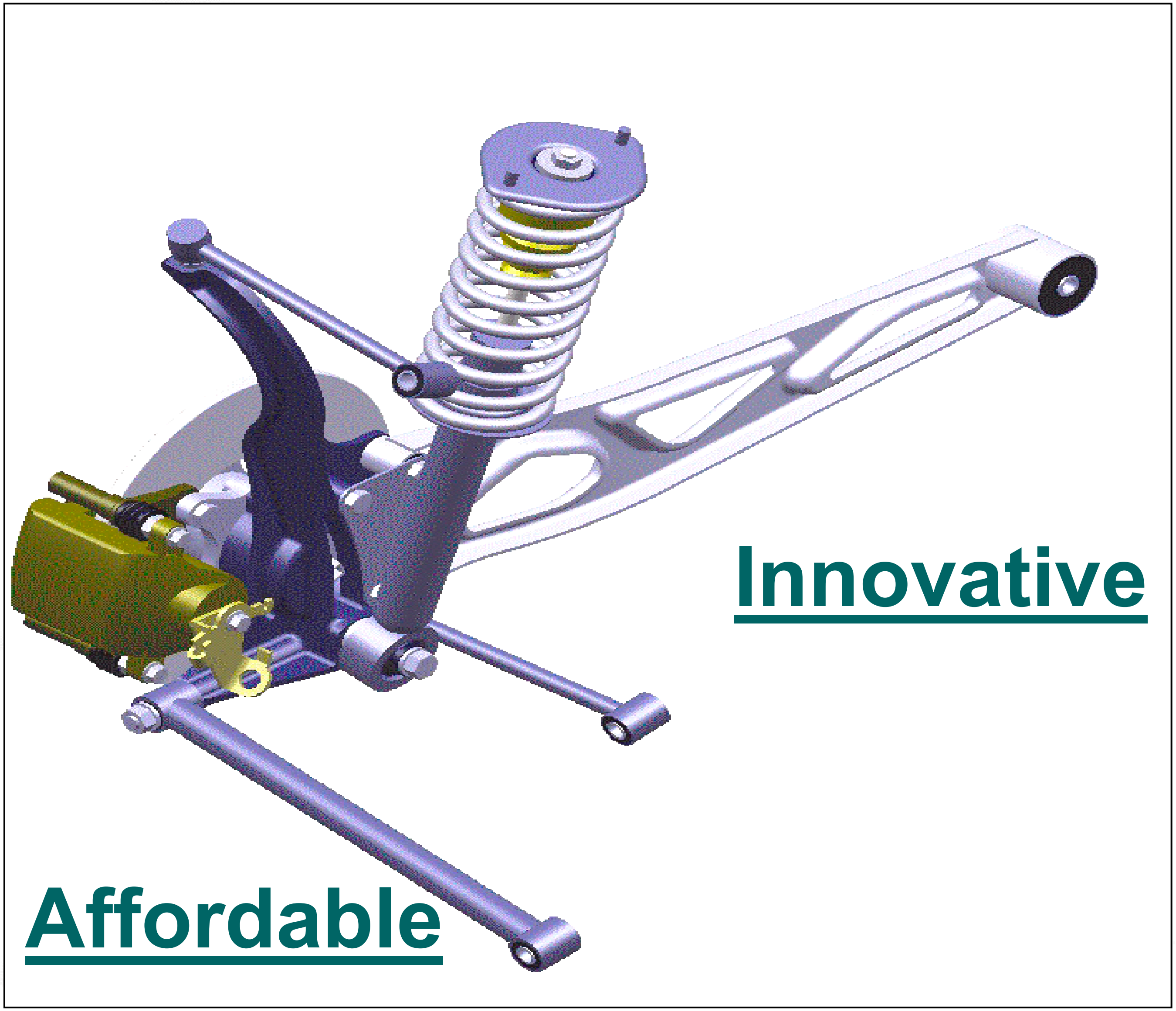
DOUBLE WISHBONE: DESIGN & FEA



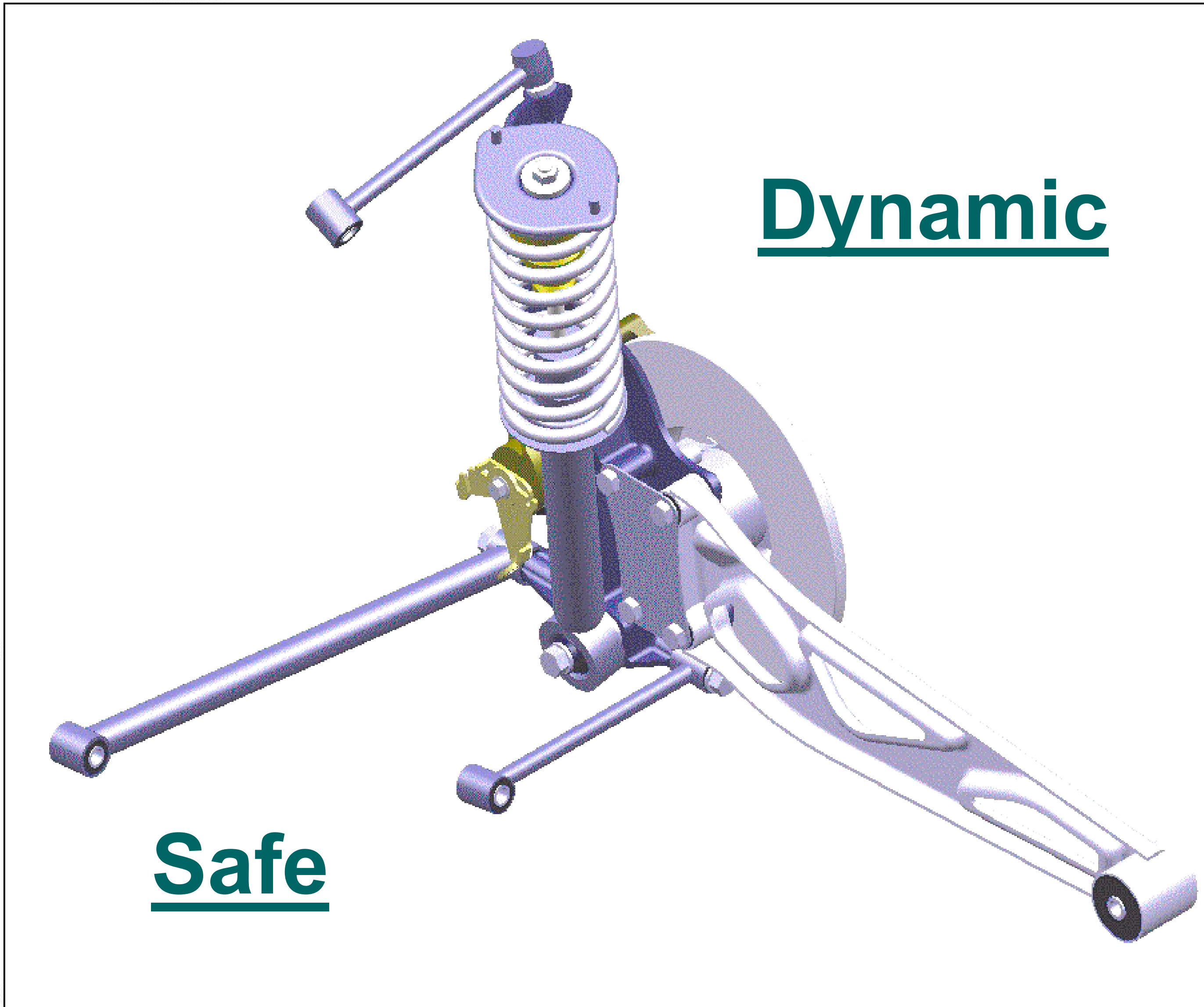


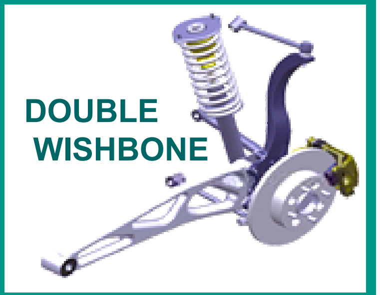
DOUBLE WISHBONE: DESIGN & FEA



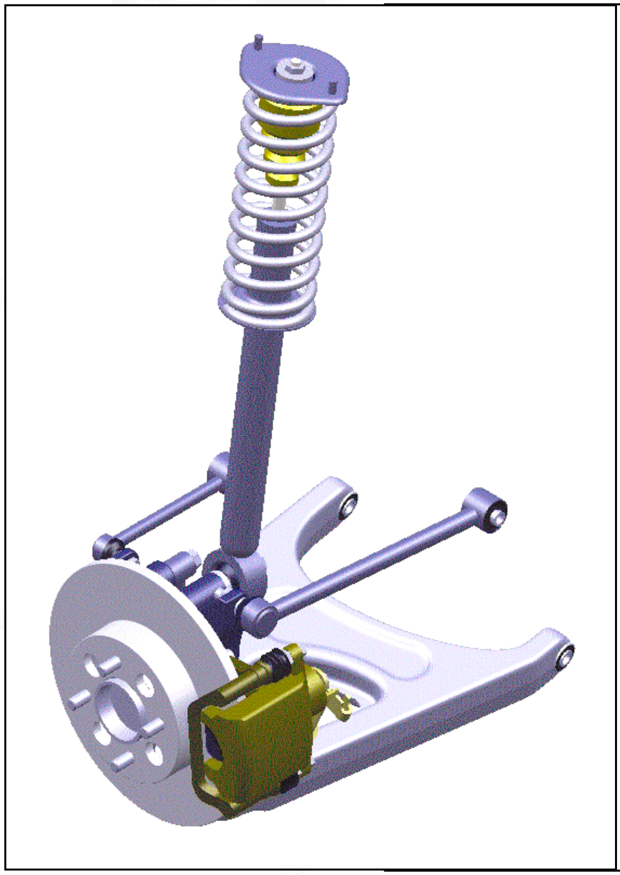


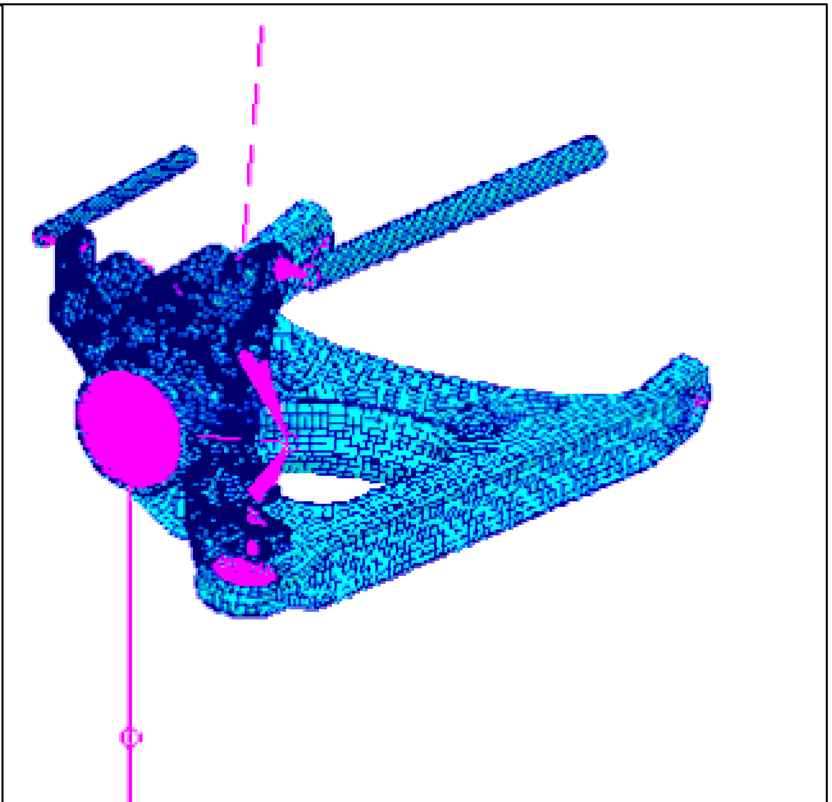
DOUBLE WISHBONE: DESIGN & FEA





DOUBLE WISHBONE: CAE STRUCTURAL APPROACH
Part Physical Geometry





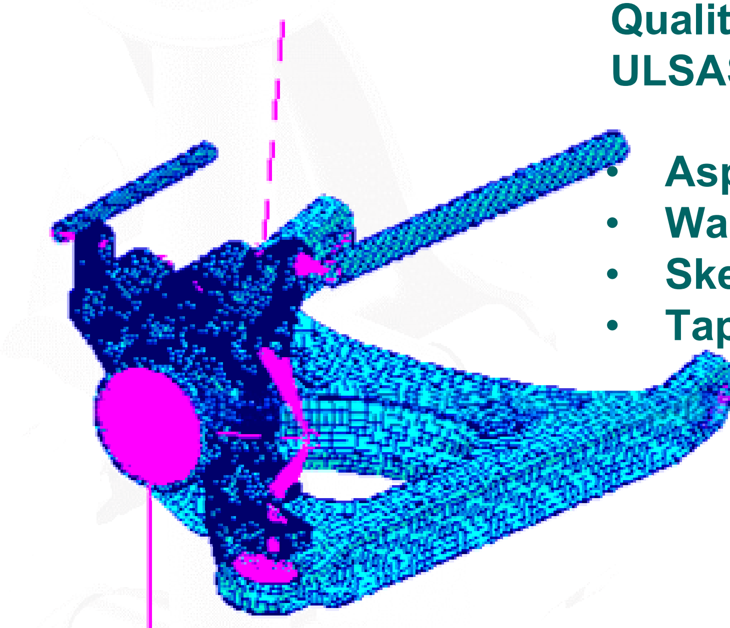
Multi-link used as example

The physical geometry of the parts used to create the finite element model was imported from the CAD environment. This was modified within the FE environment using the many tools available.

DOUBLE WISHBONE: CAE STRUCTURAL APPROACH

Finite Elements

Multi-link used as example



Quality indices adapted throughout the ULSAS Programme for shell elements:

• Aspect Ratio	<	5:1
• Warp Angle	<	7 degrees
• Skew Angle	<	30 degrees
• Taper	>	0.8

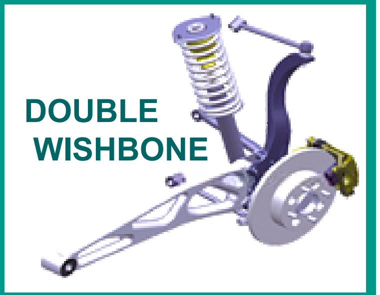
An FE mesh was created using the imported CAD geometry. This was undertaken by using either manual or auto meshing techniques. Beam, shell or solid elements are used depending upon the underlying geometry. Once the mesh has been created, it is checked for free edges, duplicates and normals. The element's quality is also checked for aspect ratio, warp angle, skew angle, and taper. Typical values for these are:

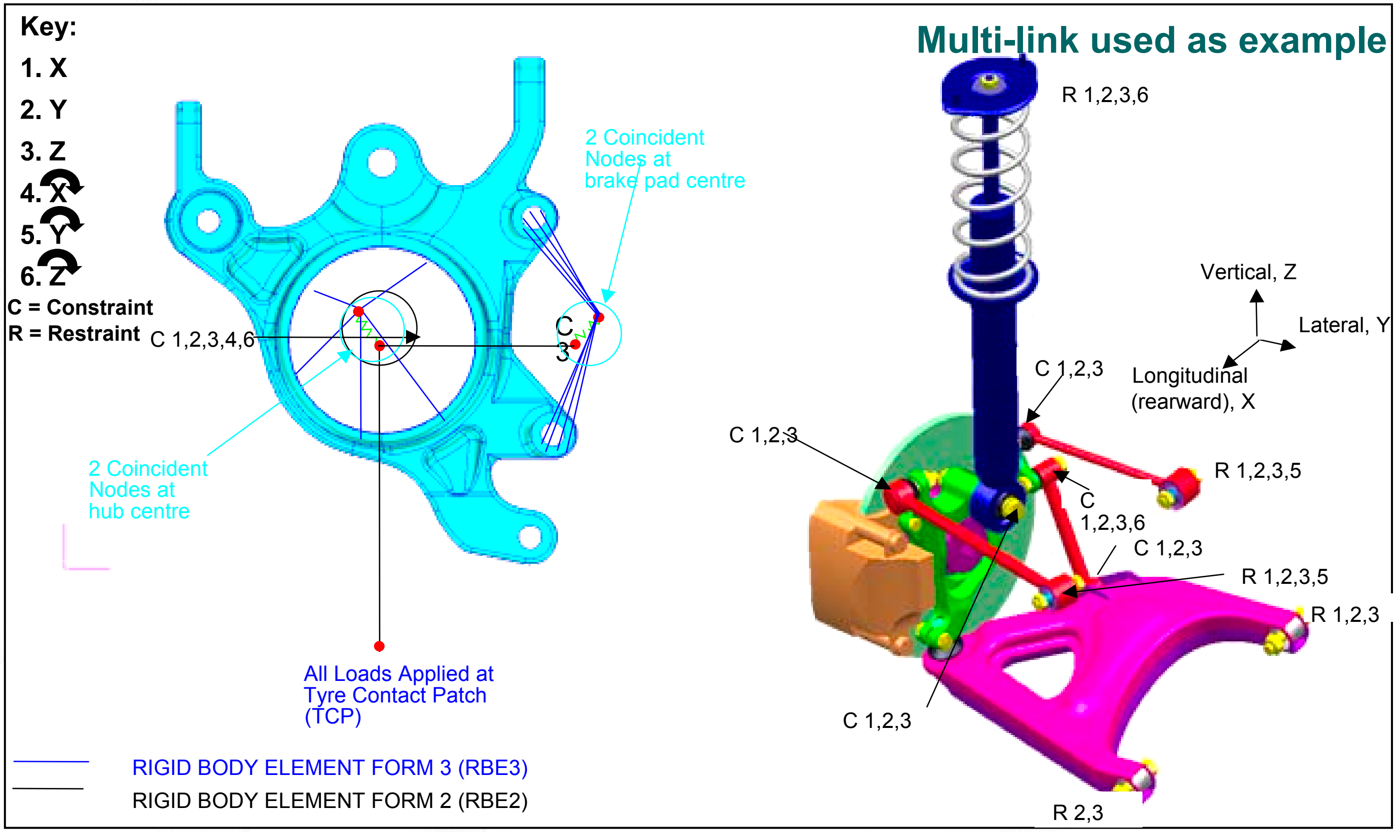
Aspect Ratio	<	5:1.
Warp Angle	<	7 degrees.
Skew Angle	<	30 degrees.
Taper	>	0.8.

These values can be doubled, but for only 10% of the FE model, and only in areas of little concern.

DOUBLE WISHBONE: CAE STRUCTURAL APPROACH

Loads and Boundary Conditions





Restraints, constraints and loads are applied to the FE model using appropriate rigid elements and springs, with the necessary degrees of freedom carefully defined. Restraints are normally RBE3s from a hole to a fixing point, and then a spring to ground. Constraints connect two components using RBE3s from holes to a common point, which is joined using springs. Loads are applied through RBE2s and RBE3s to the structure.

DOUBLE WISHBONE: CAE STRUCTURAL APPROACH

Materials

Material models are obtained from the FE software database, or else are created explicitly. Linear analysis only requires the elastic modulus and Poisson ratio. A non linear analysis also requires the yield point and a plastic hardening modulus.

Properties

Spring, beam and shell properties are defined for each type of element. Springs require stiffnesses and degrees of freedom, beams require section properties and orientations, and shells require thicknesses.

DOUBLE WISHBONE: CAE STRUCTURAL APPROACH
Load Cases

ULSAS Standard Load Cases

Load Case Description (2)	X direction	Y direction	Z direction (1)	Position of force Application
Reverse Curb Strike	- 0.5 g	0	3 g	Tyre contact patch
Lateral Curb Strike 1	0	(-) 1.5 g (based on axle weight)	1g with weight transfer	Wheel rim lower position
Lateral Curb Strike 2	0	(-) 1.5 g (based on xle weight)	1g with no weight transfer	Wheel rim lower position
Vertical Bump	0	0	4 g	Tyre contact patch
Forward Braking (With ABS)	1.1 g	0	1g with no weight transfer	Tyre contact patch
Combined Bump and Cornering	0.316 g at wheel including yaw and longitudinal	(-) 0.58 g (based on axle weight)	3g with weight transfer	Tyre contact patch
Pot hole	1.5 g	0	4 g	Tyre contact patch

Actual forces are calculated including dynamic effects (e.g. weight transfer for lateral acceleration) unless stated.

Sign Convention:

X =Positive rearward
Y =Positive to the right
Z =Positive upwards

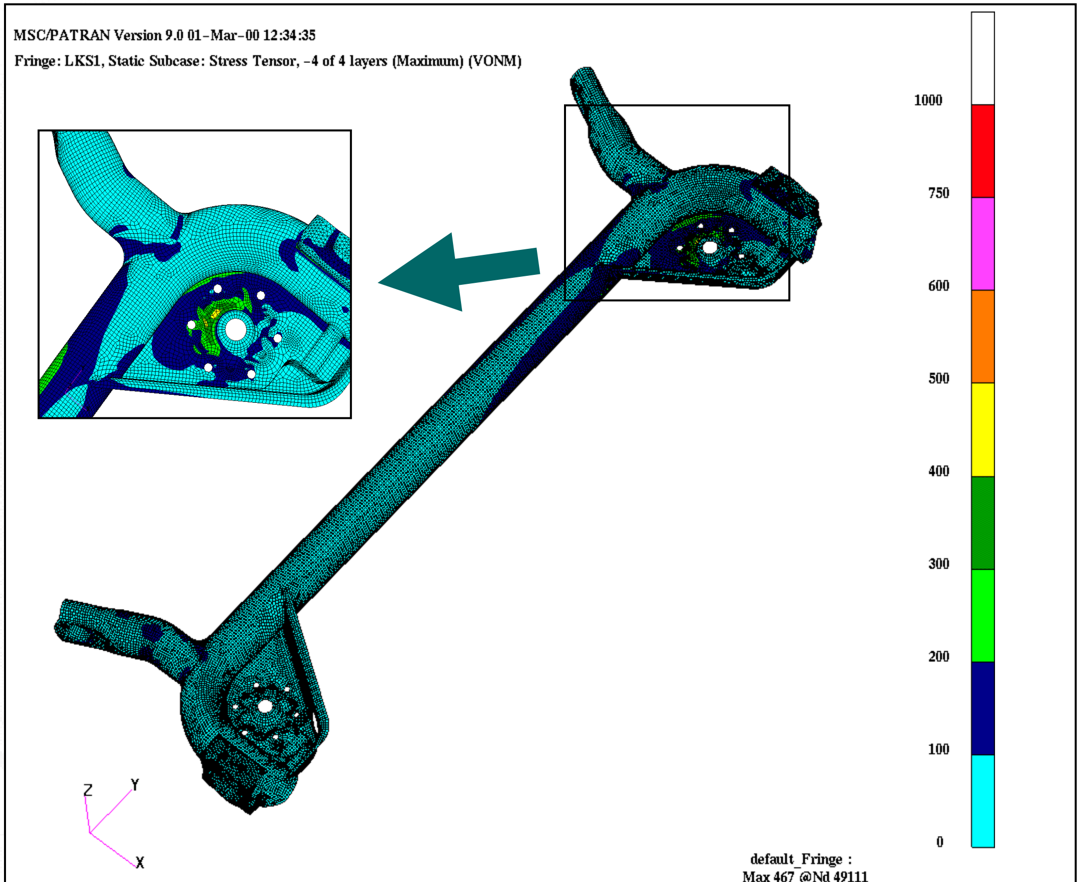
Notes:
(1) Z direction loading includes 1g static load
(2) Loads to be calculated assuming that the vehicle is in the Gross Mass condition.

Unit loads are applied to the FE models at the tyre contact patch and any other specific application areas. These are then combined to produce the standard proof load cases for stiffness and strength assessment. The proof load cases are obtained from Lotus' in house software and are as follows:

Reverse Curb Strike.
Lateral Curb Strike With Load Transfer.

DOUBLE WISHBONE: CAE STRUCTURAL APPROACH

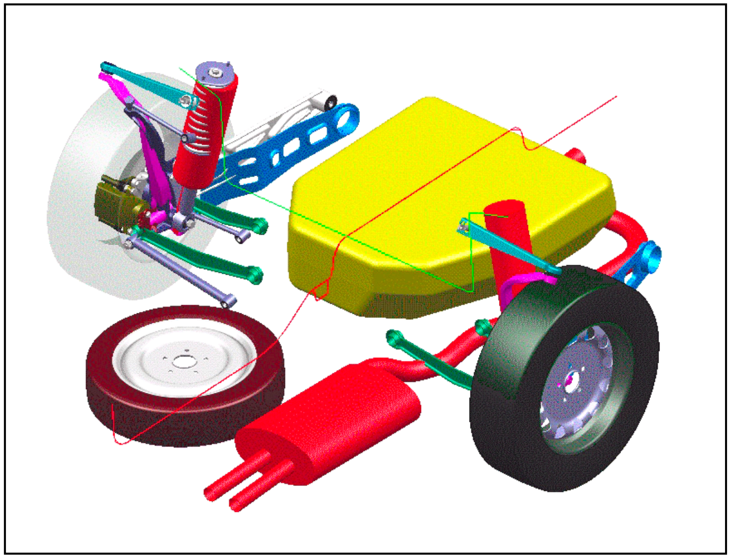
Analysis

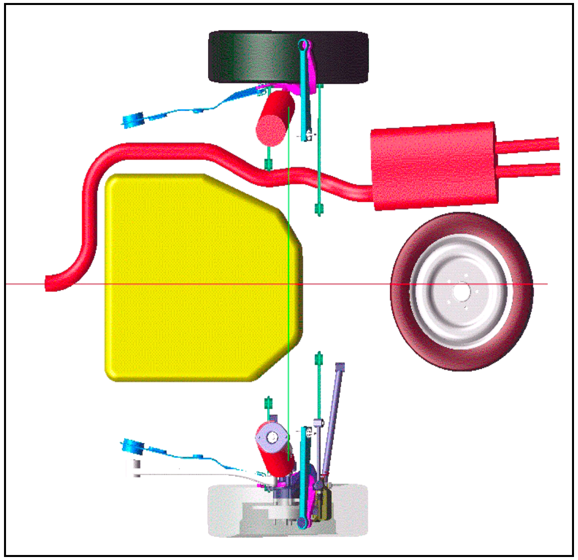


Twistbeam used as example

The two main types of analysis performed are linear static, and nonlinear static. For the nonlinear static analysis the nonlinear material model has to be specified, and the nonlinear load case must also be defined. (It is not possible to combine nonlinear static results.)

DOUBLE WISHBONE: PACKAGING





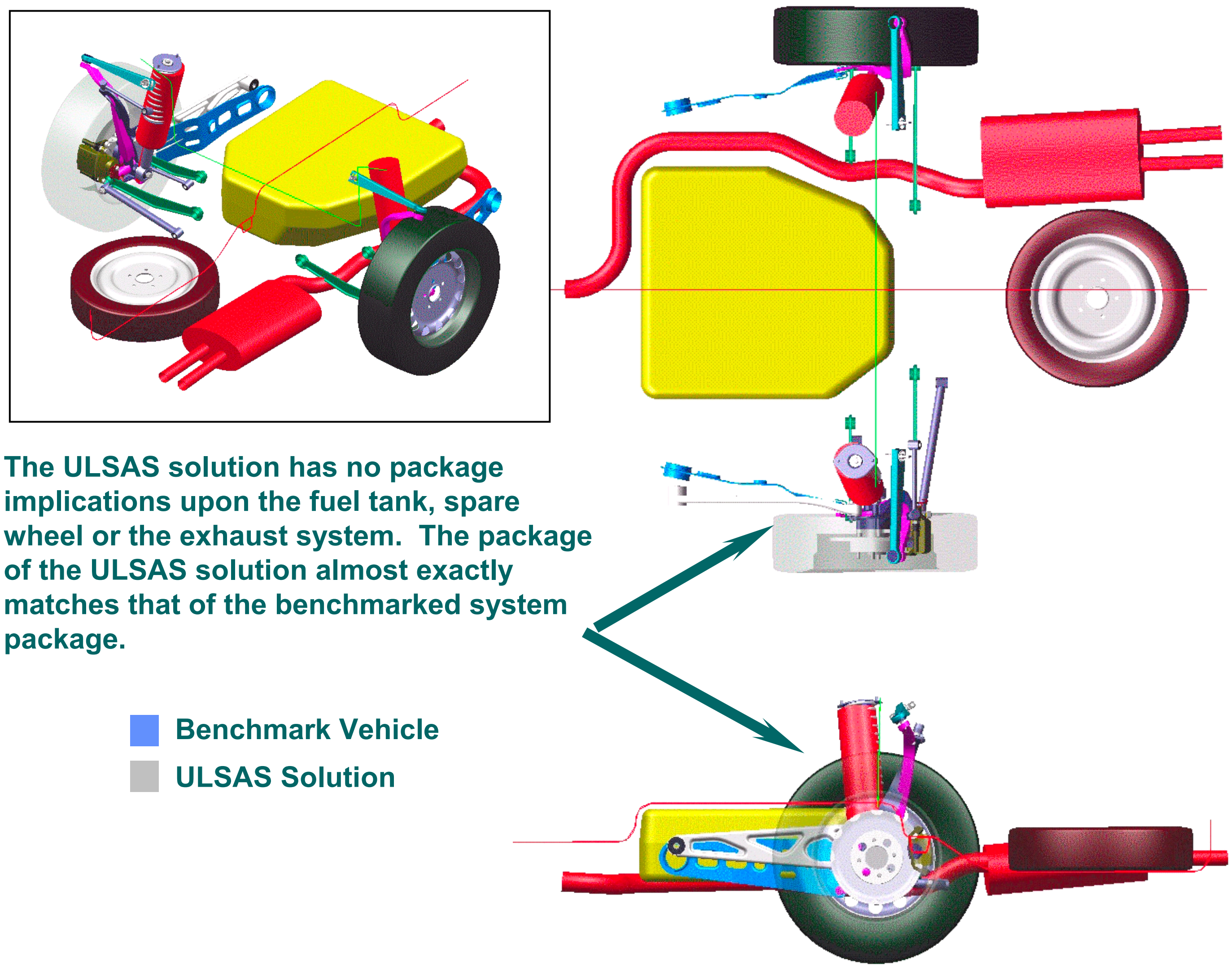
An evaluation of the packaging implications of the proposed suspension system was carried out. This compared the ULSAS system to the benchmarked vehicle in the following areas:

- **Systems Packaging**
- **Interior Space**

DOUBLE WISHBONE: PACKAGING

Systems

DOUBLE WISHBONE



The ULSAS solution has no package implications upon the fuel tank, spare wheel or the exhaust system. The package of the ULSAS solution almost exactly matches that of the benchmarked system package.

Benchmark Vehicle

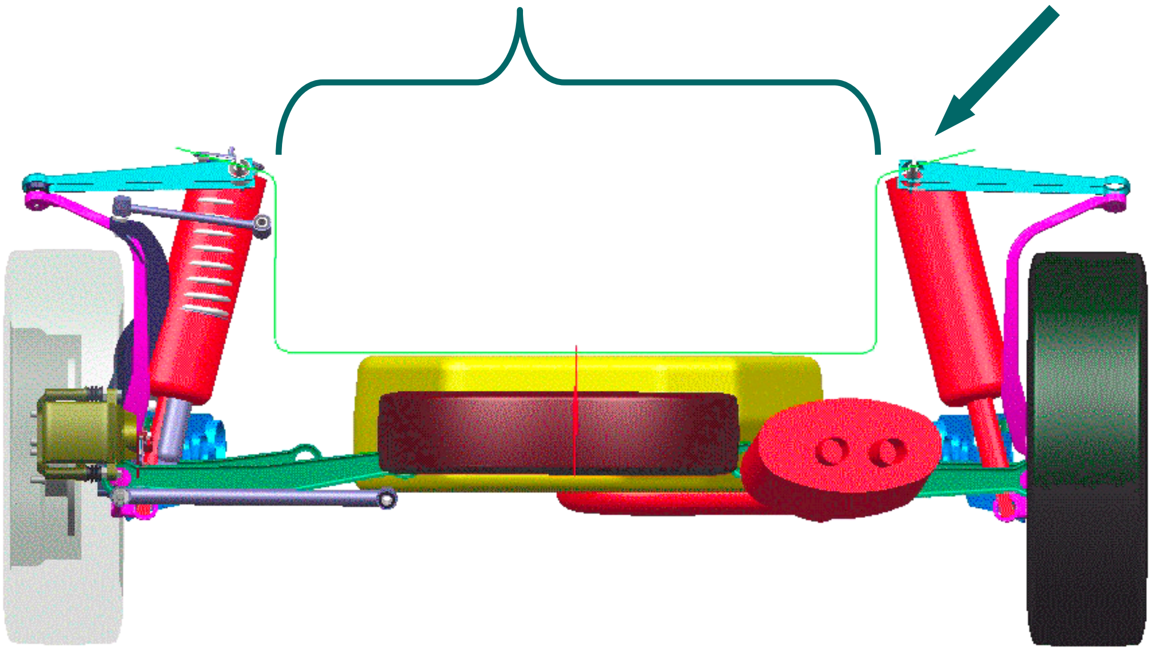
ULSAS Solution

DOUBLE WISHBONE: PACKAGING

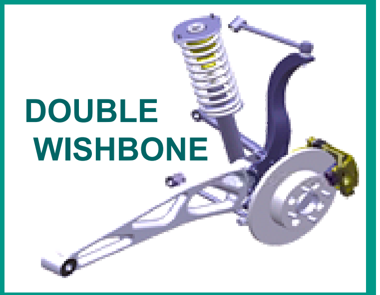
Interior

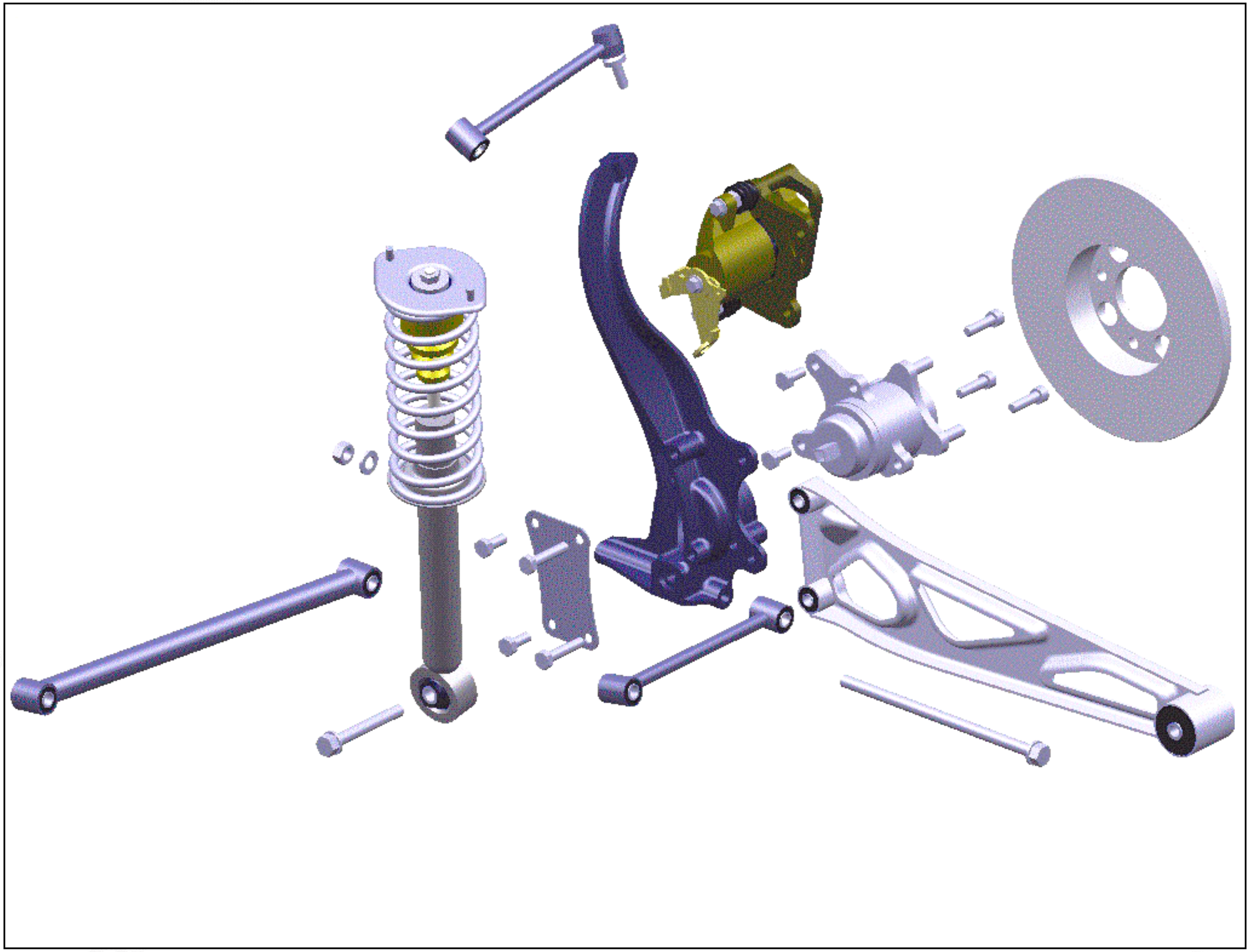
The ULSAS solution has no package disadvantages over the benchmark system in respect of luggage compartment width. This is best illustrated in the spacing of the damper units which is virtually identical for both systems.

The longer stroke dampers utilised to ensure good ride comfort have been packaged within the same envelope as the benchmarked system. This was possible due to the application of compact UHSS springs.



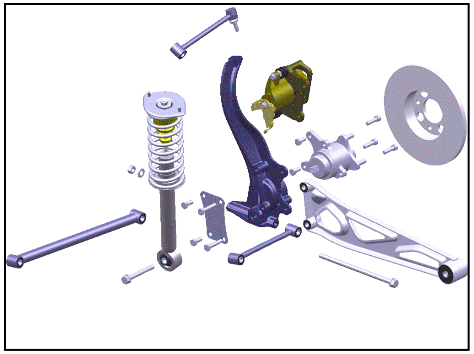
DOUBLE WISHBONE: MANUFACTURING





DOUBLE WISHBONE: TIMING

Sub-Assembly

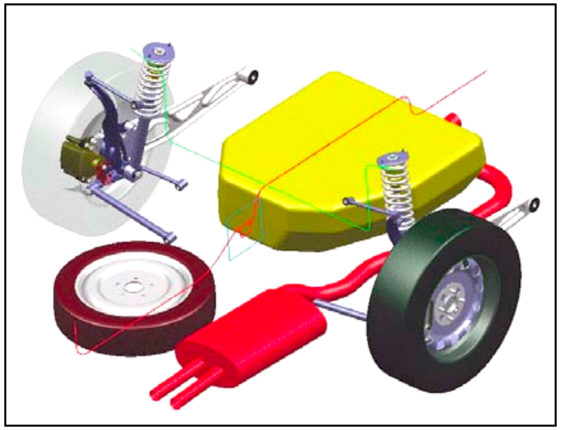


BREAKDOWN OF TIMING FOR SUB-ASSEMBLY OF DOUBLE WISHBONE SUSPENSION SYSTEM

SUB-ASSEMBLY			First Time	Subsequent	Total Time
Operation	number	Code	(man minutes)	(man minutes)	(man minutes)
FIT HUB	2	FIX1H	0.05	0.05	0.1
FIX HUB	6	TFPTN	0.11	0.35	0.46
FIT BRAKE DISK	2	FIX1H	0.05	0.05	0.1
LOAD ASSY. TO FIXTURE	2	FIX2H	0.09	0.09	0.18
LOAD BRAKE CALIPER	2	FIX1H	0.05	0.05	0.1
FIX BRAKE CALIPER	4	TFPTN	0.11	0.21	0.32
LOAD TRAILING ARM	2	FIX1H	0.05	0.05	0.1
LOAD CLOSER PLATE	2	FIXFN	0.04	0.04	0.08
FIX CLOSER PLATE	8	TFPTN	0.11	0.49	0.6
LOAD FR LATERAL LINK	2	FIX1H	0.05	0.05	0.1
LOAD RR LATERAL LINK	2	FIX1H	0.05	0.05	0.1
FIT BOLT	2	FITFN	0.07	0.04	0.11
FIT WASHER	2	FWASH	0.04	0.02	0.06
FIT NUT	2	TFPTN	0.11	0.07	0.18
LOAD DAMPER ASSY.	2	FIX1H	0.05	0.05	0.1
FIX BOLT	2	TFPTN	0.11	0.07	0.18
				TOTAL	2.87

DOUBLE WISHBONE: TIMING

Final Vehicle Assembly

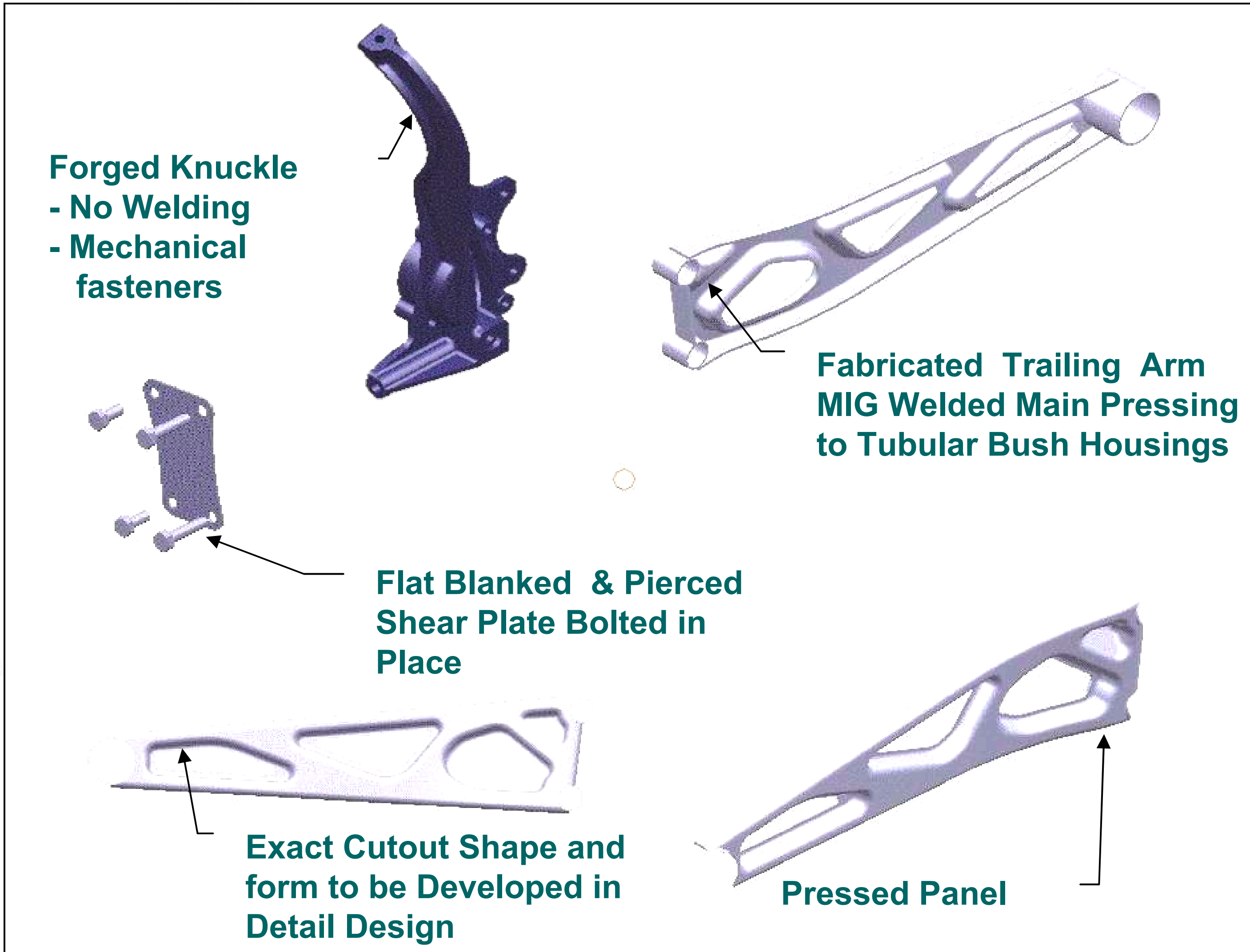


BREAKDOWN OF TIMING FOR FINAL ASSEMBLY OF DOUBLE WISHBONE SUSPENSION TO THE VEHICLE

FINAL ASSEMBLY Operation	number	Code	First Time (man minutes)	Subsequent (man minutes)	Total Time (man minutes)
FIT UPPER LINK	2	FIX1H	0.05	0.05	0.1
FIT UPPER LINK BOLT	2	FITFN	0.07	0.04	0.11
FIX UPPER LINK NUT	2	TFPTN	0.11	0.07	0.18
FIT LONGITUDINAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LONGITUDINAL NUT	2	TFPTN	0.11	0.07	0.18
FIT LATERAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LATERAL NUT	2	TFPTN	0.11	0.07	0.18
FIT LATERAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LATERAL NUT	2	TFPTN	0.11	0.07	0.18
FIX UPPER LINK	2	TFPTN	0.11	0.07	0.18
FIX DAMPER	4	TFPTN	0.11	0.21	0.32
				TOTAL	**1.76**

DOUBLE WISHBONE: MANUFACTURING

Feasibility

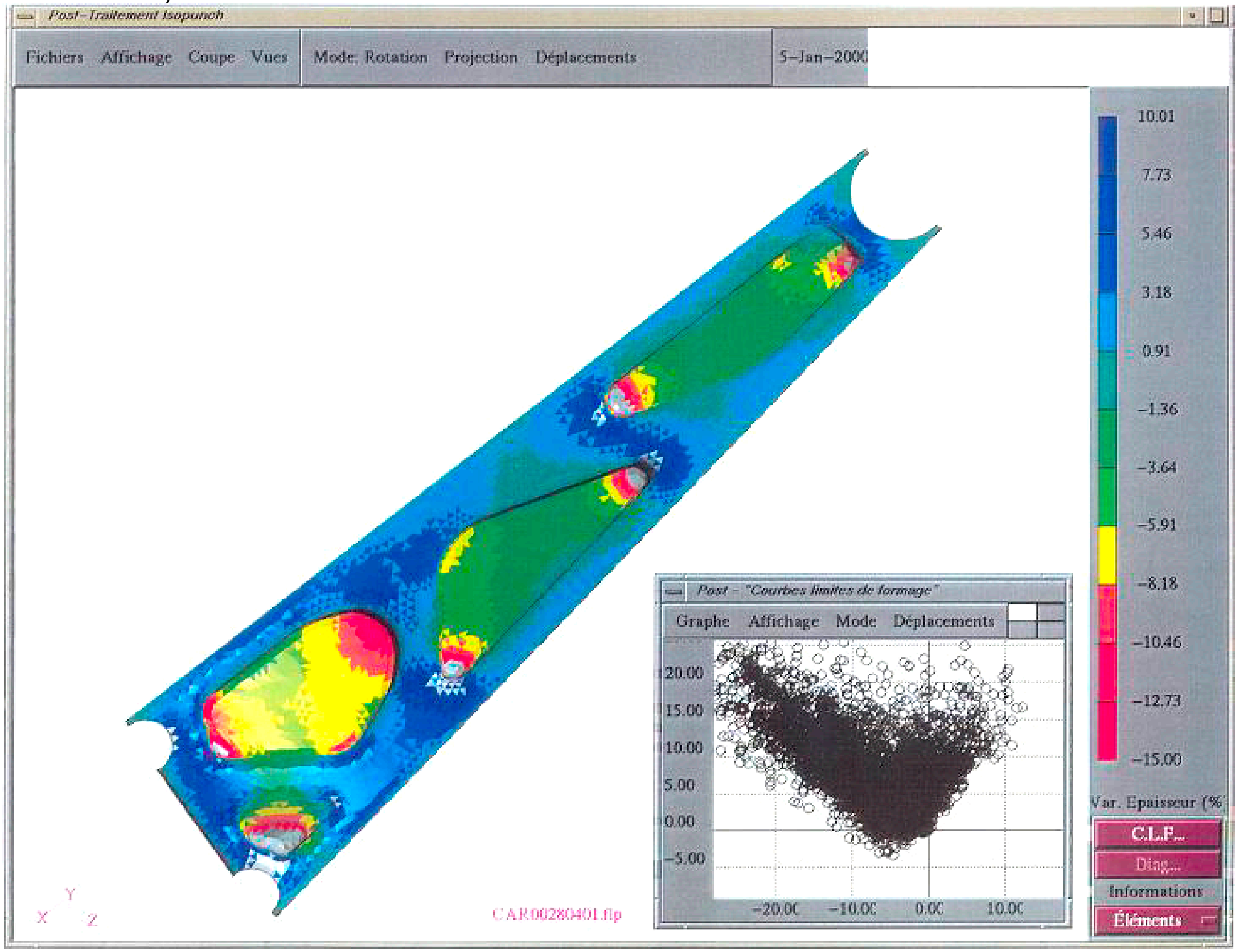


ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: MANUFACTURING

Feasibility

Trailing Arm :- Manufacturing feasibility was carried out on the main pressing

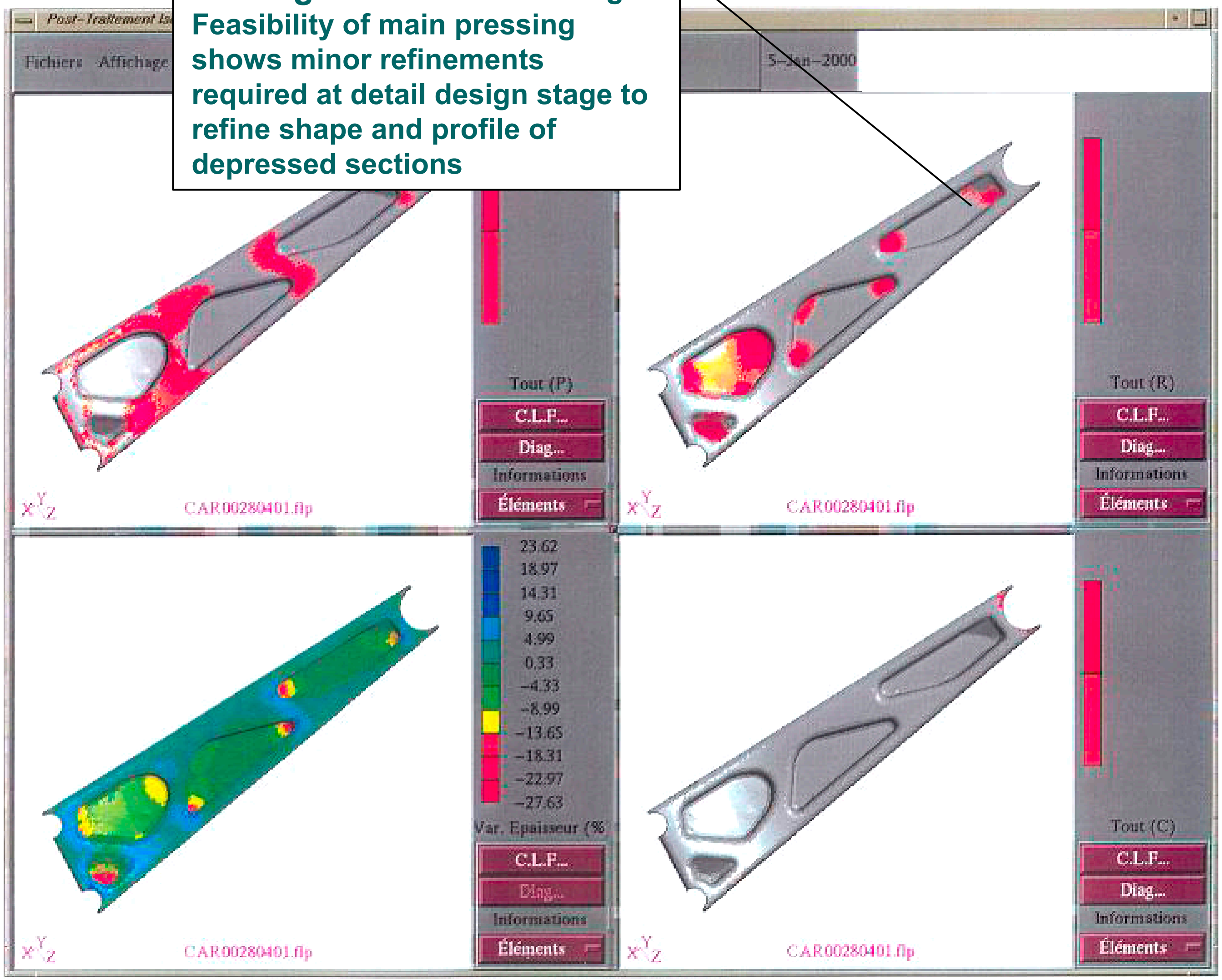


STEEL AUTO SUSPENSION

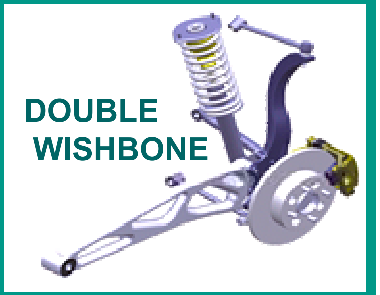
DOUBLE WISHBONE: MANUFACTURING

Feasibility

Trailing Arm:- Manufacturing Feasibility of main pressing shows minor refinements required at detail design stage to refine shape and profile of depressed sections



DOUBLE WISHBONE: MANUFACTURING



ULSAS MANUFACTURING SUPPORT:

- Manufacturing Feasibility
- Material Requirement Analysis
- Assembly Analysis
- Assembly Time Estimates for input into the Costing Analysis
- Consortium Member Input

Throughout the ULSAS Programme the manufacturing implications of the designs were reviewed. Close liaison between the Lotus design team, manufacturing department and Consortium Members ensured the ULSAS systems are lightweight, safe, affordable and manufacturable.

Reviewing the manufacturing feasibility of the designs is an integral part of the iterative design process. This has resulted in a high level of confidence in the manufacturing feasibility of the ULSAS concept designs.

The material requirements of the components were reviewed on an individual basis throughout the design process. Where applicable, i.e. beneficial to mass or cost, high strength near reach materials have been incorporated. Combinations of high and extra high strength steel sheet and forging grades were considered to satisfy perfomance requirements.

DOUBLE WISHBONE: MANUFACTURING

ULSAS MANUFACTURING PROCEDURE:

- Manufacturing Component Feasibility
- Material Requirements
- Assembly
- Timing Study
- Welding

DOUBLE WISHBONE: MANUFACTURING

- ## ULSAS MANUFACTURING PROCEDURE:

Feasibility studies of pressed sheet, forged and fabricated components commenced at the earliest possible stage in the design loop and continued on a simultaneous basis throughout the design process. Detailed formability evaluation was carried out in conjunction with forming simulation analysis on selected parts to further enhance manufacturing input into component design. Simplification of component design was considered at all stages to aid ease of manufacture and reduce the associated tooling costs. This was done whilst avoiding, where possible, compromises to the components performance for example non-handed parts. Consideration was also given to commercial availability of grades and target volume requirements.

Detailed finite element analysis (FEA) techniques were used to validate part stiffness properties and structural integrity performance, which provided data to support material requirements, in terms of material properties for the components. Prior to FEA, an estimation of the applicable material properties was made to enable feasibility studies to commence. In addition to structural demands, each unique component was reviewed on an individual basis in order to consider manufacturing requirements based on the component design.

Detailed drawings of the designs were studied both in hardcopy and on the CAD workstations. This formed the basis of the assembly analysis. The complex multi-link system was subjected to a detailed assembly analysis using a industry recognised software package. This has the advantage of linking with the Catia generated design files to ensure assembly feasibility.

The timing study was carried out using the industry recognised manual assembly data manual assembly data system PMTS (Pre Determined Motion Time System). A manual system was used to ensure equality for comparison purposes. A more detailed procedure is available on the following page.

Welding feasibility studies were carried out in conjunction with The Welding Institute Cambridge, UK.

DOUBLE WISHBONE: MANUFACTURING

ULSAS TIMING STUDY ASSUMPTIONS:

- During assembly, the largest possible unit is fitted.
- Torque sensing power tools utilised wherever possible.
- No confirmation actions such as paint marking are carried out.
- Bolts would be supplied complete with any washers required.
- For the fitting operation the unit or units are already lifted in place.
- The systems have been assembled on a single site.
- All parts and tools are ergonomically situated for optimum performance.
- Estimates are for total system including fitment of brakes and calipers.

In order to make a labour cost analysis of the systems investigated and to compare this with the benchmarked systems, it was necessary to establish the time taken for fitting and sub assembly.

For the purposes of this investigation Lotus has chosen to use the Integrated Business Controls, Motor Industry Assembly Data system. This system was developed for quick estimating, particularly in pre-production or design office situations. IBC uses data blocks of work that can be described in simple terms, be easily recognised and counted with a known statistical variation. The IBC data blocks look at each individual operation as a whole. Therefore the times quoted include elements such as picking up parts and tools, aligning, fitting together and putting down any tools required.

In order to carry out this study the above assumptions, in common with those used on the benchmark vehicles, have been made.

DOUBLE WISHBONE: MANUFACTURING

ULSAS MATERIAL SELECTION ASSUMPTIONS: Pressings

Material Selection - Sheet Grades

Sheet steel grades would be specified to meet the strength requirements as determined by CAE analysis. The nearest available grade with a strength level equal to or higher than the minimum requirement would need to be selected. Commercially available high strength grades would meet many of the requirements for high strength combined with good formability. There are a number of considerations when specifying appropriate sheet grades:

Allowance should be made on parts where springback/shape problems could be an issue following forming. Material influences such as gauge reduction and high yield requirements, in addition to geometrical influences such as open ended panel designs, can promote the susceptibility to panel shape loss through springback. Consideration of these influences should be included in material selection. For example, grades with a lower yield to UTS ratio for a given strength reduce the potential for springback.

Stretched flanges or holes require good edge ductility, an influence not only of the quality of cut edge, but also the edge forming characteristics of the material. Certain grades delivering equal strength can offer superior edge ductility.

Weight reduction requirements dictate grades of thinner gauge offering high strength characteristics. A consequence of these extremes of grade is the current limited commercial availability. Opportunities exist for availability of such grades to be made more widespread, in line with promoting opportunities for near reach high and ultra-high strength grades.

Specific requirements and commercial availability should be discussed in detail with the appropriate Consortium Member Companies.

NB:All material strength requirements quoted are for minimum yield levels

DOUBLE WISHBONE: MANUFACTURING

ULSAS MATERIAL SELECTION ASSUMPTIONS: Tubes

Material Selection - Tube Grades

Tube steel grades would be specified to meet the strength requirements as determined by CAE analysis. The nearest available grade with a strength level equal to or higher than the minimum requirement would need to be selected. Commercially available high strength grades would meet many of the requirements for high strength and good weldability. Specification of appropriate tube grades would be as follows:

-Tube requirements would primarily be met with conventional welded tube.
-Extreme requirements for combinations of high gauge/small diameters may need to be specified as cold drawn tube.

Specific requirements and commercial availability should be discussed in detail with the appropriate steel supplier(s).

NB: All material strength requirements quoted are for minimum yield level

DOUBLE WISHBONE: MANUFACTURING

ULSAS MATERIAL SELECTION ASSUMPTIONS: Forgings

Material Selection - Forging Grades

Forging grades would be specified to meet the strength requirements as determined by CAE analysis. The nearest available grade with a strength level equal to or higher than the minimum requirement would need to be selected. There are a number of considerations when specifying appropriate forging grades:

-Air cooled forging grades are preferable through elimination of secondary heat treatment operations for lower strength requirements.
-The associated increase in carbon content for the higher strength grades could cause weldability issues. Preheat and possibly post weld heat treatment of the components following welding could be carried out in order to achieve higher strength levels, but would be unacceptable on the basis of the volume requirements for these parts.
-Strength levels can vary with the section size of the individual forged components.

There is ongoing research on air cooled forging steels in the steel industry to offer grades to meet higher strength requirements, while maintaining a lower carbon content to avoid the need for pre/post weld heat treatment.

There is a specific requirement for a high strength forging grade with a minimum yield >750MPa, for the Multi-link configuration. Heat treatment following forging would be required to obtain this strength level. However, for production purposes, it is favourable to avoid post operations such as heat treating. Unfortunately, air cooled grades are not currently commercially available to meet these high strength requirements, signalling a real opportunity for grades of this type to be developed to meet customer needs in the longer term.

These issues would need to be investigated further at the detailed design stage with trials being carried out where necessary to validate fully. All requirements should be discussed in detail with the appropriate steel supplier(s).

DOUBLE WISHBONE: MANUFACTURING

ULSAS MATERIAL COATING ASSUMPTIONS:

Coating/Corrosion Considerations

Opportunities exist for extensive use of pre-zinc coated steels. Coated steels will help to meet warranty requirements and place less reliance on protection offered by secondary coatings. Further weight/cost savings may be achieved through avoidance of wax injecting and/or the use of thinner additional coatings.

Organic coating methods such as Electrocoating, are commonly applied to provide a barrier against corrosion. Internal coating of the assembly would require access holes for the in-flow and out-flow of the fluid. The addition of tooling holes (added at the detailed design stage) could also benefit the coating process.

Clearly the type and level of corrosion protection required would be dictated by the manufacturers own corrosion requirements. Allowance for the type and method of corrosion protection to be employed would need to be considered at the detailed design stage.

ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: MANUFACTURING

DOUBLE WISHBONE

ULSAS WELDING ASSUMPTIONS:

Laser Welding/Trimming

Edge Welding Panels/Blanks
Edge or butt laser welding requires very close control of gap and offset tolerances. As a guide, the requirement for welding panels is as follows (assuming 2mm gauge material):

Offset tolerance 1mm max
Gap tolerance 0.2mm max.

Control to these tolerances when welding together finished panels in volume production is difficult, particularly with application of thinner high strength grades were shape/springback issues increase dimensional inconsistency of parts. It is recommended that MIG welding be used as an alternative for joining butt edges in these instances where appropriate.

Laser welding of sheet/blanks is a well-developed technology, where significantly tighter offset tolerances can be achieved providing accurate edge treatment is carried out prior to welding.

STEEL AUTO SUSPENSION

DOUBLE WISHBONE: MANUFACTURING

ULSAS WELDING ASSUMPTIONS:

DOUBLE WISHBONE

Flange/Lap Welding

Through wall lap welding from one side can be achieved on flanges. Welding can occur just off the radius of the flange where two flat surfaces can be guaranteed. A weld width of 1.0 to 1.5mm should be deposited onto the flange. A gap tolerance between the laps of 0.2mm maximum can be tolerated and is ordinarily achieved by clamping the flange during welding. It is possible to increase this tolerance through the use of feed wire, but this would be at the expense of welding speed and mass. Gauge limitations for laser lap welding are well in excess of normal automotive gauge requirements.

The size of flange is primarily a clamping requirement as opposed to a welding limitation. The force/area required to maintain a flat area within the aforementioned 0.2mm max. tolerance would need to be determined. The required flange width may fall inside that conventionally required for spot welding to the advantage of weight reduction, although trial work would be required to validate this (laser trimming the flange back to the weld would reduce the flange size further - see following passage). This method is further limited by the geometrical design of the component and allowing access for clamp tooling.

DOUBLE WISHBONE: MANUFACTURING

DOUBLE WISHBONE

ULSAS WELDING ASSUMPTIONS:

MIG Welding

MIG welding with the associated filler requires control of gap and offset tolerances within the following limits (assuming 2mm gauge material):

Offset tolerance is 2mm max
Gap tolerance is 2mm max.
(Total offset and gap tolerances together should not exceed 2mm - i.e. 1mm offset and 1mm gap tolerance is acceptable or any variation as long as the total remains at 2mm or below)

Welding rates for MIG are approximately 0.75 to 1.2m/min, depending on the thickness of the material being welded. Distortion created by welding due to the greater heat input over spot and laser weld is a consideration, particularly where dimensional control is critical. Trials may need to be carried out to fully validate implications.

Spot-Welding/Flange Welding

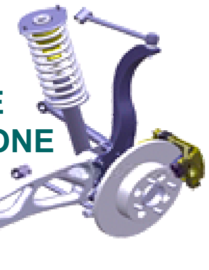
A minimum flange width (typically around 16mm) is required to allow electrode access. Wide variations in gauge thicknesses can be tolerated with spot welding. Ratios of 3:1 are typically used.

Please note: Welding feasibility studies were carried out in conjunction with The Welding Institute, Cambridge, UK.

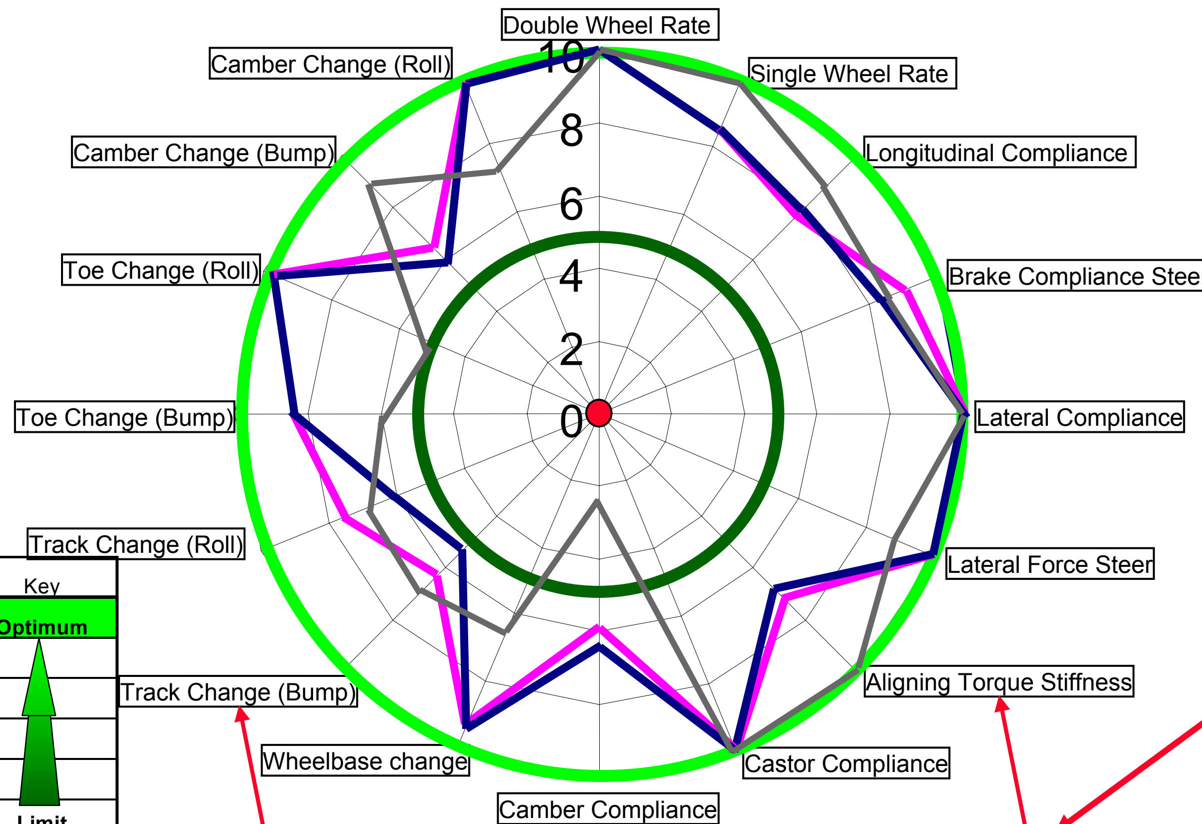
ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE: Performance

DOUBLE WISHBONE



DOUBLE WISHBONE SYSTEM PERFORMANCE RATING Vs TARGETS



Rating	Key
10	Optimum
9	
8	
7	
6	
5	Limit
4	
3	
2	
1	
0	Unacceptable

To View Result Of Any of the 16 Tests Click On Its Title

- Target Limit
- Optimum
- ULSAS D Class
- ULSAS P Class
- Benchmark D Class

STEEL AUTO SUSPENSION

ULSAS CAE DYNAMICS APPROACH

DOUBLE WISHBONE

Mechanical Dynamics Industries ADAMS Software.

- System structural components are represented as Rigid Elements.
- Compliant joints are represented by ADAMS Bushing statements.
- Ball joints are represented by ADAMS Spherical Joint statements.
- Wheel bearing and strut bending compliances were represented using ADAMS Bushing statements.

The suspension geometries for the ULSAS programme suspensions were developed using Mechanical Dynamics Industries ADAMS software, version 9.1.

System structural components (links, arms, hub carriers, etc) were represented as rigid elements.

Compliant joints (bushes) were represented by ADAMS BUSHING statements.

Ball joints were represented by ADAMS SPHERICAL JOINT statements.

Wheel bearing, and where appropriate strut bending, compliances were represented using ADAMS BUSHING statements.

ULSAS CAE DYNAMICS APPROACH

The models were used to:

- Generate the kinematic characteristics of the suspensions with respect to vertical wheel displacement.
- Establish the contribution of non-structural components of the system to overall system compliance characteristics.
- The system geometry and compliant joint stiffnesses were carefully tuned to obtain a solution which satisfied the programme kinematic and compliance targets.

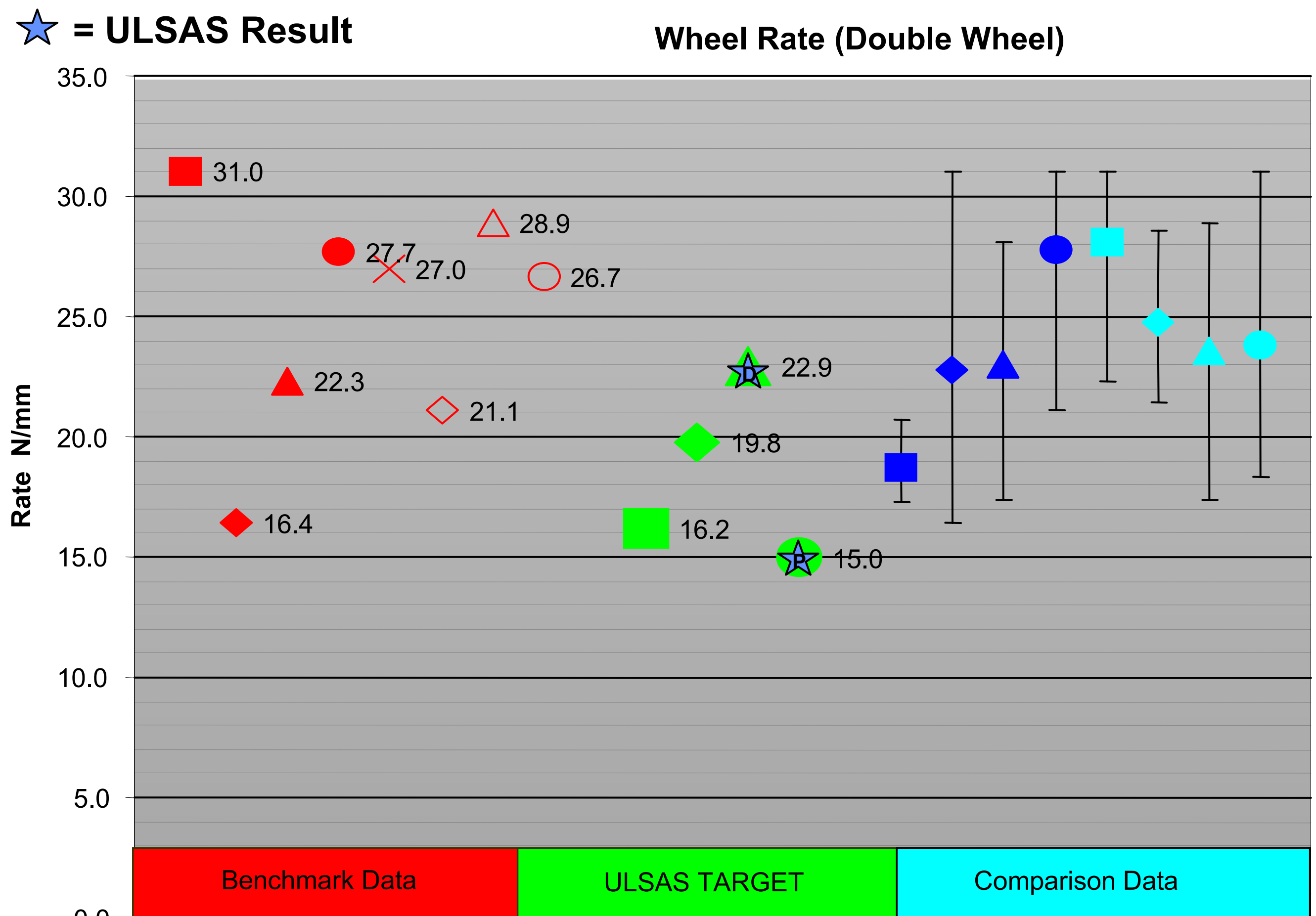
Analysis results were subsequently converted to predicted ratings (0 to 10) using Lotus in-house algorithms.

The models were used to generate the kinematic characteristics of the suspensions with respect to vertical wheel displacement, and to establish the contribution of non-structural components of the system to overall system compliance characteristics with respect to lateral and longitudinal forces applied at the tyre contact patch centre, and torque applied about a vertical axis through the tyre contact patch centre.

The system geometry and compliant joint stiffnesses were varied to obtain a solution which satisfied the kinematic and compliance targets generated by the target setting process.

Potential NVH ratings were estimated from the models by considering the relationship between bush stiffnesses, component stiffnesses and body mounting point stiffnesses and positions.

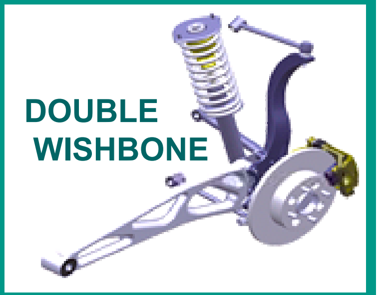
DOUBLE WISHBONE: Performance

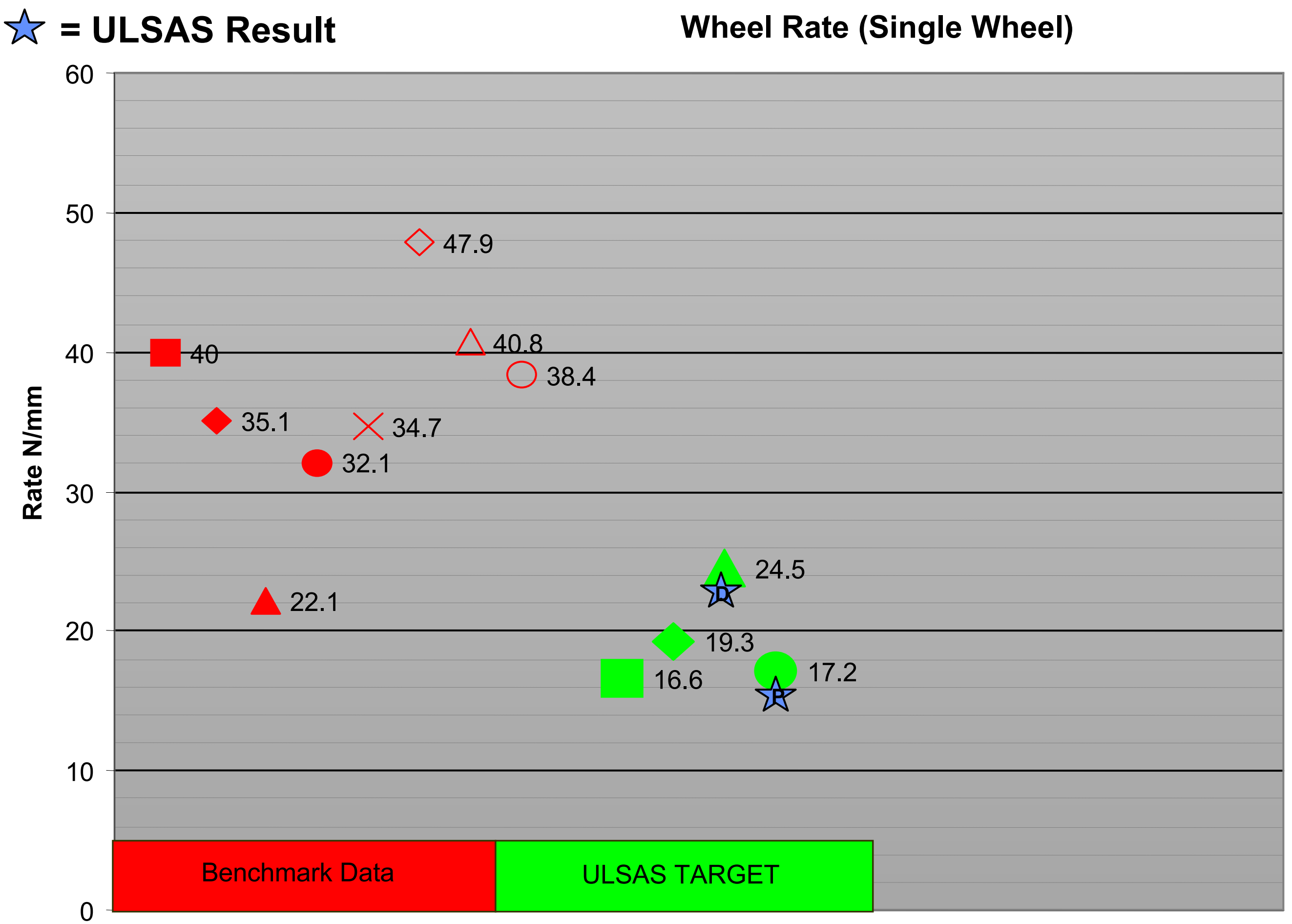


Comments:

Wheel rates have exactly matched targets by a combination of spring design and suspension parasitic rate. The rate for single wheel bump will be the same as for double wheel bump in this independent system.

DOUBLE WISHBONE: Performance



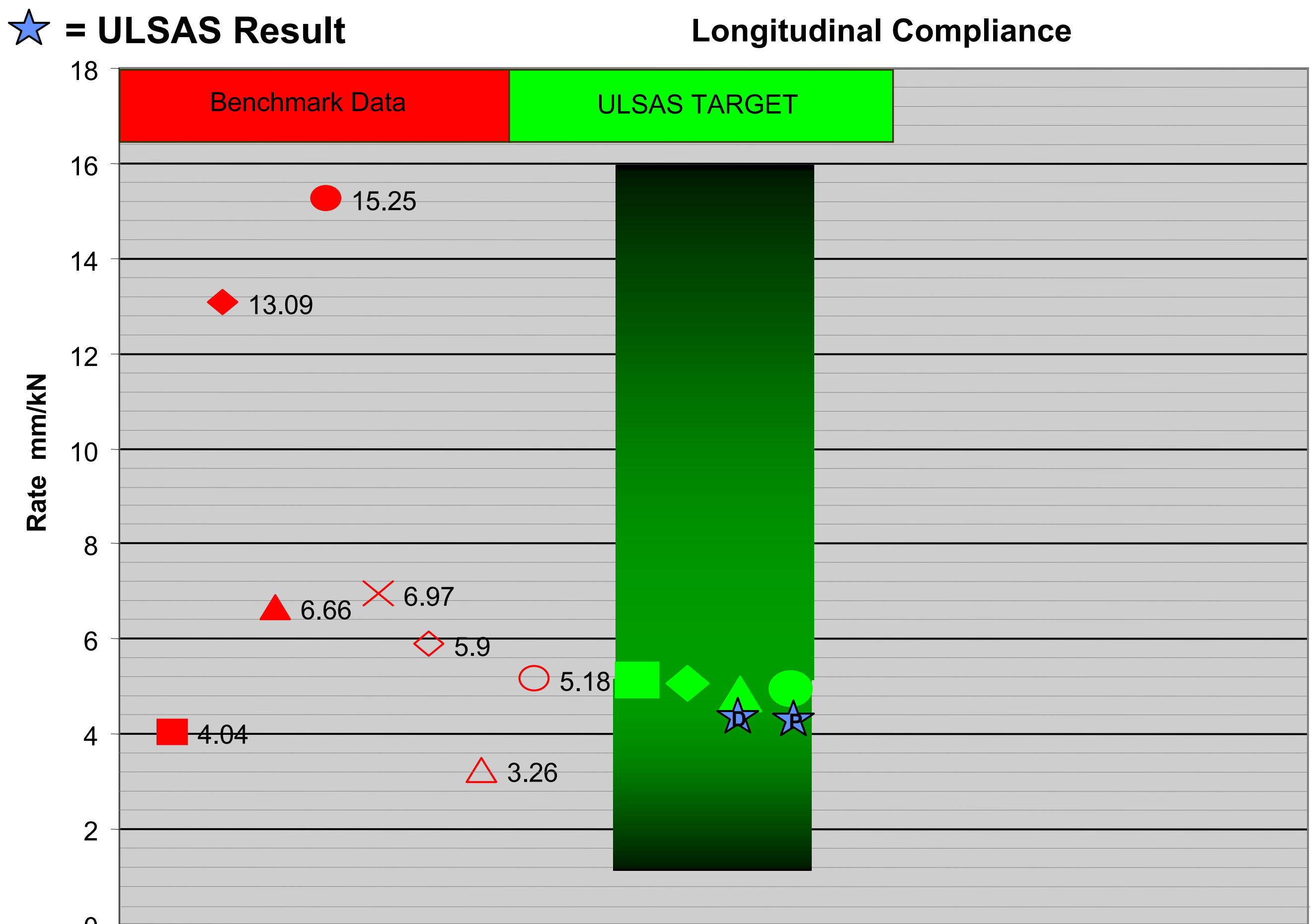


Comments:

Single wheel rate is slightly low, therefore an additional anti-roll bar may be required. The additional rate however is fairly small and so many manufacturers would not add an anti-roll bar for reasons of cost and weight whilst others may add one for the purpose of giving some vehicle characterisation.

DOUBLE WISHBONE: Performance

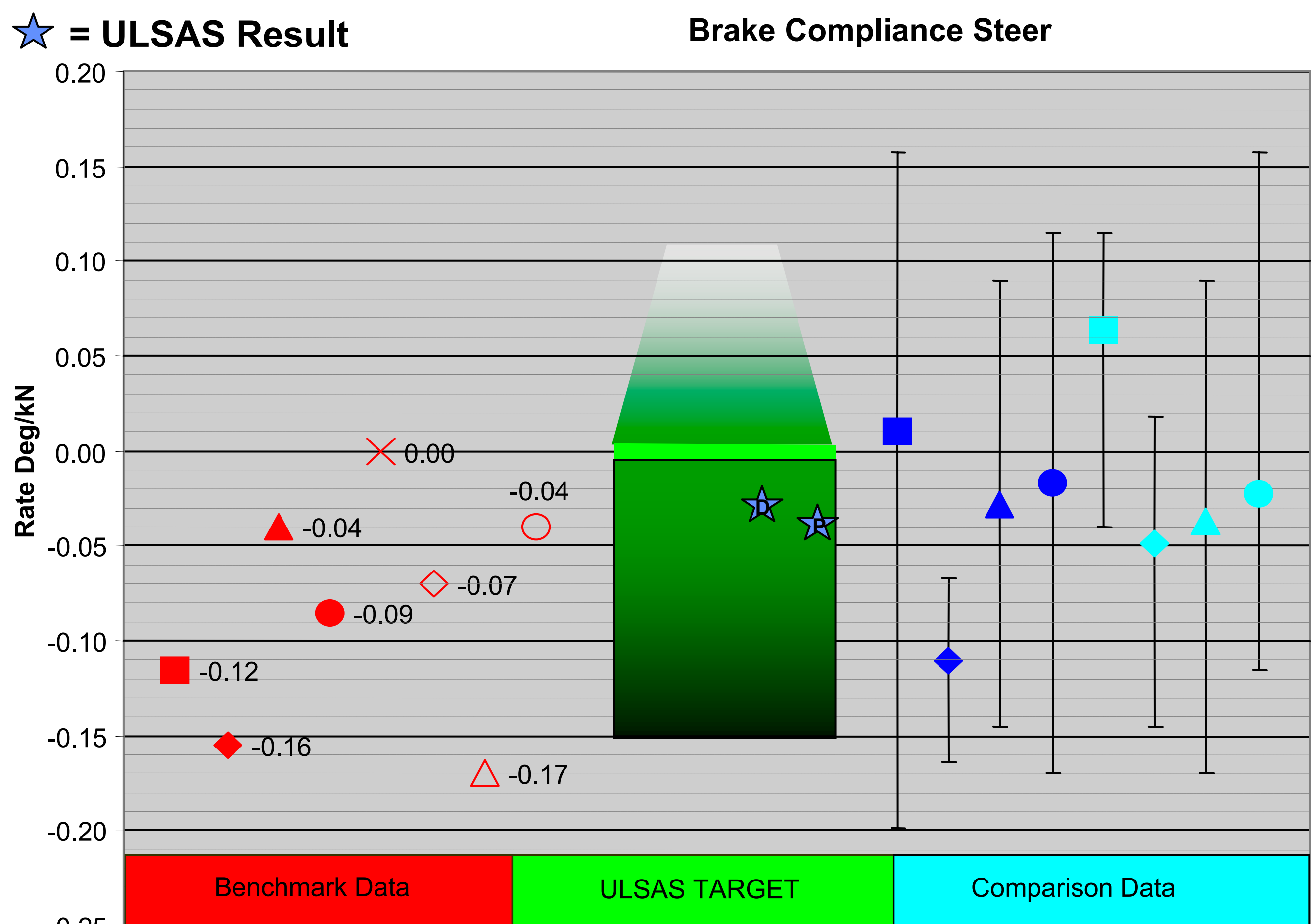
DOUBLE WISHBONE



Comments:

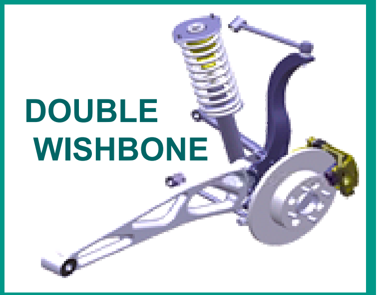
The longitudinal compliance achieved is close to the optimum value.

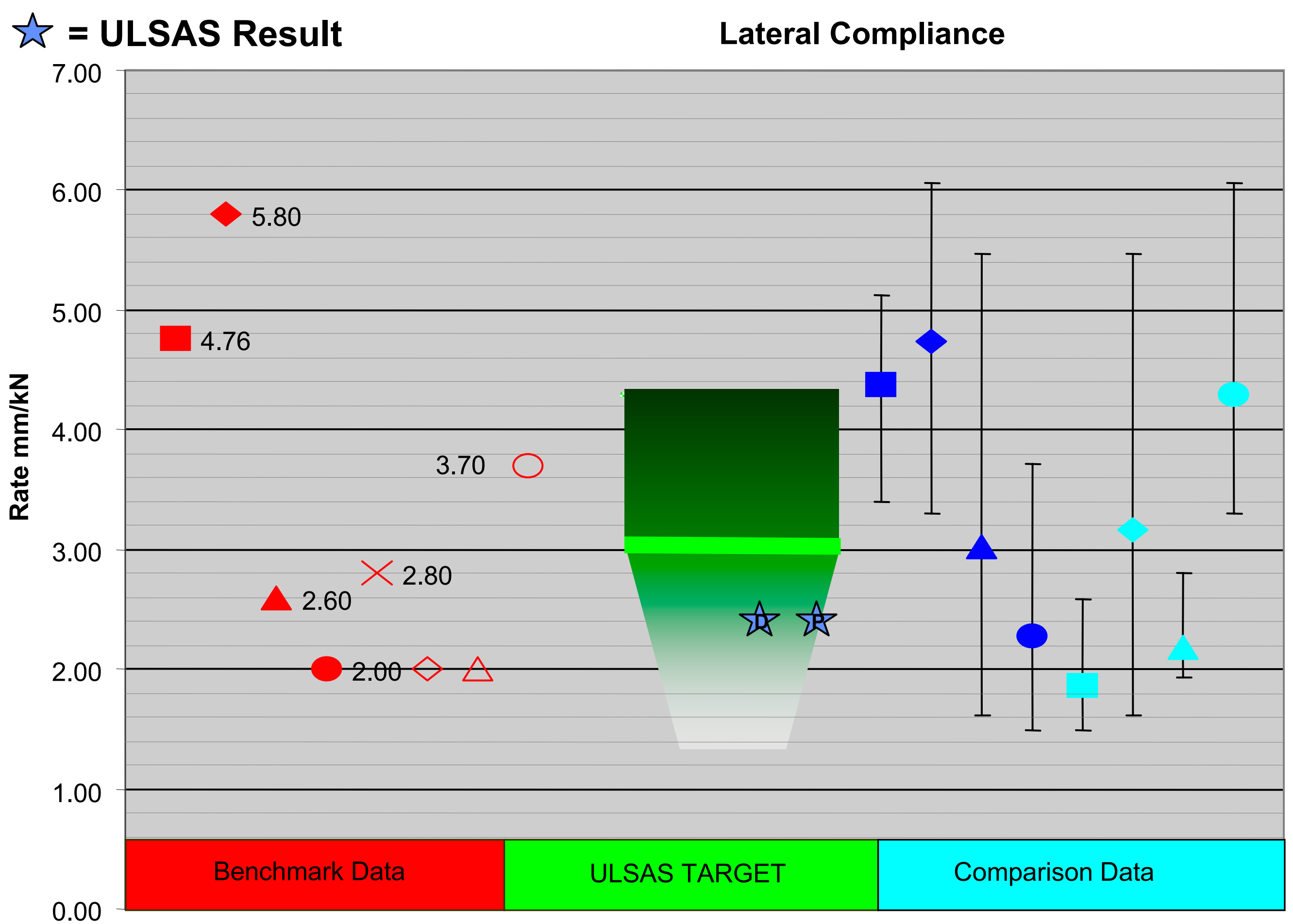
DOUBLE WISHBONE: Performance



Comments:
A good level of control has been achieved. The final result whilst, not ideal, compares favourably to the benchmark vehicles.

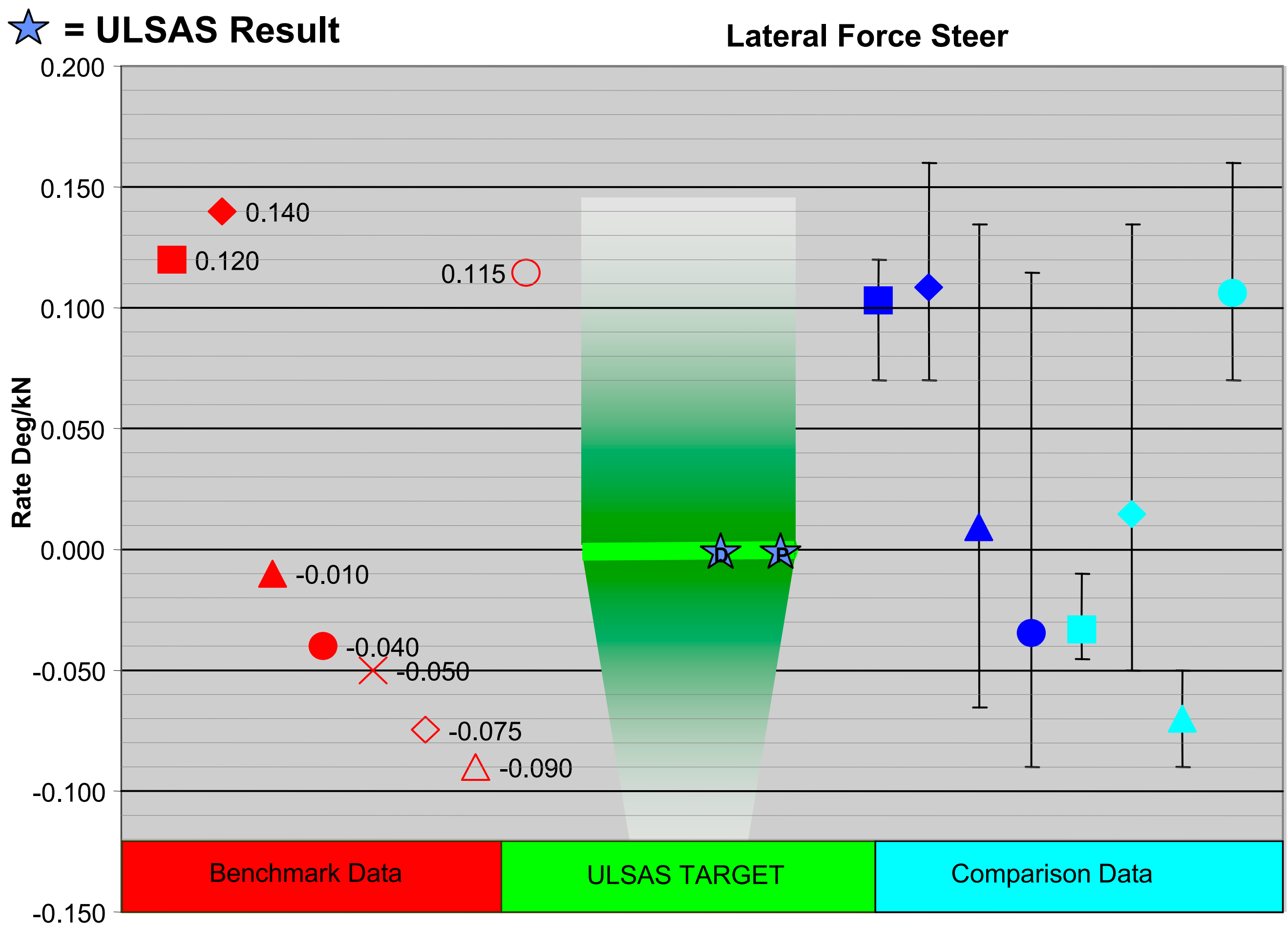
DOUBLE WISHBONE: Performance





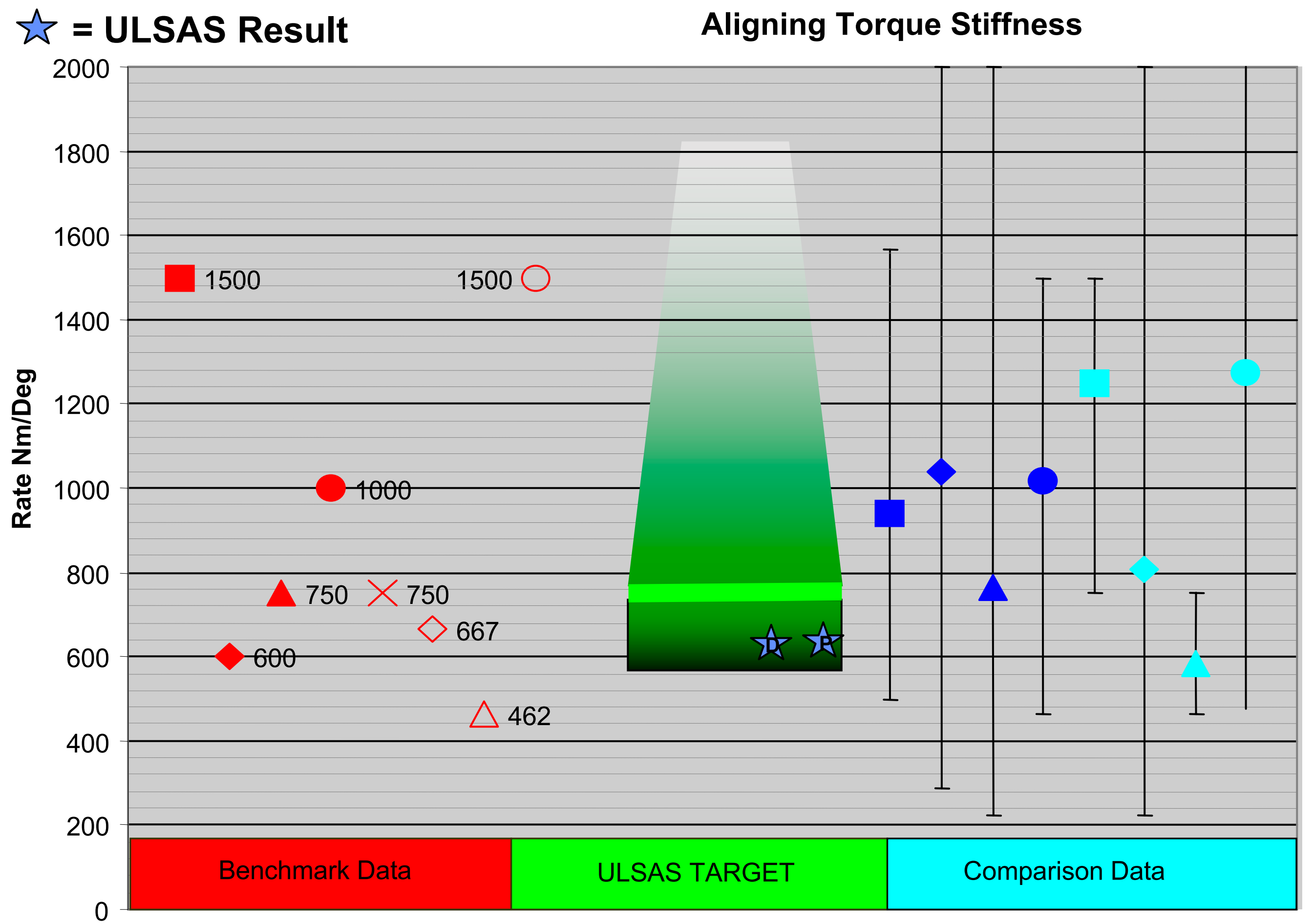
Comments:
Good control has been achieved with a level which exceeds the target value.

DOUBLE WISHBONE: Performance



Comments:
Both ULSAS Double Wishbone designs have achieved the target ideal value.

DOUBLE WISHBONE: Performance

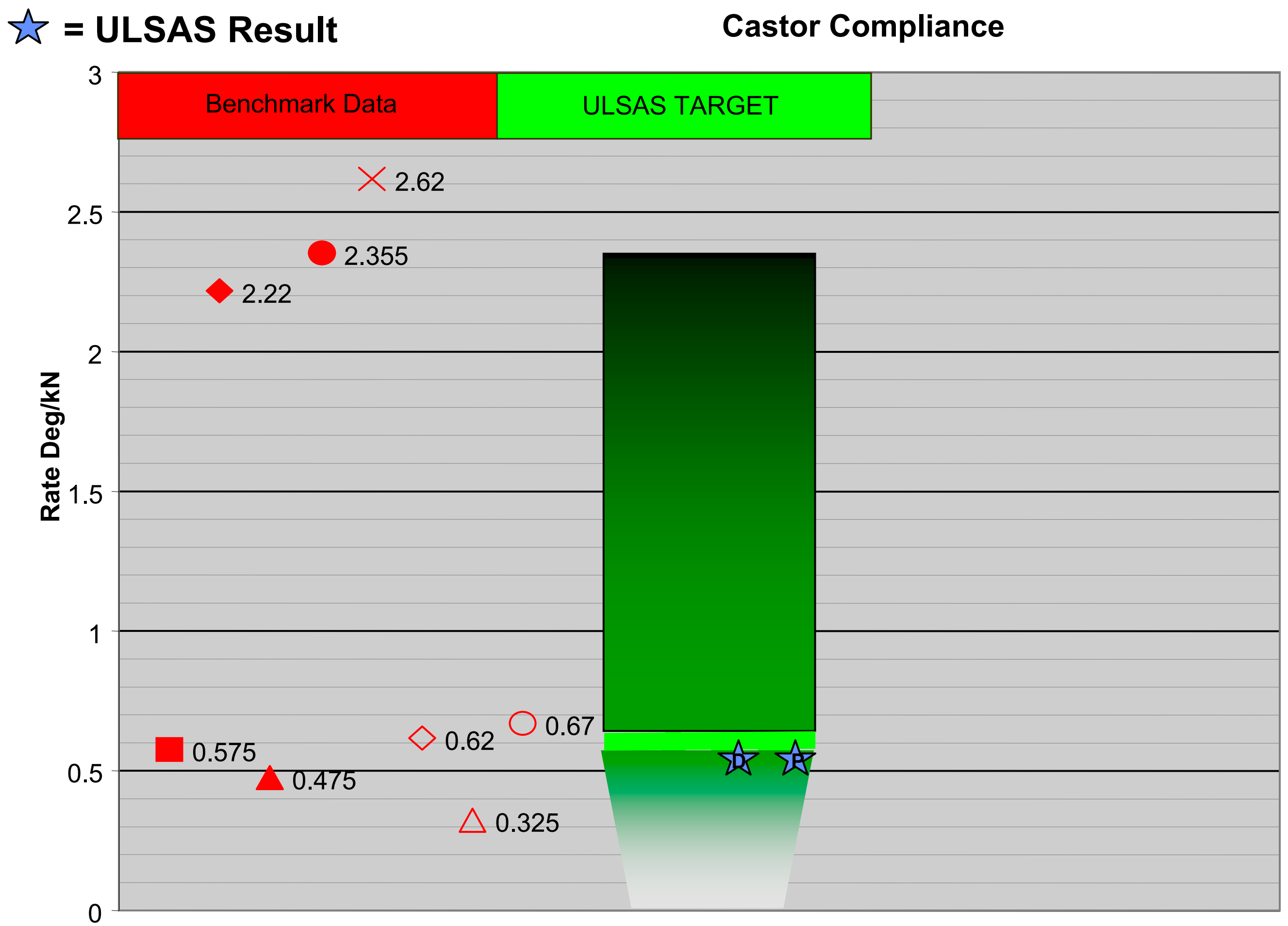


Comments:

The level of stiffness achieved is within the target range for Aligning Torque Stiffness

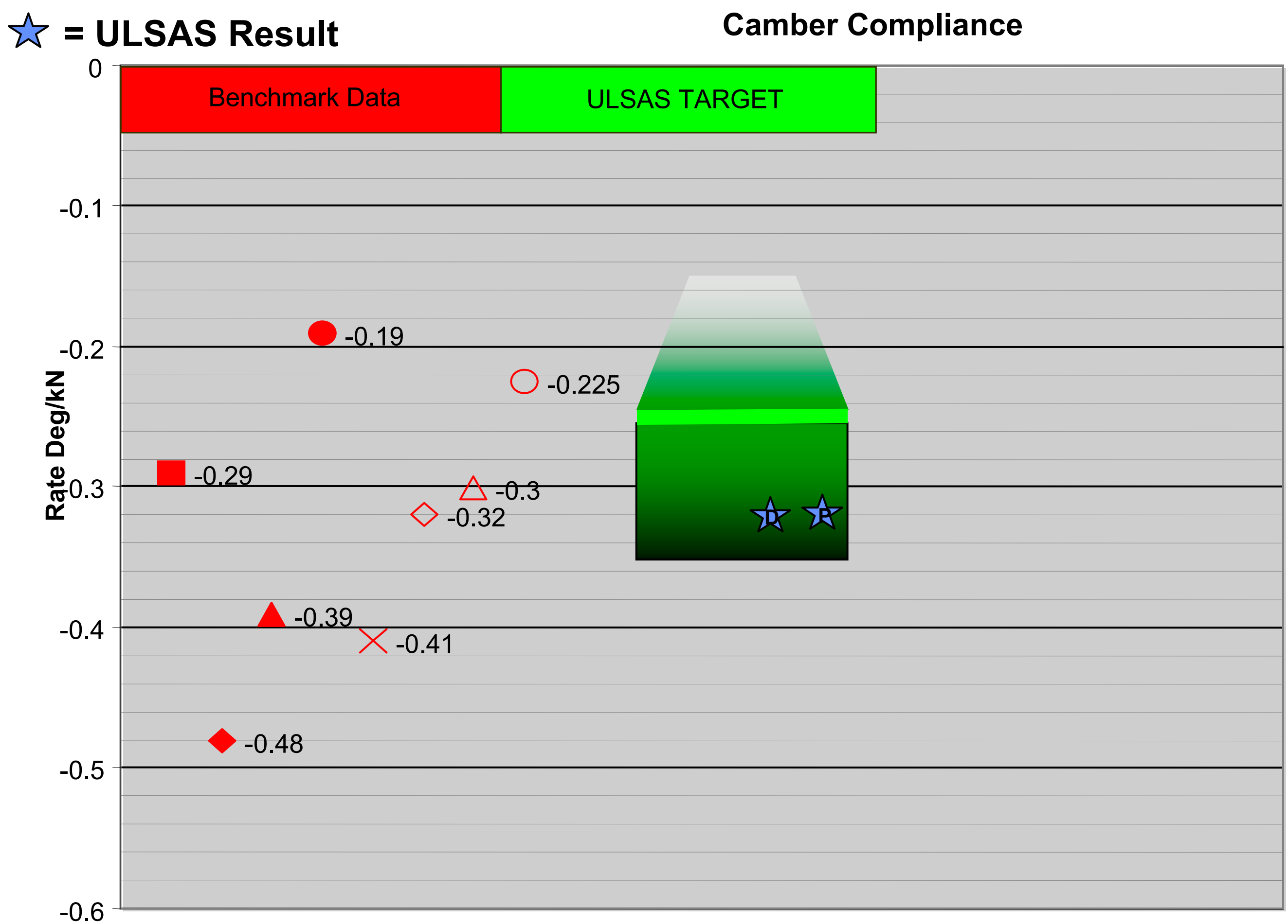
DOUBLE WISHBONE: Performance

DOUBLE WISHBONE



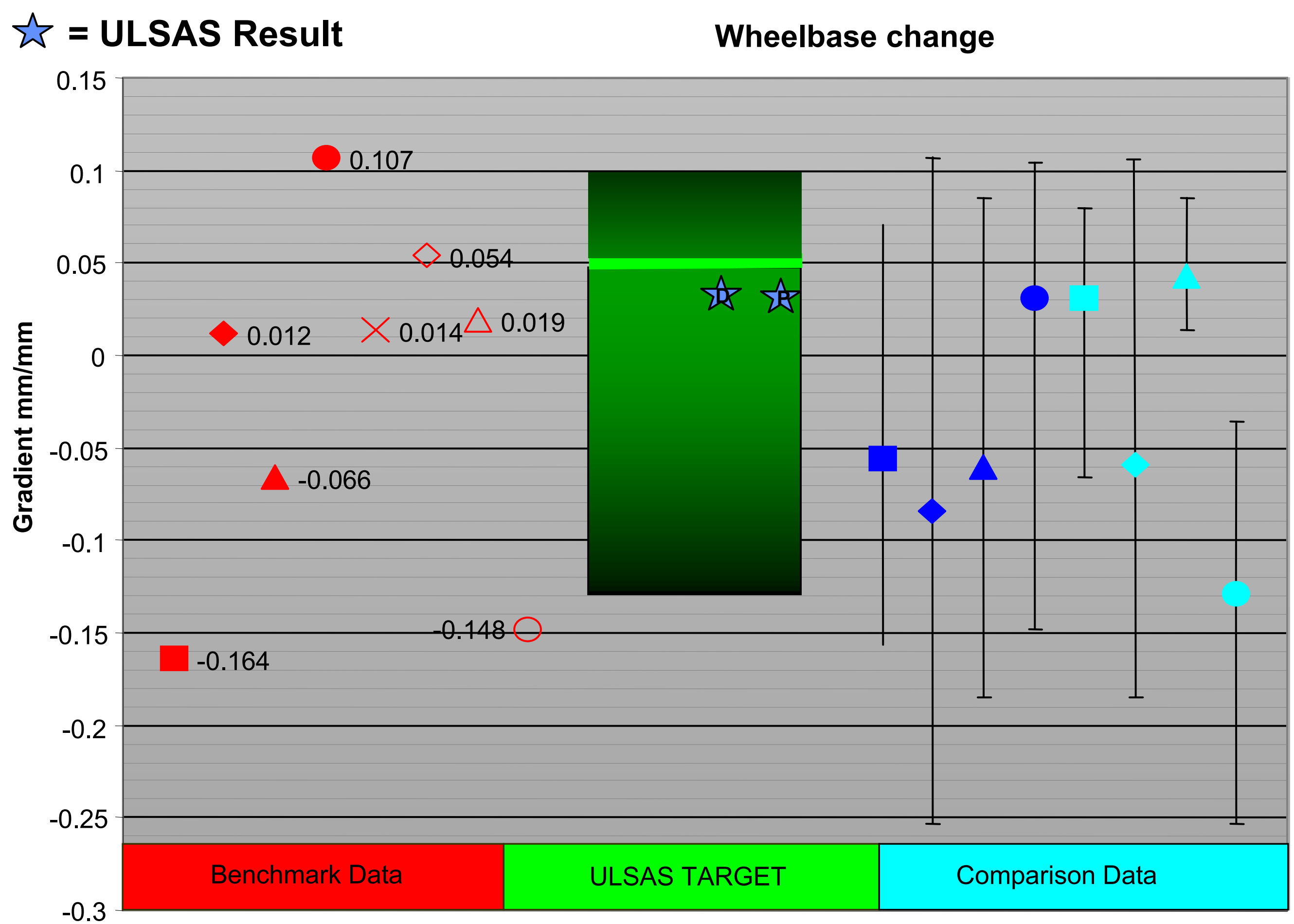
Comments:
The target rate is exceeded by the ULSAS Double Wishbone designs.

DOUBLE WISHBONE: Performance



Comments:
Sufficient Camber stiffness has been achieved within the required tolerance bands.

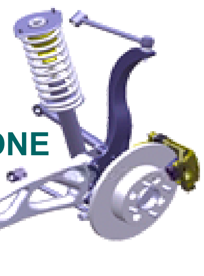
DOUBLE WISHBONE: Performance

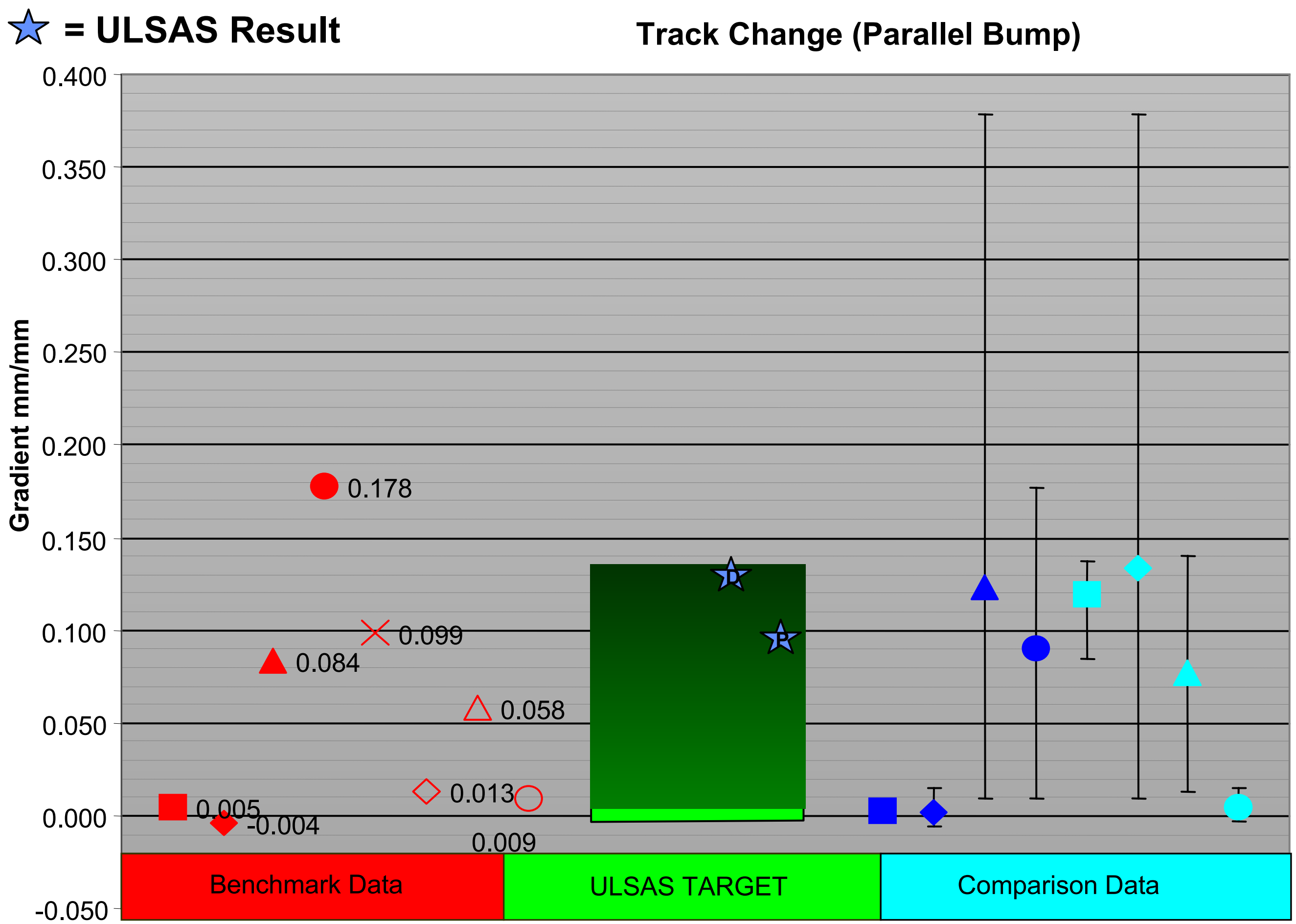


Comments:
Good characteristics have been achieved close to the ideal targets which will help maximise ride quality.

DOUBLE WISHBONE: Performance

DOUBLE WISHBONE



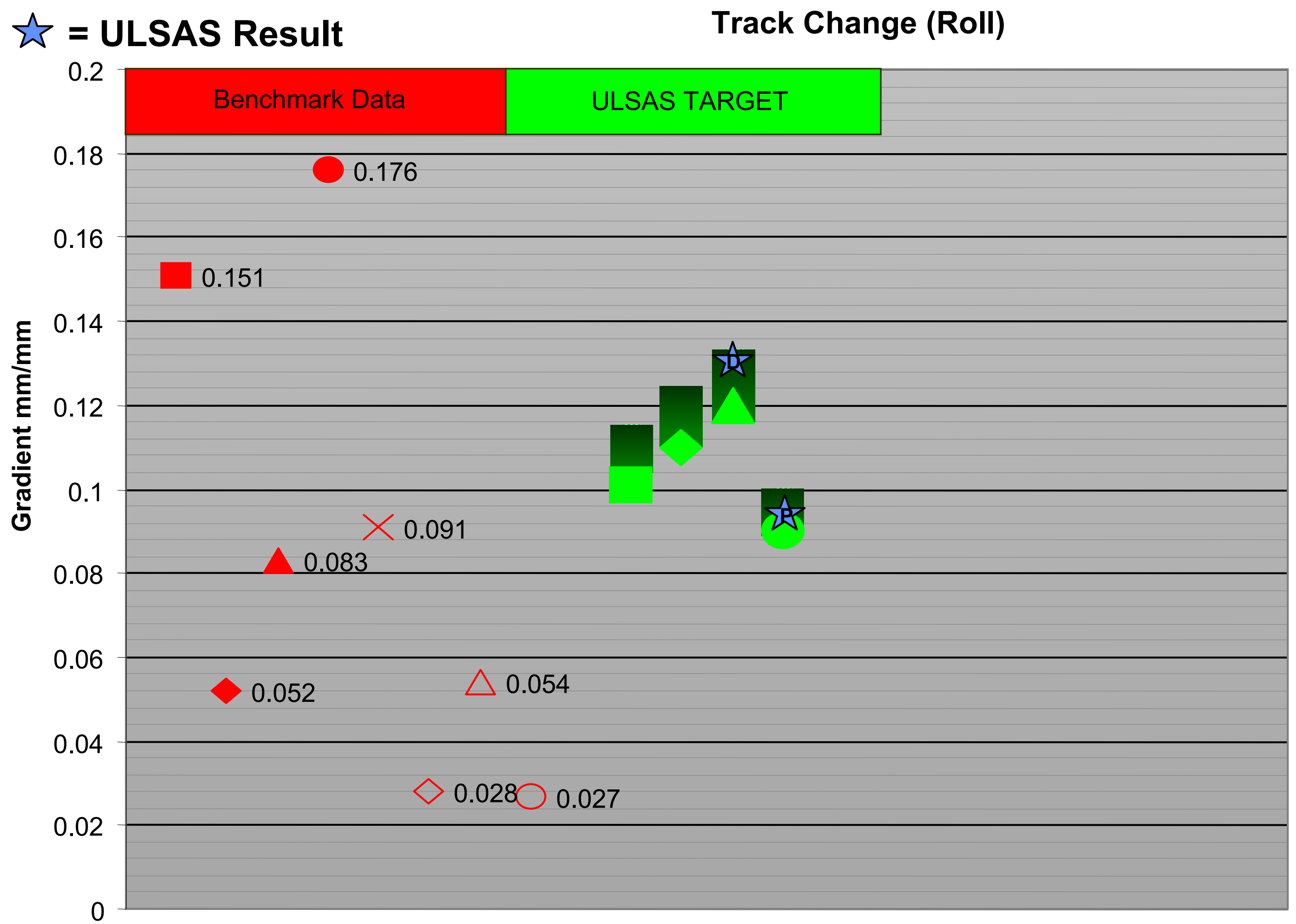


Comments:

Control of track in parallel bump is the same as in roll for the Double Wishbone system.
The levels achieved are within the required tolerance.

DOUBLE WISHBONE: Performance

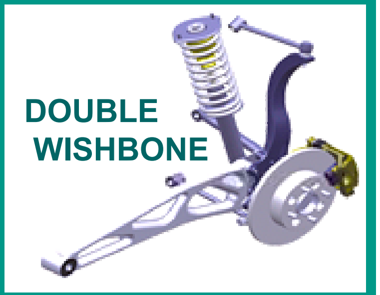
DOUBLE WISHBONE

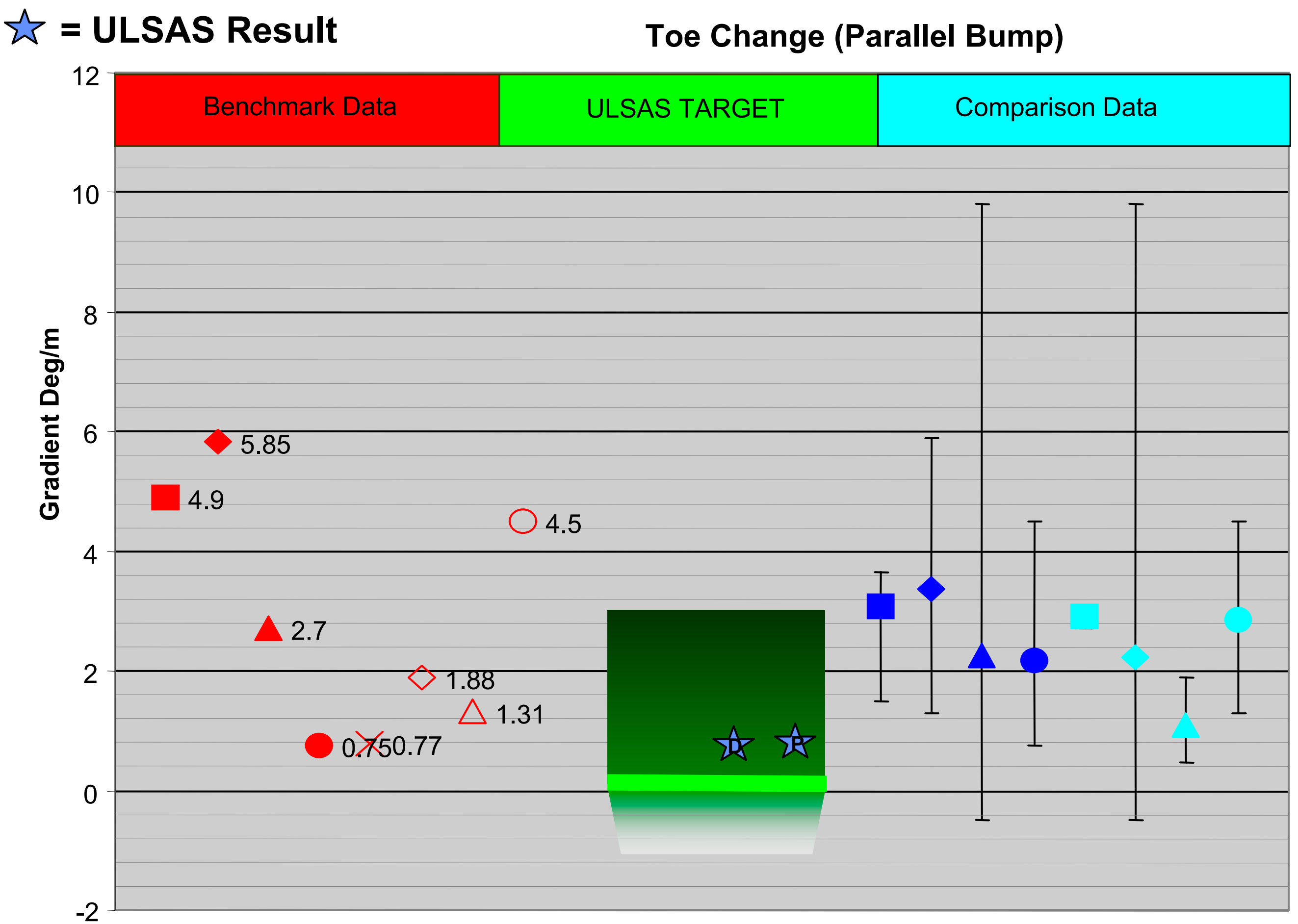


Comments:

Close tolerances are required to control Roll Centre position. The level of track change control in roll is within the desired target range for both ULSAS Double Wishbone designs.

DOUBLE WISHBONE: Performance



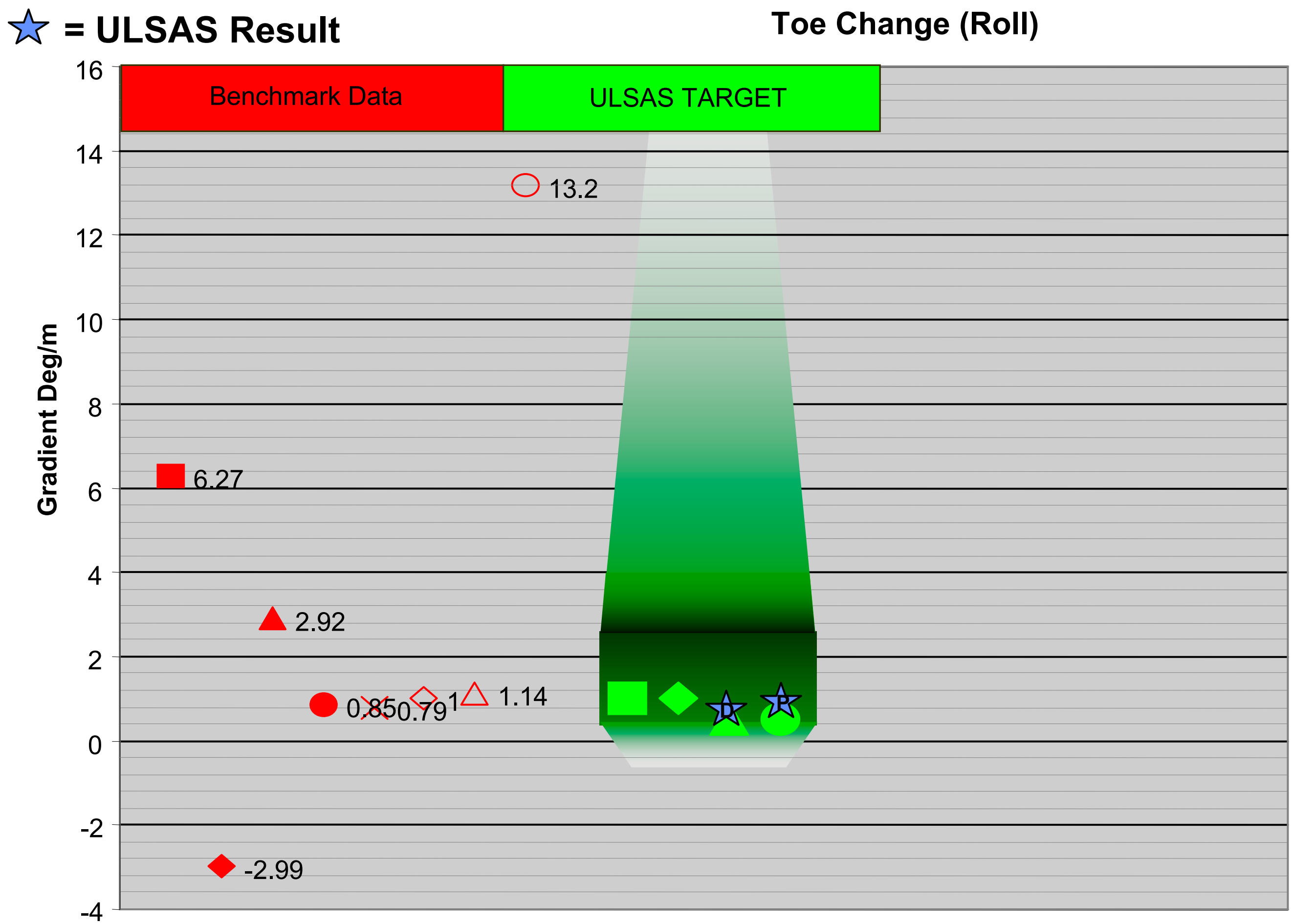


Comments:
Good control has been achieved with a small amount of Toe-in in bump.

DOUBLE WISHBONE: Performance

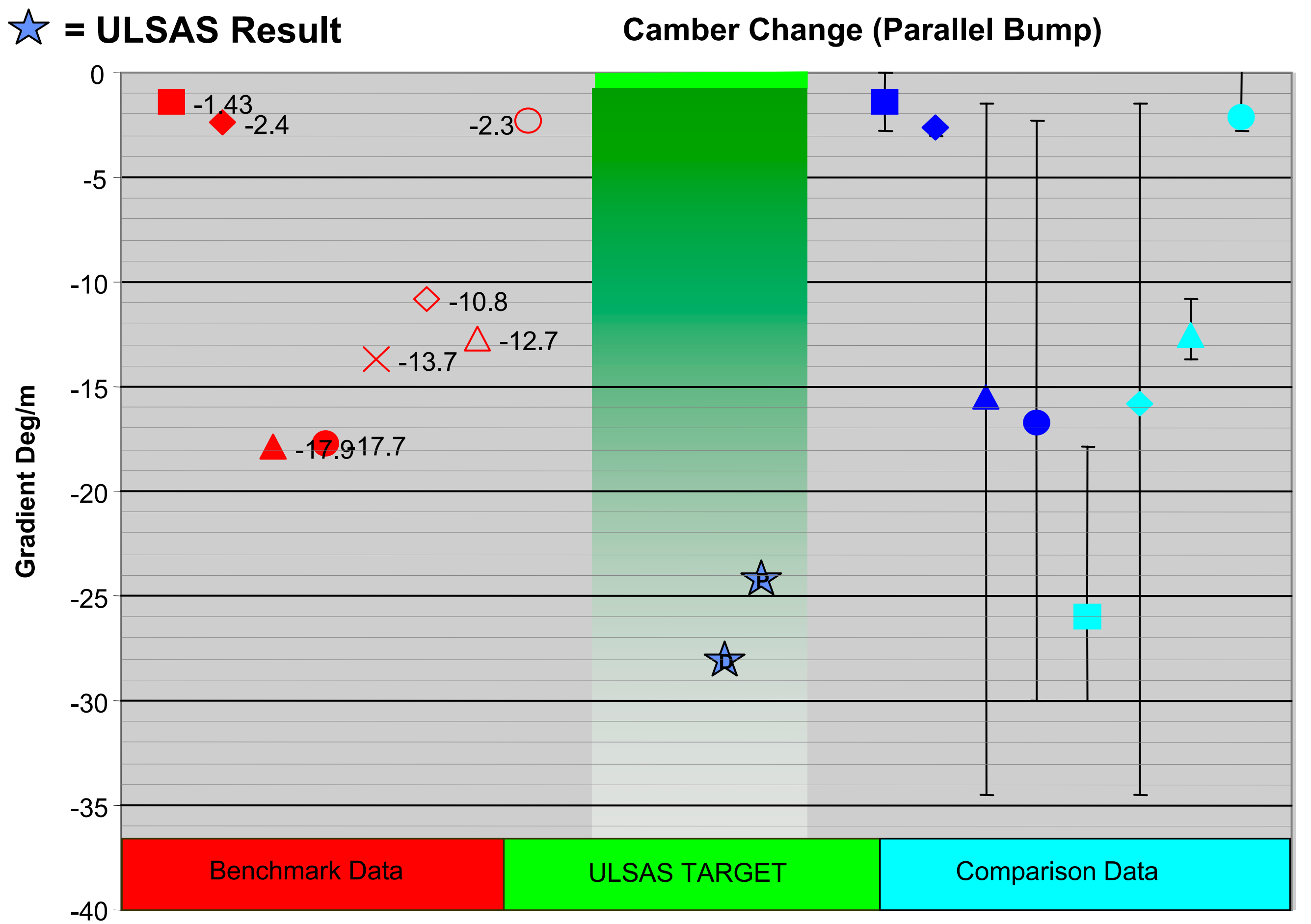
ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE



Comments:
Toe change in roll is the same as in parallel bump for the Double Wishbone system. Good balance has been achieved between these two requirements, with both results close to the Targets

DOUBLE WISHBONE: Performance

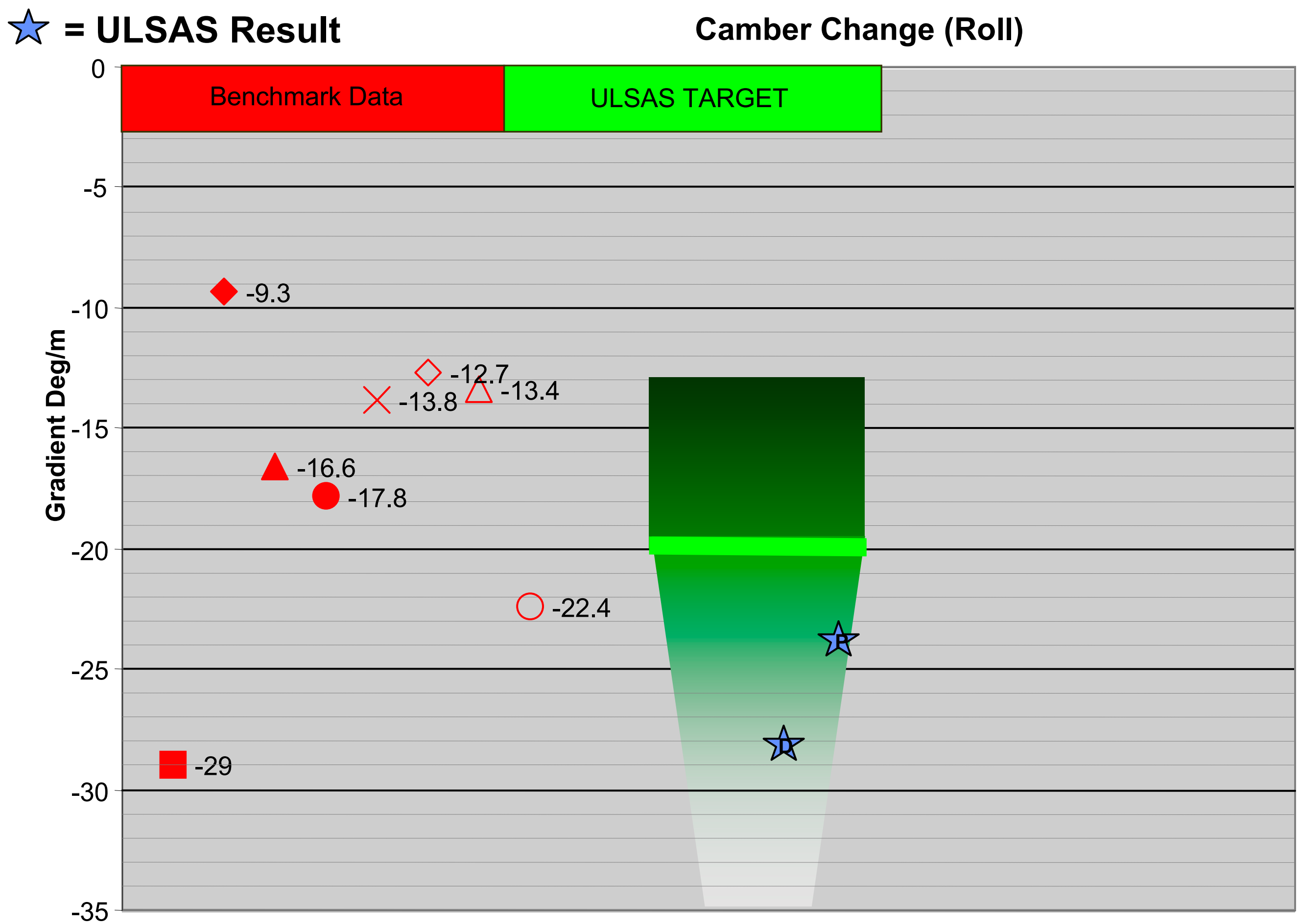


Comments:
The characteristics achieved are within the acceptable levels of the tolerance band. A balance has been achieved with the requirements in roll.

DOUBLE WISHBONE: Performance

ULTRALIGHT STEEL AUTO SUSPENSION

DOUBLE WISHBONE



Comments:

Camber change in roll is the same as in parallel bump for the Double Wishbone system.

The higher levels of Camber change in roll will give enhanced cornering performance.

DOUBLE WISHBONE: Performance

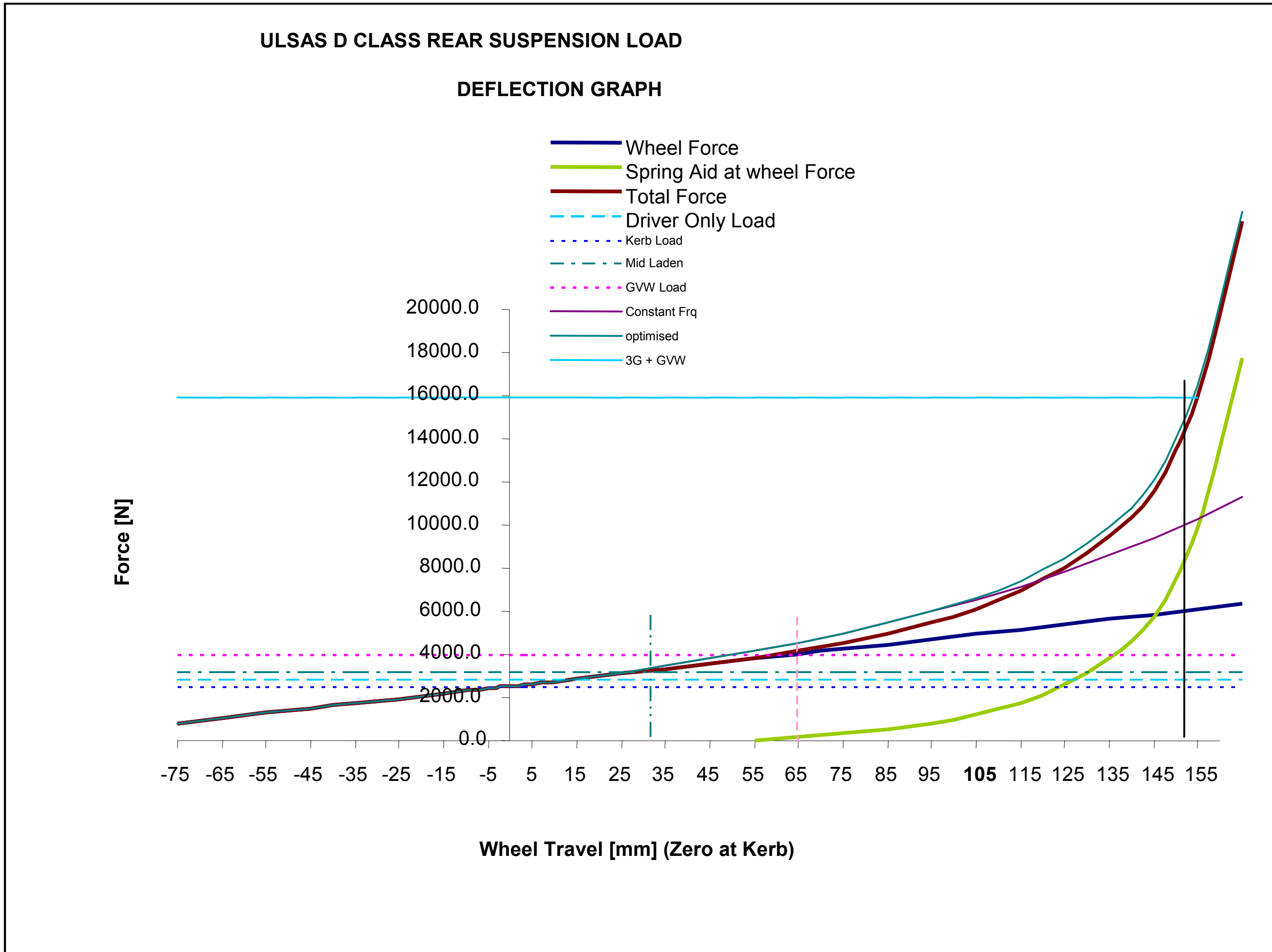
SYSTEM COMPLIANCES : Detailed Results Breakdown

(Bushes Vs Structural Contributions)

Characteristic	Units	Bush D Class	Bush P Class	Structural	TOTAL D Class	TOTAL P Class
Longitudinal Force at TCP						
TCP Longitudinal Compliance	mm/kN	3.65	3.59	0.57	4.22	4.16
Steer Compliance	deg/kN	0.05	0.04	-0.01	0.04	0.03
Castor Compliance	deg/kN	0.44	0.43	0.10	0.54	0.53
Lateral Force at TCP						
TCP Lateral Compliance	mm/kN	1.28	1.30	0.33	1.61	1.63
Steer Compliance	deg/kN	-0.01	-0.01	0.01	0.00	0.00
Camber Compliance	deg/kN	0.25	0.25	0.07	0.32	0.33
Aligning Torque at TCP						
Steer Stiffness	Nm / deg	739.00	755.00	4671.00	638.05	649.95

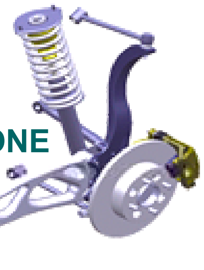
DOUBLE WISHBONE: Performance

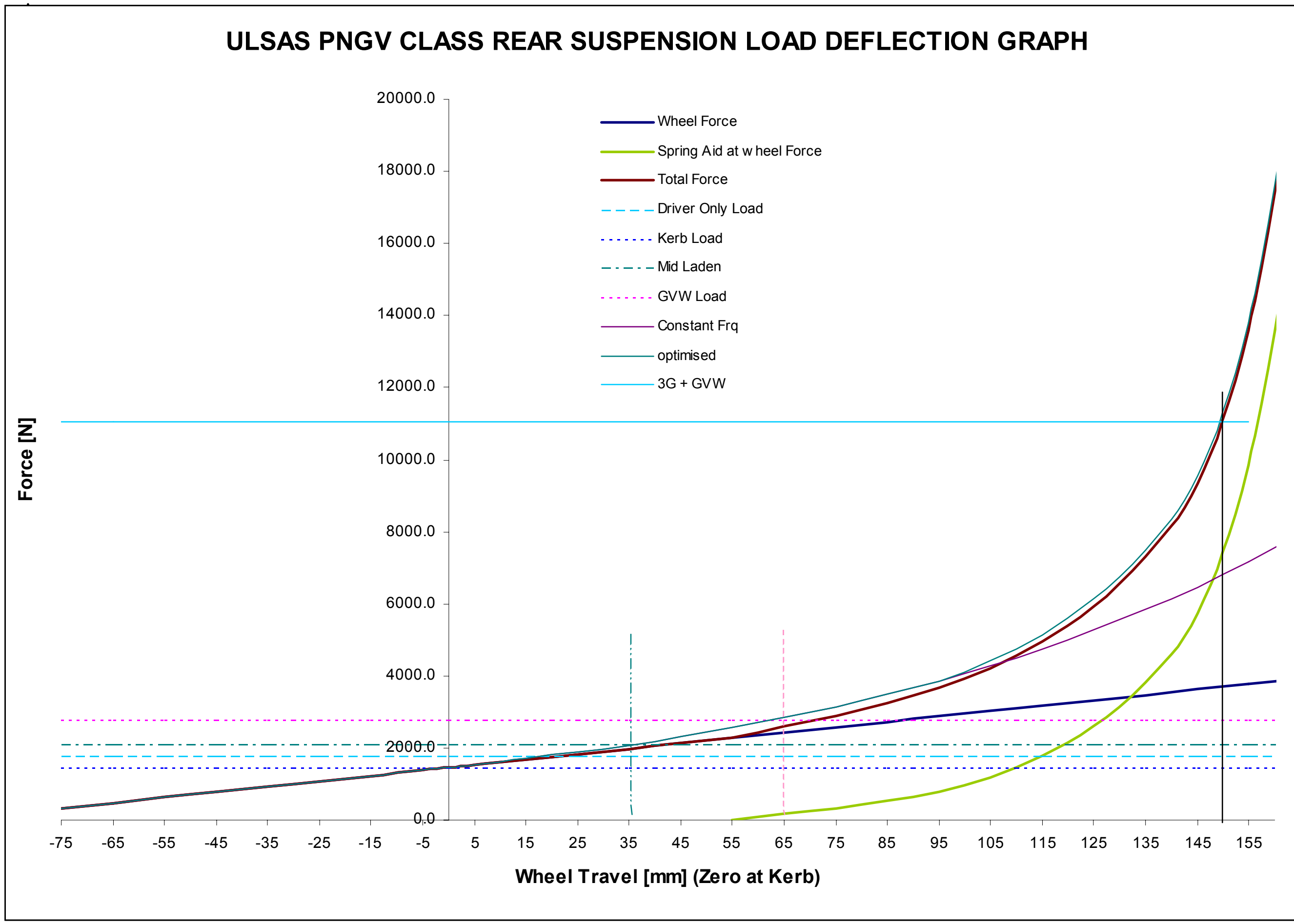
DOUBLE WISHBONE



DOUBLE WISHBONE: Performance

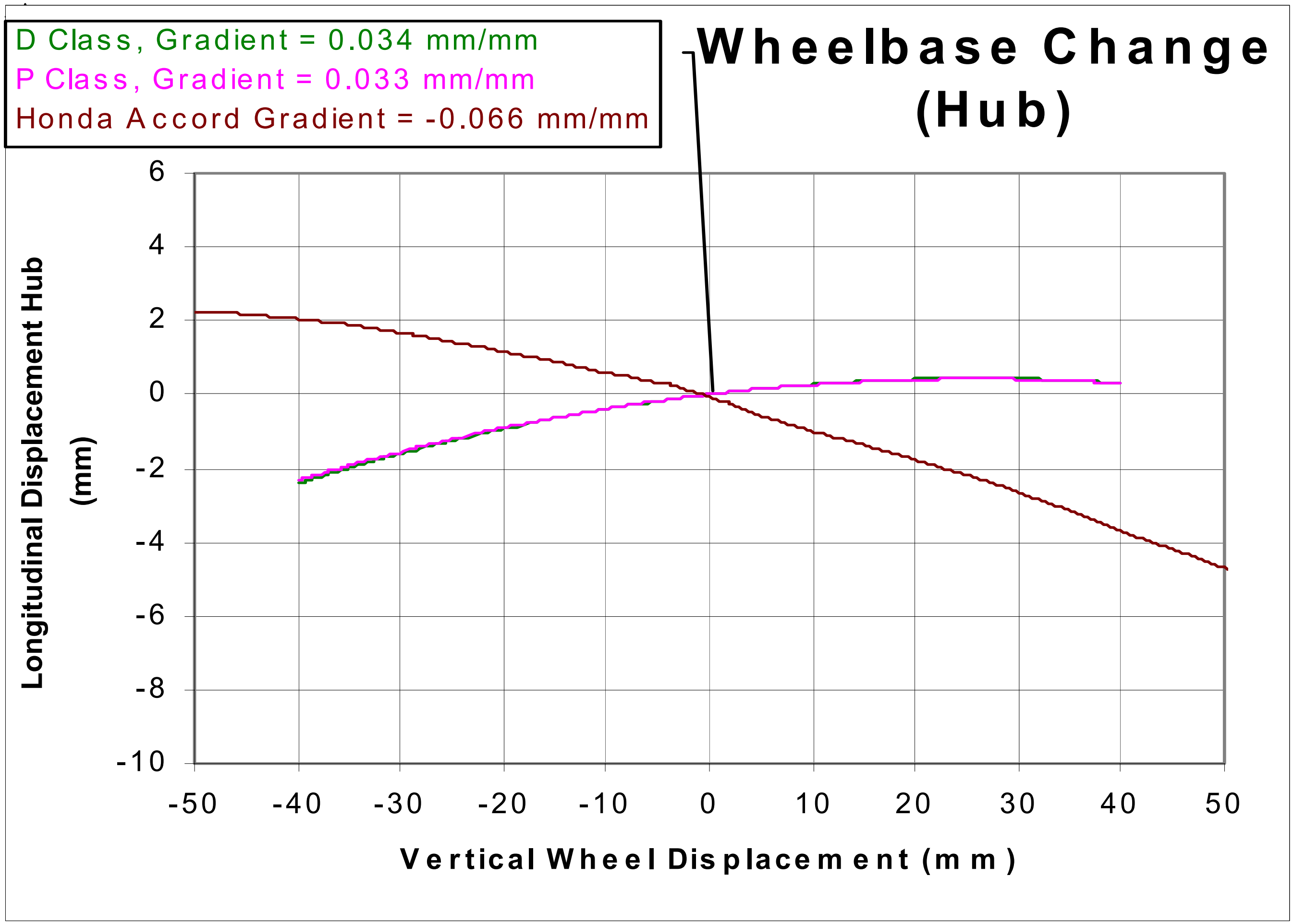
DOUBLE WISHBONE





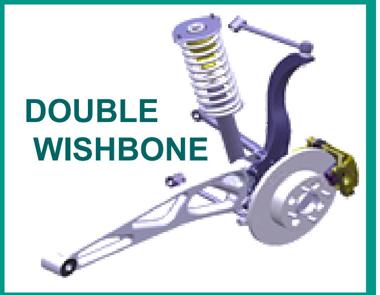
DOUBLE WISHBONE: Performance

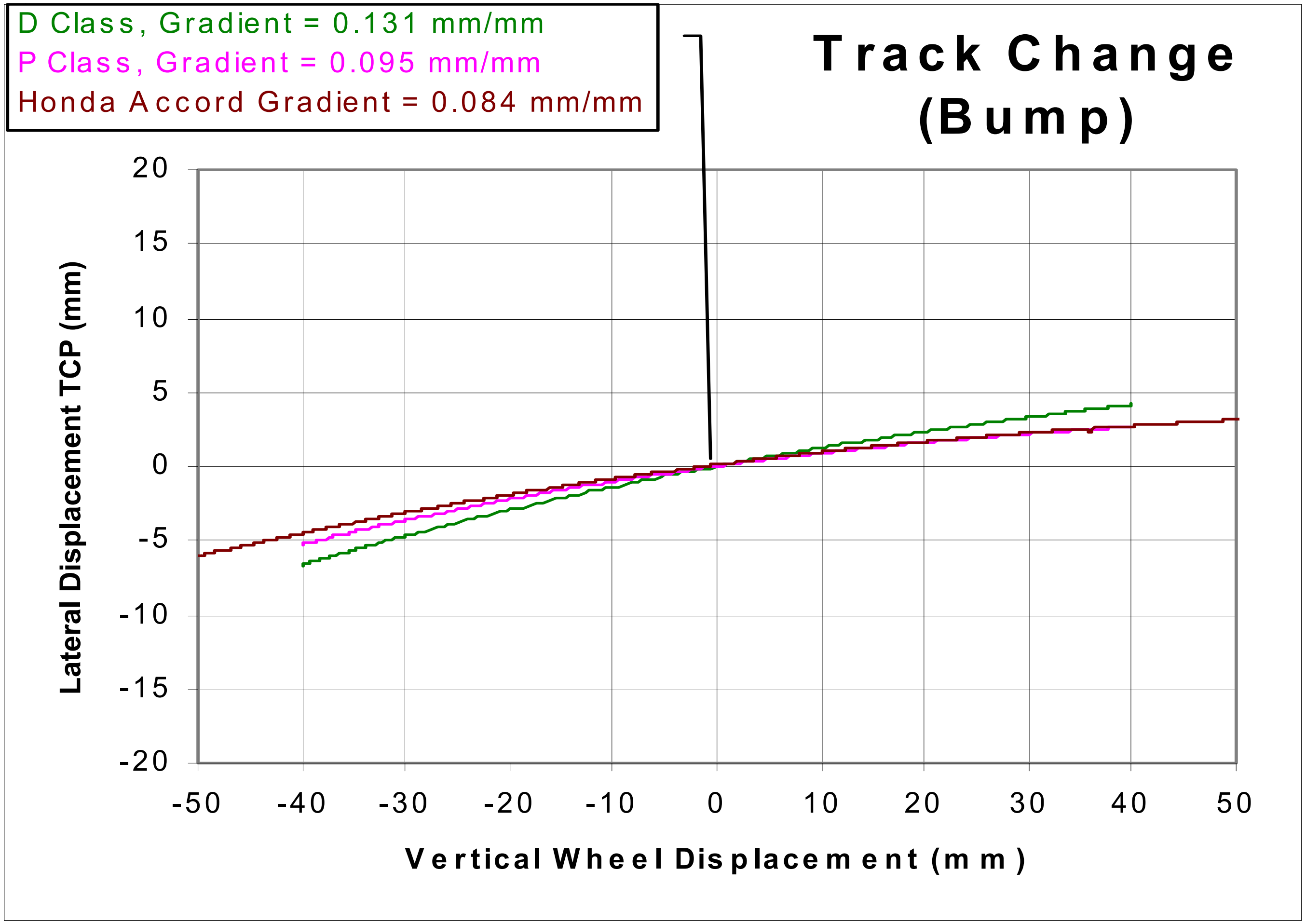
DOUBLE WISHBONE



Instantaneous gradient taken at wheel displacement zero

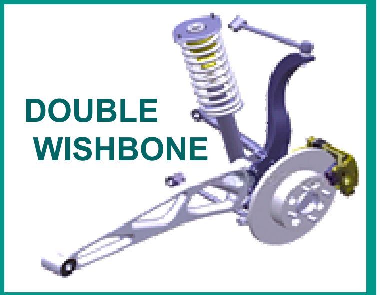
DOUBLE WISHBONE: Performance

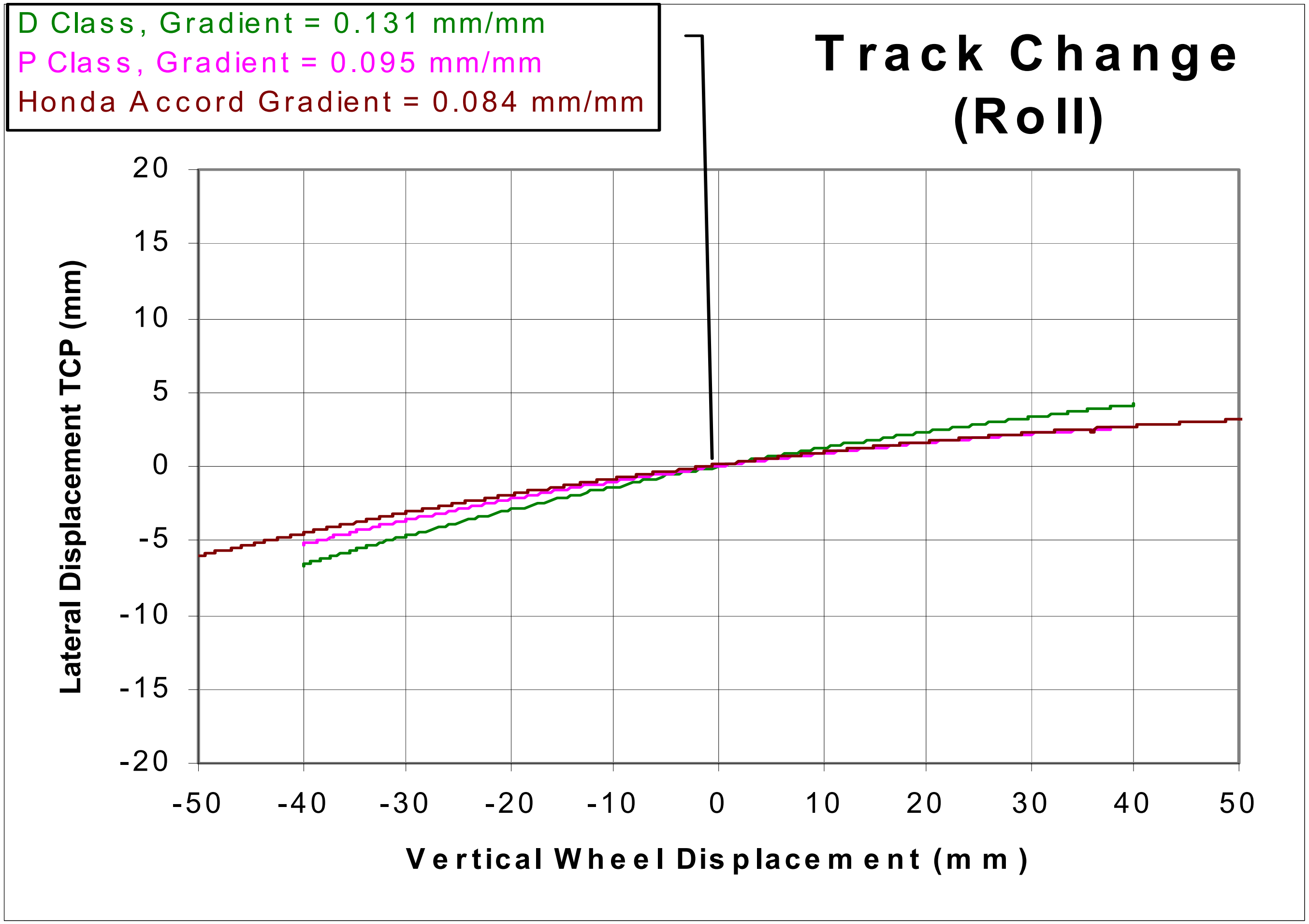




Instantaneous gradient taken at wheel displacement zero

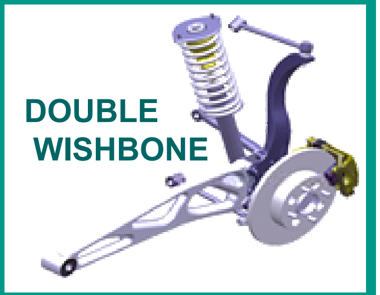
DOUBLE WISHBONE: Performance

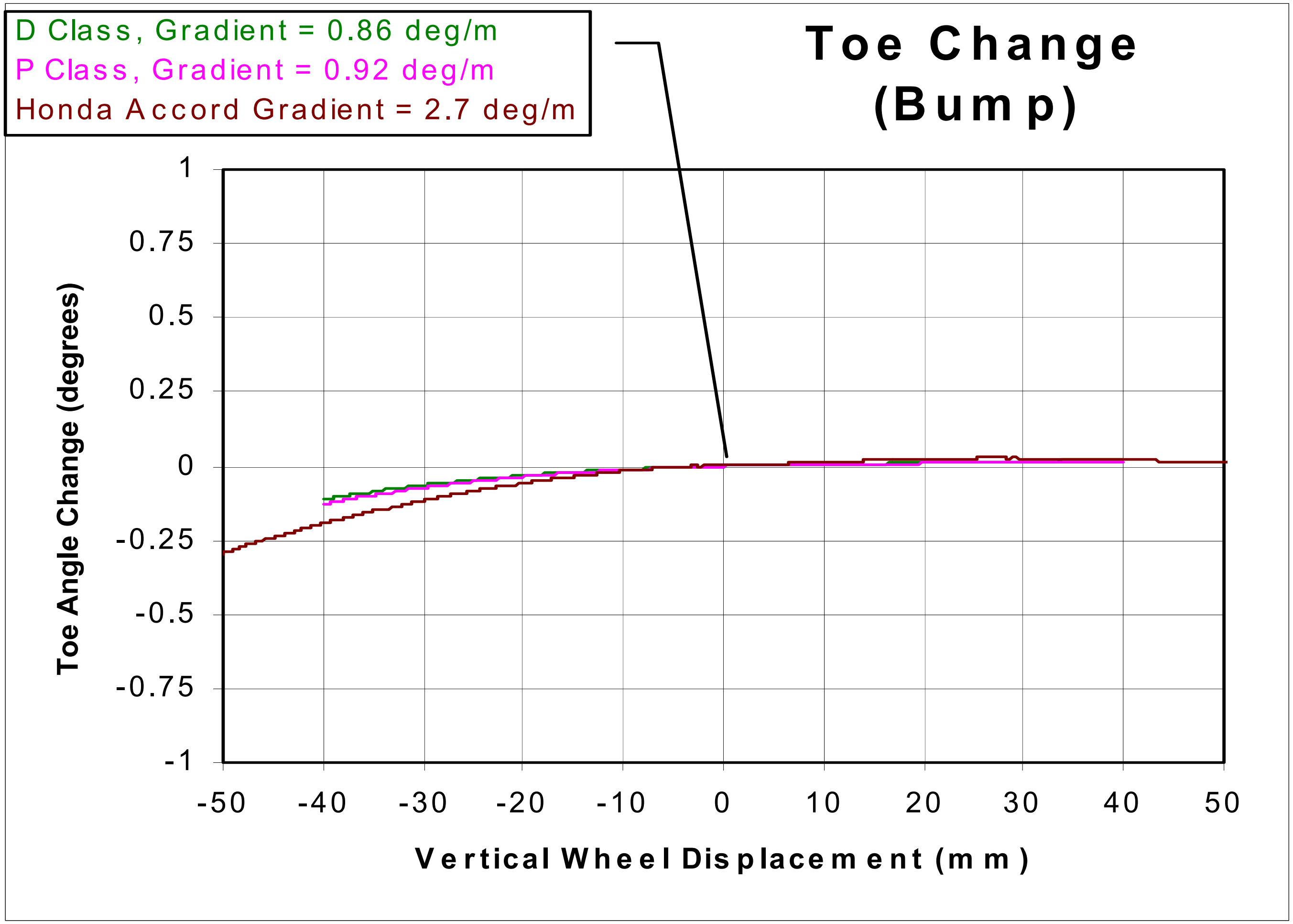




Instantaneous gradient taken at wheel displacement zero

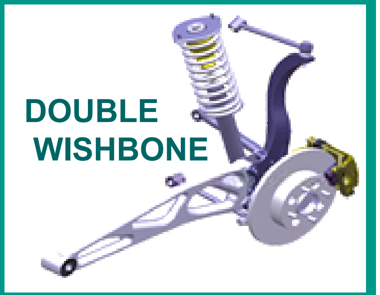
DOUBLE WISHBONE: Performance

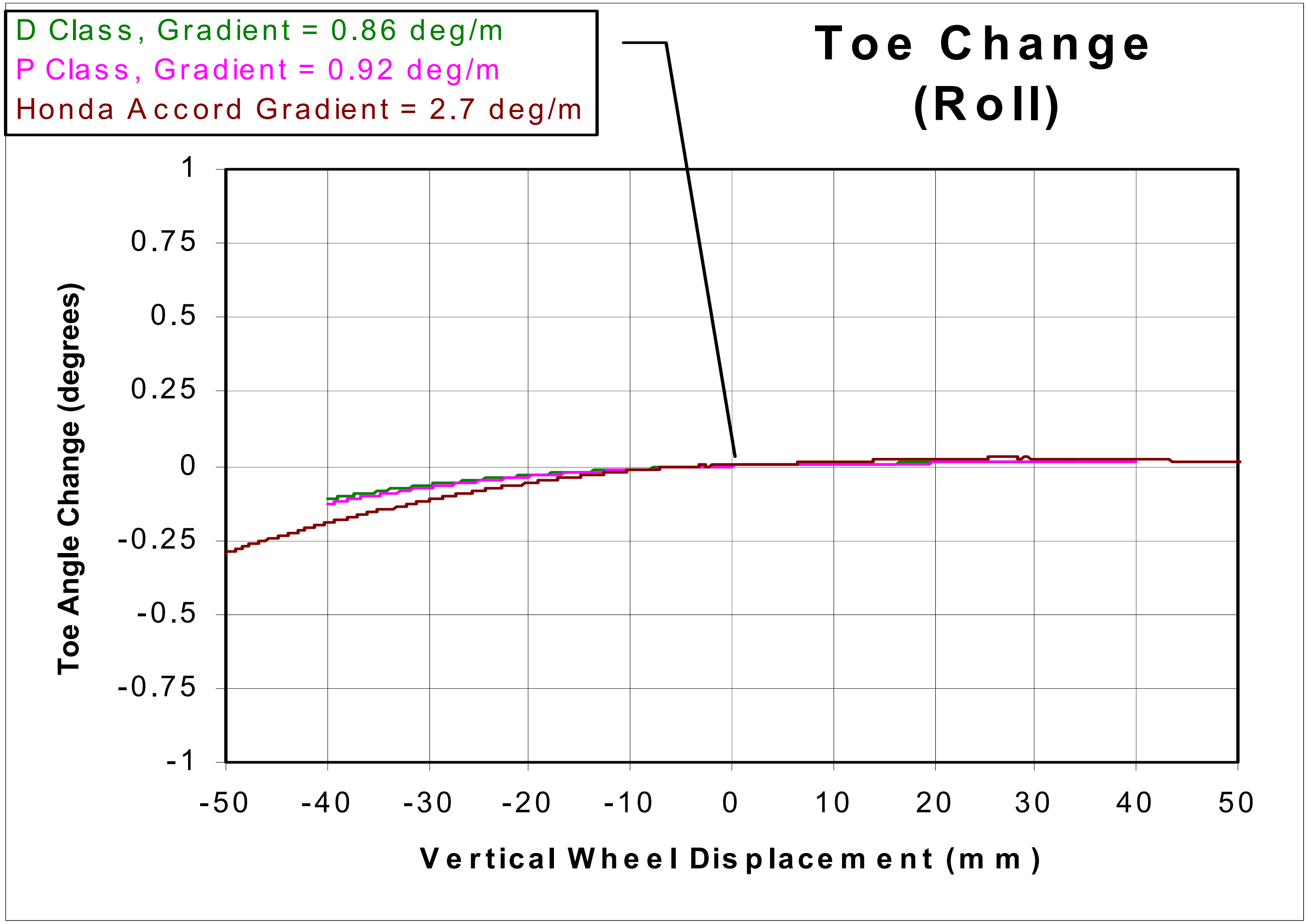




Instantaneous gradient taken at wheel displacement zero

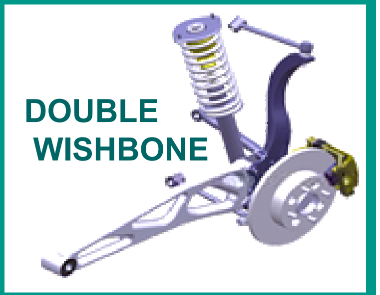
DOUBLE WISHBONE: Performance

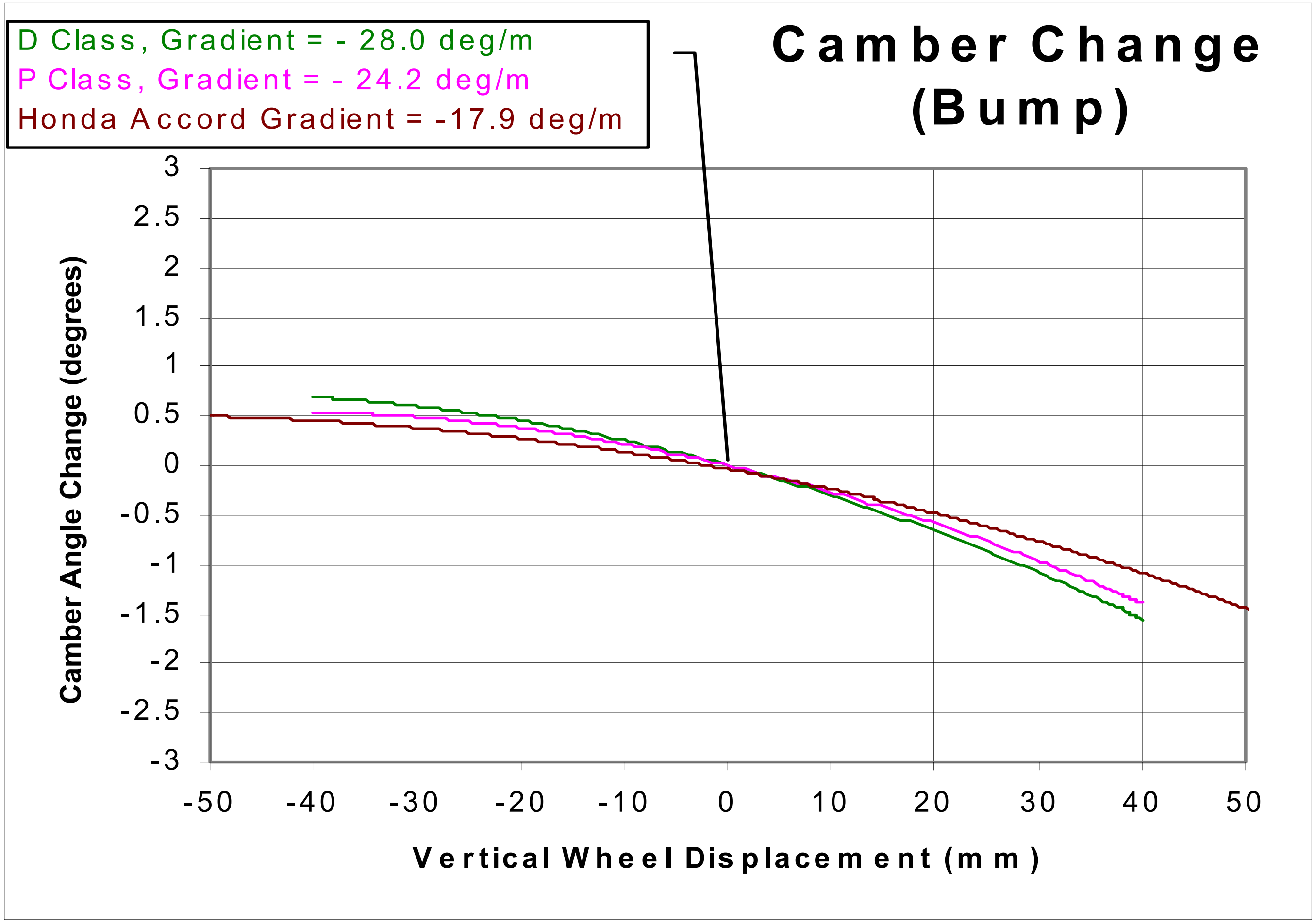




Instantaneous gradient taken at wheel displacement zero

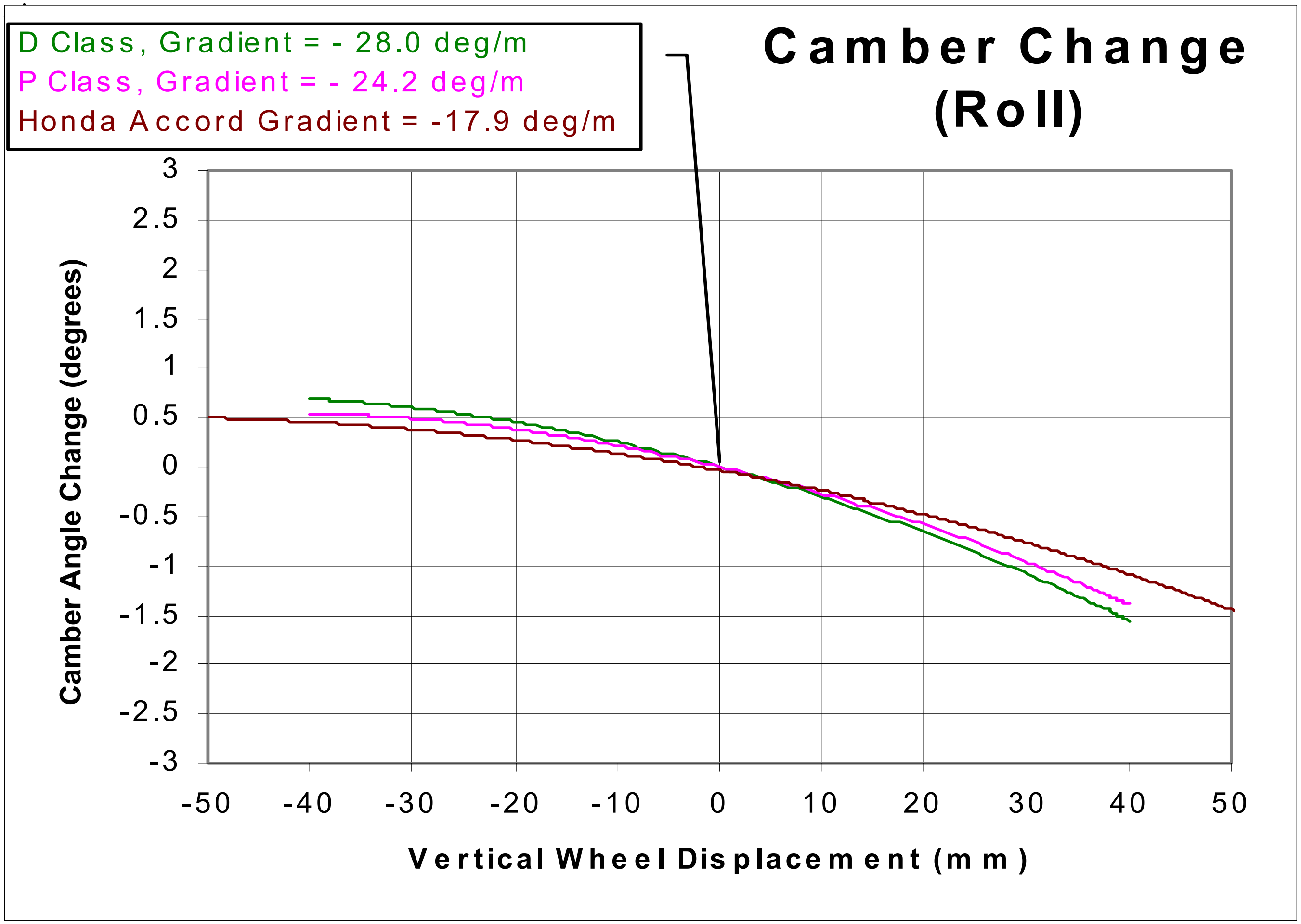
DOUBLE WISHBONE: Performance





Instantaneous gradient taken at wheel displacement zero

DOUBLE WISHBONE: Performance



Instantaneous gradient taken at wheel displacement zero

ULTRALIGHT STEEL AUTO SUSPENSION

PERFORMANCE RESULTS GRAPHS KEY

DOUBLE WISHBONE

Key to Objective Targets Graphs:

Optimum value (ULSAS Target)

= ULSAS Result

Tolerance Bands

Min Performance

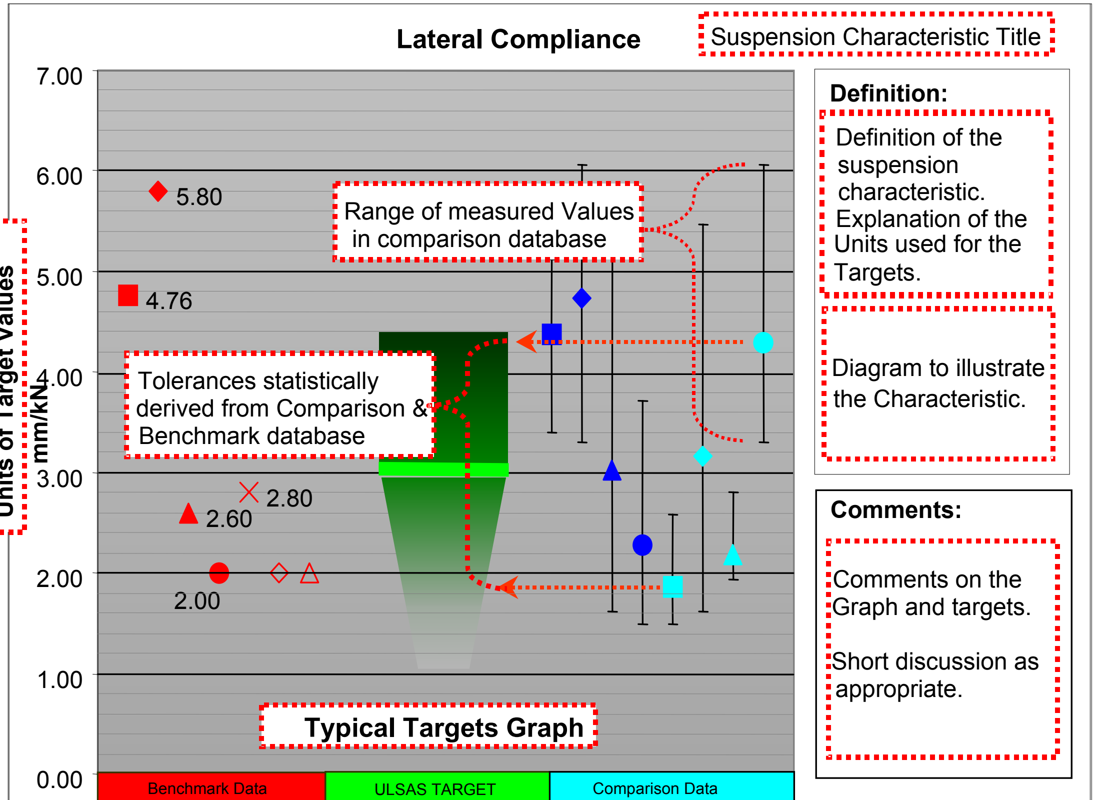
Band showing areas of acceptable Performance. Darker areas show Min Performance levels.

Band showing areas of acceptable Performance. Lighter areas indicate reduced performance levels with no clear minimum.

Low Performance

Diminishing Efficiency

Band showing areas of Performance above the required optimum level. Lighter areas indicate diminishing efficiency, ie: levels of performance that are beyond those required, but at the expense of Mass or Cost.

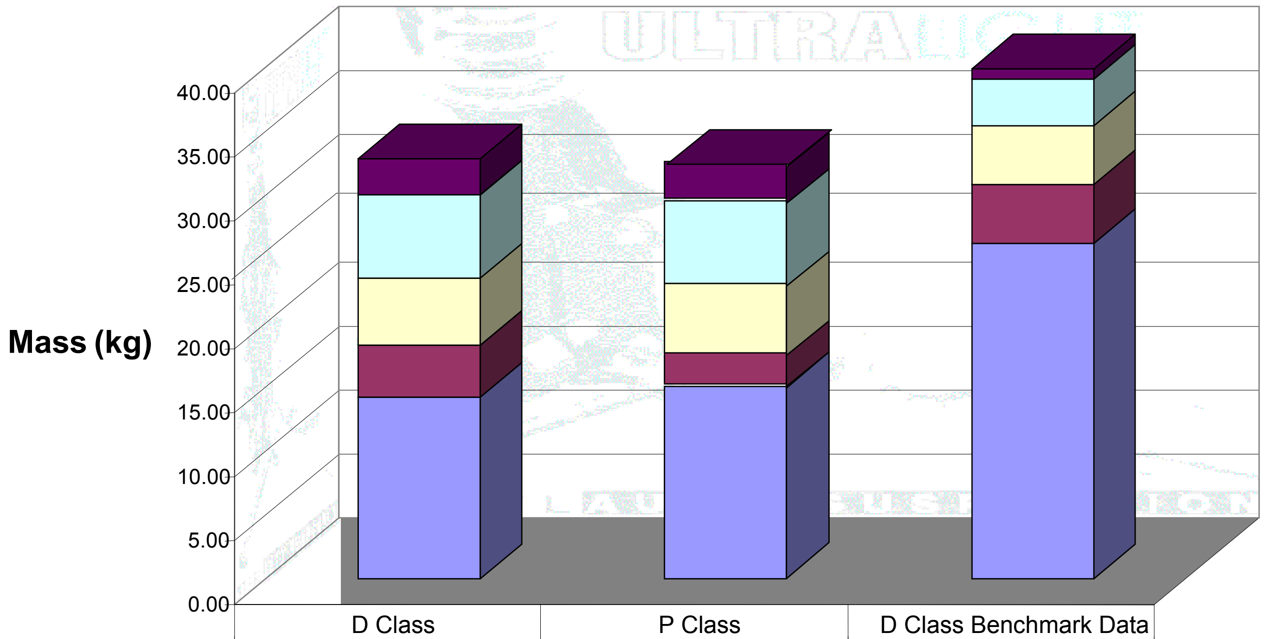


- VW Golf
- Peugeot 306
- Honda Accord
- BMW 528
- Dodge Intrepid
- Ford Taurus
- Chevrolet Lumina
- Audi A6
- ULSAS TARGET B
- ULSAS TARGET C
- ULSAS TARGET D
- ULSAS TARGET PNGV
- B Class Typical
- C Class Typical
- D Class Typical
- E Class Typical
- Double Wishbone Typical
- Multilink Typical
- Struts&Links Typical
- Twistbeam Typical

STEEL AUTO SUSPENSION

DOUBLE WISHBONE: MASS

Comparison



	D Class	P Class	D Class Benchmark Data
BUSHES & FIXINGS	2.83	2.83	0.72
HUBS	6.50	6.50	3.74
DAMPER ASSY	5.30	5.30	4.56
SPRING	4.04	2.45	4.62
STRUCTURE *	14.21	14.21	26.20
TOTAL SYSTEM	32.88	31.29	39.84

Mass Of ULSAS Solutions Vs Benchmark Vehicles

Description	B	C	D	E	P
Benchmark (kg)			39.84		
ULSAS solution (kg)			32.88		31.29
Saving vs Benchmark			17%		

* Structure includes knuckle and links

DOUBLE WISHBONE: MASS

Approach

DOUBLE WISHBONE

- Mass estimations were established for:
  - Components
  - Sub-assemblies / Proprietary Parts
- Mass estimates for Lotus designed parts derived from Mass Property Tables in the C.A.D software or the analysis C.A.E software.
- For Proprietary Parts the results were generated using a combination of Lotus experience and judgement supported by confirmation from suppliers and consortium members.
- For other standard parts Indicative estimates were obtained through Lotus relationships with suppliers.

DOUBLE WISHBONE: MASS

D Class

DOUBLE WISHBONE

PARTS LIST			D Class			D Class Benchmark Data		
ITEM No.	DESCRIPTION	QTY Veh	System (kg)	Sub Assy (kg)	Parts (kg)	System (kg)	Sub Assy (kg)	Parts (kg)
1	ASSEMBLY, DOUBLE WISHBONE	1	32.88			39.84		
2	KNUCKLE ASSEMBLY, RH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
3	KNUCKLE ASSEMBLY, LH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
4	HUB BEARING UNIT	2	**6.50**	**3.250**	3.250	**3.74**		1.870
5	SHEAR PLATE	2	**0.25**	**0.126**	0.126			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
9	TRAILING ARM ASSEMBLY, LH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
10	TRAILING ARM BUSH, REAR	4			0.040			
11	TRAILING ARM BUSH, FRONT	2			0.476			
12	TRAILING ARM, RH	1			1.254			
13	TRAILING ARM, LH	1			1.254			
14	DAMPER	2	**4.20**	**2.100**		**4.56**		2.280
15	SPRING	2	**4.04**	**2.018**	2.018	**4.62**		2.310
16	MOUNT, UPR, SPRING & DAMPER	2	**1.10**	**0.550**				
17	SHORT LATERAL LINK ASSEMBLY	2	**0.31**	**0.153**	0.153	**1.85**		0.925
18	LONG LATERAL LINK ASSEMBLY	2	**1.46**	**0.729**	0.729	**2.33**		1.165
19	LINK BUSH HOUSING	8			0.034			
20	SHORT LINK	2			0.085			
21	LONG LINK	2			0.661			
22	UPPER LINK ASSEMBLY	2	**0.61**	**0.307**	0.307	**2.16**		1.080
23	BALL JOINT	2			0.140			
24	LINK	2			0.134			
25	BUSH HOUSING, UPPER LINK	2			0.033			
26	VARIOUS BUSHES AND JOINTS		**1.63**					
27	ASSORTED FIXINGS		**1.20**			**0.72**		

DOUBLE WISHBONE: MASS

P Class

PARTS LIST			P Class			D Class Benchmark Data		
ITEM No.	DESCRIPTION	QTY Veh	System (kg)	Sub Assy (kg)	Parts (kg)	System (kg)	Sub Assy (kg)	Parts (kg)
1	ASSEMBLY, DOUBLE WISHBONE	1	**31.29**			**39.84**		
2	KNUCKLE ASSEMBLY, RH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
3	KNUCKLE ASSEMBLY, LH	1	**3.98**	**3.980**	3.980	**7.40**		7.400
4	HUB BEARING UNIT	2	**6.50**	**3.250**	3.250	**3.74**		1.870
5	SHEAR PLATE	2	**0.25**	**0.126**	0.126			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
9	TRAILING ARM ASSEMBLY, LH	1	**1.81**	**1.810**	1.810	**2.53**		2.530
10	TRAILING ARM BUSH, REAR	4			0.040			
11	TRAILING ARM BUSH, FRONT	2			0.476			
12	TRAILING ARM, RH	1			1.254			
13	TRAILING ARM, LH	1			1.254			
14	DAMPER	2	**4.20**	**2.100**		**4.56**		2.280
15	SPRING	2	**2.45**	**1.226**	1.226	**4.62**		2.310
16	MOUNT, UPR, SPRING & DAMPER	2	**1.10**	**0.550**				
17	SHORT LATERAL LINK ASSEMBLY	2	**0.31**	**0.153**	0.153	**1.85**		0.925
18	LONG LATERAL LINK ASSEMBLY	2	**1.46**	**0.729**	0.729	**2.33**		1.165
19	LINK BUSH HOUSING	8			0.034			
20	SHORT LINK	2			0.085			
21	LONG LINK	2			0.661			
22	UPPER LINK ASSEMBLY	2	**0.61**	**0.307**	0.307	**2.16**		1.080
23	BALL JOINT	2			0.140			
24	LINK	2			0.134			
25	BUSH HOUSING, UPPER LINK	2			0.033			
26	VARIOUS BUSHES AND JOINTS		**1.63**					
27	ASSORTED FIXINGS		**1.20**			**0.72**		

DOUBLE WISHBONE: MATERIAL

D Class

DOUBLE WISHBONE

PARTS LIST				MATERIAL	
ITEM No.	DESCRIPTION	QTY Veh	REMARKS	Gauge (mm)	Grade (MPa)
1	ASSEMBLY, DOUBLE WISHBONE	1	FULL SUSPENSION ASSEMBLY		
2	KNUCKLE ASSEMBLY, RH	1	FORGED PART	na	600
3	KNUCKLE ASSEMBLY, LH	1	FORGED PART	na	600
4	HUB BEARING UNIT	2	GEN 3 WITH ACTIVE ABS SENSOR		
5	SHEAR PLATE	2	BLANK & PIERCE	2	500
6	DISC, BRAKE	2	SOLID, CAST IRON		
7	CALIPER, BRAKE	2	INTEGRATED HANDBRAKE MECHANISM		
8	TRAILING ARM ASSEMBLY, RH	1	FABRICATION (ITEMS:- 10,11,12)		
9	TRAILING ARM ASSEMBLY, LH	1	FABRICATION (ITEMS:- 10,11,13)		
10	TRAILING ARM BUSH, REAR	4	TUBE	3	500
11	TRAILING ARM BUSH, FRONT	2	TUBE	3	500
12	TRAILING ARM, RH	1	PRESSING	3	500
13	TRAILING ARM, LH	1	PRESSING	3	500
14	DAMPER ASSEMBLY	2	INCL SPRING SEAT & BUMP RUBBER	See note	
15	SPRING	2	SHEAR STRESS 1300MPa	Ø 10.91	1300
16	MOUNT, UPR, SPRING & DAMPER	2	2 BOLT FIXING TO BIW.		
17	SHORT LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,20)		
18	LONG LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,21)		
19	LINK BUSH HOUSING	8	TUBE	3	250
20	SHORT LINK	2	TUBE	Ø 14 x 1.5	250
21	LONG LINK	2	TUBE	Ø 25 x 3	250
22	UPPER LINK ASSEMBLY	2	WELD AND PRESS FIT (ITEMS:- 23,24,25)		
23	BALL JOINT	2			
24	LINK	2	TUBE	Ø 13 x 1.5	250
25	BUSH HOUSING, UPPER LINK	2	TUBE	1.5	250
26	VARIOUS BUSHES AND JOINTS		RUBBER BUSHES & SPHERICAL JOINTS		
27	ASSORTED FIXINGS		NUTS, BOLTS & WASHERS ETC		

Note : Damper Assembly Consists of 4 Main Components

Damper Body Assumes 350 Mpa Material

Damper Rod Assumes Dia 13mm x 3mm tube

Spring Pan Assumes 350 Mpa Material

Bump Rubber Assumes Polyurethane Material

DOUBLE WISHBONE: MATERIAL

P Class

PARTS LIST				MATERIAL	
ITEM No.	DESCRIPTION	QTY Veh	REMARKS	Gauge (mm)	Grade (MPa)
1	ASSEMBLY, DOUBLE WISHBONE	1	FULL SUSPENSION ASSEMBLY		
2	KNUCKLE ASSEMBLY, RH	1	FORGED PART	na	600
3	KNUCKLE ASSEMBLY, LH	1	FORGED PART	na	600
4	HUB BEARING UNIT	2	GEN 3 WITH ACTIVE ABS SENSOR		
5	SHEAR PLATE	2	BLANK & PIERCE	2	500
6	DISC, BRAKE	2	SOLID, CAST IRON		
7	CALIPER, BRAKE	2	INTEGRATED HANDBRAKE MECHANISM		
8	TRAILING ARM ASSEMBLY, RH	1	FABRICATION (ITEMS:- 10,11,12)		
9	TRAILING ARM ASSEMBLY, LH	1	FABRICATION (ITEMS:- 10,11,13)		
10	TRAILING ARM BUSH, REAR	4	TUBE	3	500
11	TRAILING ARM BUSH, FRONT	2	TUBE	3	500
12	TRAILING ARM, RH	1	PRESSING	3	500
13	TRAILING ARM, LH	1	PRESSING	3	500
14	DAMPER ASSEMBLY	2	INCL SPRING SEAT & BUMP RUBBER	See note	
15	SPRING	2	SHEAR STRESS 1300MPa	Ø 9.08	1300
16	MOUNT, UPR, SPRING & DAMPER	2	2 BOLT FIXING TO BIW.		
17	SHORT LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,20)		
18	LONG LATERAL LINK ASSEMBLY	2	FABRICATION (ITEMS:- 19,21)		
19	LINK BUSH HOUSING	8	TUBE	3	250
20	SHORT LINK	2	TUBE	Ø 14 x 1.5	250
21	LONG LINK	2	TUBE	Ø 25 x 3	250
22	UPPER LINK ASSEMBLY	2	WELD AND PRESS FIT (ITEMS:- 23,24,25)		
23	BALL JOINT	2			
24	LINK	2	TUBE	Ø 13 x 1.5	250
25	BUSH HOUSING, UPPER LINK	2	TUBE	1.5	250
26	VARIOUS BUSHES AND JOINTS		RUBBER BUSHES & SPHERICAL JOINTS		
27	ASSORTED FIXINGS		NUTS, BOLTS & WASHERS ETC		

Note : Damper Assembly Consists of 4 Main Components

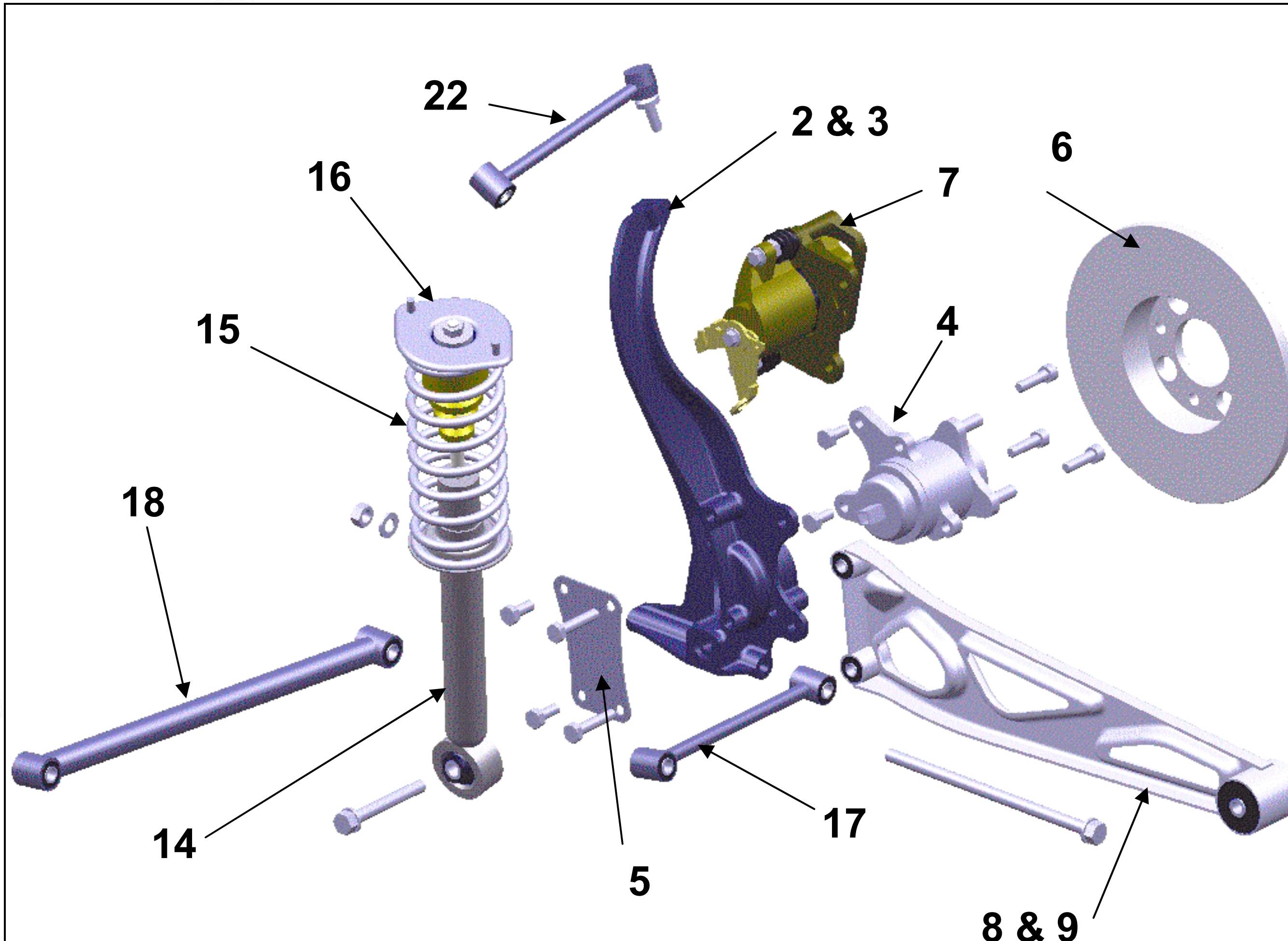
Damper Body Assumes 350 Mpa Material

Damper Rod Assumes Dia 13mm x 3mm tube

Spring Pan Assumes 350 Mpa Material

Bump Rubber Assumes Polyurethane Material

DOUBLE WISHBONE: EXPLODED VIEW

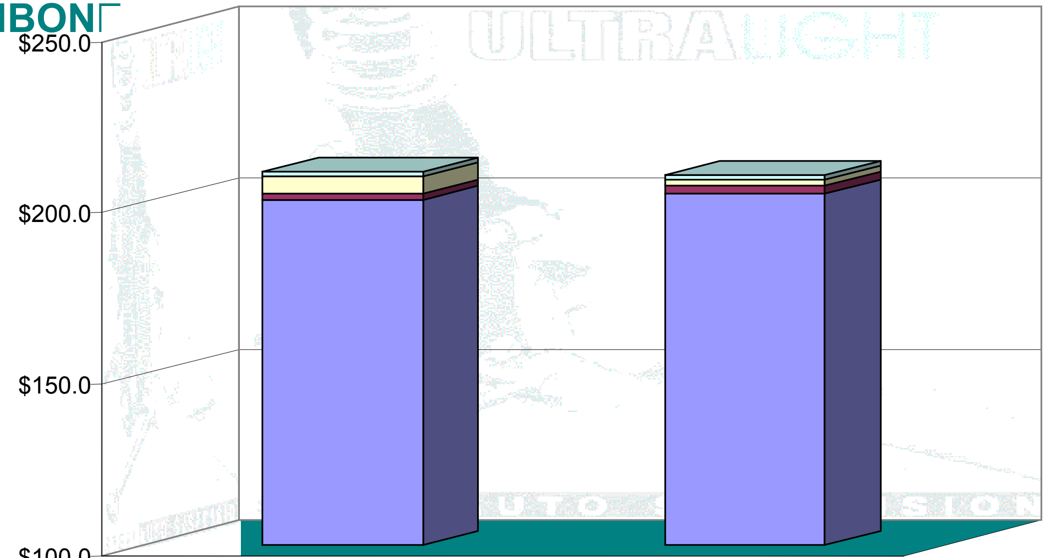


1 = Full Suspension Assembly

DOUBLE WISHBONE: COST

DOUBLE WISHBONE

COST BREAKDOWN DOUBLE WISHBONE



	BENCHMARK (D Class)	ULSAS D Class
VEHICLE FITTING COST	$1.3	$1.3
SYSTEM ASSEMBLY COST	$4.8	$2.1
TOOLING COST	$2.0	$2.2
PIECE COST	$200.7	$202.5
TOTAL COST	**$208.9**	**$208.1**

DOUBLE WISHBONE: COST

(US$)	Double Wishbone	
	Benchmark D Class	ULSAS D Class
COMPONENT COST	**$200.7**	**$202.5**
TOTAL TOOLING COST ($,000)	**$4,192**	**$4,340**
5 YEAR Volume (Assumptions)	2,075,000	2,000,000
TOOLING COST	$2.0	$2.2
TOTAL SYSTEM COST	$202.7	$204.7
SYSTEM ASSY		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Assembly Mins	6.59	2.87
SYSTEM ASSEMBLY COST	$4.83	$2.10
VEHICLE FITTING		
Labour Rate (US$/min on $44/Hr)	$0.73	$0.73
Fitting Mins	1.83	1.76
VEHICLE FITTING COST	$1.34	$1.29

Total Cost ($)	**$208.9**	**$208.1**
Cost Saving($)		$0.8
Cost Saving %		**0%**

Reduction in assembly time is due mainly to greater levels of parts integration in the ULSAS design.

DOUBLE WISHBONE: COST

Bill of Materials

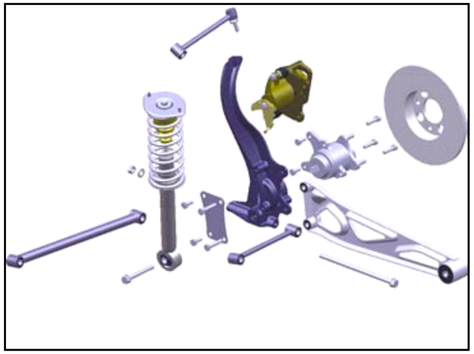
DOUBLE WISHBONE

N.B. All Costs in US $,   Tooling in US$(,000)

PARTS LIST			D Class			Benchmark D Class		
ITEM No.	DESCRIPTION	QTY Veh	PART COST	SYSTEM COST	TOOLING COST	PART COST	SYSTEM COST	TOOLING COST
1	ASSEMBLY, DOUBLE WISHBONE	1		202.50	4340.00		200.70	4192.00
2	KNUCKLE ASSEMBLY, RH	1	$24.0	$24.0	$600	$17.3	$17.3	$578
3	KNUCKLE ASSEMBLY, LH	1	$24.0	$24.0	$600	$17.3	$17.3	
4	HUB BEARING UNIT	2	$19.0	$38.0	$0	$8.3	$16.6	$149
5	SHEAR PLATE	2	$1.1	$1.1	$30			
6	DISC, BRAKE	2						
7	CALIPER, BRAKE	2						
8	TRAILING ARM ASSEMBLY, RH	1	$12.0	$12.0	$1,100	$17.3	$34.6	$990
9	TRAILING ARM ASSEMBLY, LH	1	$12.0	$12.0	$1,100			
10	TRAILING ARM BUSH, REAR	4						
11	TRAILING ARM BUSH, FRONT	2						
12	TRAILING ARM, RH	1						
13	TRAILING ARM, LH	1						
14	DAMPER	2	$16.0	$32.0	$360	$23.1	$46.2	$495
15	SPRING	2	$5.5	$11.0	$0			
16	MOUNT, UPR, SPRING & DAMPER	2	$1.6	$3.2	$250			
17	SHORT LATERAL LINK ASSEMBLY	2	$3.6	$7.2	$100	$6.6	$13.2	$660
18	LONG LATERAL LINK ASSEMBLY	2	$4.5	$9.0	$100	$9.6	$19.2	$660
19	LINK BUSH HOUSING	8						
20	SHORT LINK	2						
21	LONG LINK	2						
22	UPPER LINK ASSEMBLY	2	$7.0	$14.0	$100	$8.4	$16.8	$660
23	BALL JOINT	2						
24	LINK	2						
25	BUSH HOUSING, UPPER LINK	2						
26	VARIOUS BUSHES AND JOINTS		$13.0	$13.0			$17.8	
27	ASSORTED FIXINGS		$2.0	$2.0			$1.7	

DOUBLE WISHBONE: TIMING

Sub-Assembly

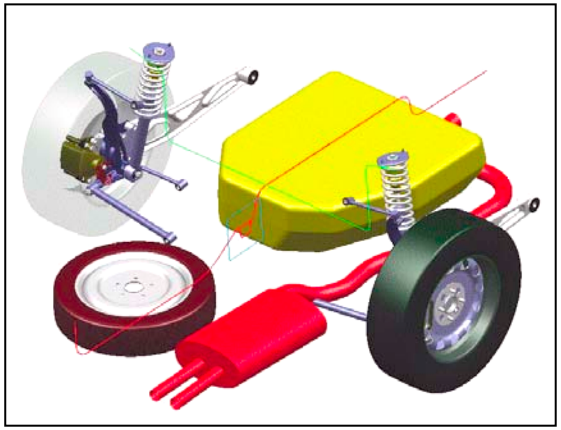


BREAKDOWN OF TIMING FOR SUB-ASSEMBLY OF DOUBLE WISHBONE SUSPENSION SYSTEM

SUB-ASSEMBLY Operation	number	Code	First Time (man minutes)	Subsequent (man minutes)	Total Time (man minutes)
FIT HUB	2	FIX1H	0.05	0.05	0.1
FIX HUB	6	TFPTN	0.11	0.35	0.46
FIT BRAKE DISK	2	FIX1H	0.05	0.05	0.1
LOAD ASSY. TO FIXTURE	2	FIX2H	0.09	0.09	0.18
LOAD BRAKE CALIPER	2	FIX1H	0.05	0.05	0.1
FIX BRAKE CALIPER	4	TFPTN	0.11	0.21	0.32
LOAD TRAILING ARM	2	FIX1H	0.05	0.05	0.1
LOAD CLOSER PLATE	2	FIXFN	0.04	0.04	0.08
FIX CLOSER PLATE	8	TFPTN	0.11	0.49	0.6
LOAD FR LATERAL LINK	2	FIX1H	0.05	0.05	0.1
LOAD RR LATERAL LINK	2	FIX1H	0.05	0.05	0.1
FIT BOLT	2	FITFN	0.07	0.04	0.11
FIT WASHER	2	FWASH	0.04	0.02	0.06
FIT NUT	2	TFPTN	0.11	0.07	0.18
LOAD DAMPER ASSY.	2	FIX1H	0.05	0.05	0.1
FIX BOLT	2	TFPTN	0.11	0.07	0.18
				TOTAL	**2.87**

DOUBLE WISHBONE: TIMING

Final Vehicle Assembly



BREAKDOWN OF TIMING FOR FINAL ASSEMBLY OF DOUBLE WISHBONE SUSPENSION TO THE VEHICLE

FINAL ASSEMBLY Operation	number	Code	First Time (man minutes)	Subsequent (man minutes)	Total Time (man minutes)
FIT UPPER LINK	2	FIX1H	0.05	0.05	0.1
FIT UPPER LINK BOLT	2	FITFN	0.07	0.04	0.11
FIX UPPER LINK NUT	2	TFPTN	0.11	0.07	0.18
FIT LONGITUDINAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LONGITUDINAL NUT	2	TFPTN	0.11	0.07	0.18
FIT LATERAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LATERAL NUT	2	TFPTN	0.11	0.07	0.18
FIT LATERAL BOLT	2	FITFN	0.07	0.04	0.11
FIX LATERAL NUT	2	TFPTN	0.11	0.07	0.18
FIX UPPER LINK	2	TFPTN	0.11	0.07	0.18
FIX DAMPER	4	TFPTN	0.11	0.21	0.32
				TOTAL	1.76

DOUBLE WISHBONE: COST

Benchmarking Phase

Costing Exercise Deliverables for both the Benchmarking Phase and the Design Phase include:

- Costed Bill of Materials
- Tooling cost estimates for each of the major components and sub-assemblies.

DOUBLE WISHBONE: COST

Benchmarking Phase

- Results were generated via a combination of Lotus experience supported by cost confirmation from suppliers and consortium members.
- Indicative quotations were obtained through Lotus relationships with suppliers.
- Potential for negotiated preferential supply rates is excluded.
- Variances between ULSAS Benchmark estimates and OEM costs exist - due to the following:
  - » Process variations
  - » Special supplier / manufacturer relationships
  - » Availability of existing tooling and facilities to the manufacturer.

DOUBLE WISHBONE: COST

Benchmarking Assumptions

- 1998 economics.
- Costs are shown in US Dollars (US$)
- Ex-works prices for sub-assemblies.
- Tooling recovery over 5 years full production.
- Supplier base cost, not OEM based.
- No capital equipment cost included.
- Component costs are shown fully finished (including coatings etc. where applicable).
- Estimated production volumes:

Manufacturer	Model	Suspension System	Volume	Assumptions
Audi	A6	Twistbeam	110,000	(2)
Ford	Taurus	Strut & Links	380,000	(1)
Honda	Accord	Double Wishbone	415,000	(1)
BMW	5 Series	Multi-link	215,000	(2)

(1)= 1997 North America **(2) = 1997 European**

DOUBLE WISHBONE: COST

Design Phase

Identical Assumptions and similar rationale to the Benchmarking Phase were applied to ensure compatibility.

DOUBLE WISHBONE

- 1998 Economics - for consistency with Benchmark data.
- Lotus Manufacturing Engineering costing experience and judgement used throughout for consistency.
- Benchmarking against known costs for components.
- Close collaboration with consortium members.
- Elegance of design reduces cost.
- Optimising tool utilisation reduces cost.
- Costs developed simultaneously with the designs.
- Volume assumptions :

SUSPENSION TYPE	VOLUME (per annum)
Twistbeam	400,000
Strut & Links	400,000
Double Wishbone	400,000
Multi-link	200,000
Lotus Unique	400,000