ULSAB Executive Summary

An UltraLight Steel Auto Body (ULSAB) structure has been assembled, weighed and tested validating results from the concept phase of a global steel industry study and satisfying the project goals. ULSAB has proven to be lightweight, structurally sound, safe, executable and affordable.

The ULSAB structure weighs merely 203 kg, 25 percent less than the average benchmarked in the concept phase of the study. Physical tests of the structure reveal similar remarkable results: torsion and bending tests showed improvements over benchmark of 80 percent and 52 percent, respectively, and 1st body structure mode indicates a 58 percent improvement. Analyses also show ULSAB satisfies mandated crash requirements, even at speeds exceeding the requirements. In addition to reduced weight and superior performance, ULSAB costs no more to build than typical auto body structures in its class and can even yield potential cost savings, according to economic analysis.

The ULSAB structure consists of 94 major parts necessary for its structural integrity, plus brackets and additional reinforcements normally included in this type of auto body structure. It does not include doors, hood or decklids, which are the subject of a separate, independent study.

Creation and testing of ULSAB body structures culminated this aggressive $22 million project to demonstrate a lightweight steel auto body structure that meets a wide range of safety and performance criteria. The ULSAB project was sponsored by a consortium of 35 steel companies representing 18 countries around the world.

The goal of the consortium was to meet the challenges issued by their automotive industry customers: reduce the weight of steel auto body structures at no additional cost, while maintaining or improving performance. The most prominent sheet steel producers from around the world joined together to design and validate an UltraLight Steel Auto Body.

The ULSAB consortium contracted Porsche Engineering Services, Inc. (PES) to provide engineering and manufacturing management for the ULSAB project and also worked with them to define the project goals. They took a two-stage approach, encompassing a concept phase and a validation phase.

The consortium is releasing patentable features of this project along with other project results freely to its customers and to the public.

Design

Benchmarking

At the beginning of the design process, PES benchmarked mid-sized four door sedans to determine current performance standards against which to measure ULSAB. PES also established package constraints through this benchmarking process. To determine an "average base model," 32 different cars representing varying worldwide customer requirements were selected for package benchmarking.

For structural benchmarking (static torsion, static bending, 1st body structure mode), PES used a cross section of nine cars that represented current performance standards. Results of that benchmarking study produced the following performance specifications:

Benchmark performance

static torsional rigidity	11,531 Nm/deg
static bending rigidity	11,902 N/mm
1st body structure mode	38 Hz
mass	271 kg

This information was then used to predict a future reference structure with which ULSAB must ultimately compare. Recognizing continuing improvements in body design and engineering, the future reference structure represents improved performance in all areas. Assumptions for that future reference structure are as follows:

Future reference structure performance

Static torsional rigidity	13,000 Nm/deg
Static bending rigidity	12,200 N/mm
1st body structure mode	40 Hz
mass	250 kg

Philosophy

Design considerations for ULSAB were, in large part, governed by mass reduction and improved performance. ULSAB's design team started with a "clean sheet of paper" and used an iterative holistic approach to design, whereby the body structure is treated as an integrated system rather than as an assembly of individual components. The holistic approach emphasizes total structure analysis. Sophisticated computer models enable design engineers to view the body structure as an integrated whole. This perspective enables them to evaluate how changes in one area affect other areas and where future optimization opportunities exist. Through each iterative step, re-analysis confirms the effectiveness of the latest optimizations. This approach promotes weight savings and improved structural integrity by enabling engineers to reduce weight in certain areas while strengthening strategic locations. The net effect is the creation of a more efficient structure.

Computer models were also used to analyze all structural aspects and to simulate specific crash events, demonstrating acceptable performance. Sophisticated architecture and refined joint designs ensure continuous load flow, which improves stiffness and strength in the body structure.

Package

ULSAB did not save mass through downsizing. Its package design includes a 3-liter V6 engine, transverse front wheel drive, rack and pinion steering, McPherson front suspension, twist beam rear suspension, generous occupant space, exhaust system routing and a 65 liter fuel tank. Its wheelbase is 2700 mm; vehicle width is 1819 mm; and vehicle length is 4714 mm.

Styling

Exterior styling of the ULSAB was necessary to create surfaces for design. Styling also provided the major feature lines for the doors, decklid, hood, fender and front and rear bumpers, which were used in development of mating structural parts. Styling also gave ULSAB a look that is easily recognized while preserving the opportunity to conduct further design studies – for doors or other closures – in the future.

Materials selection and processes

Advanced materials and technologies were employed to meet the project goals. The design relies on high strength steels, steel sandwich materials, tailored blanking, hydroforming and assembly laser welding for reduced weight and structural efficiency.

Materials and Processes

The materials for the body structure were chosen to meet mass, performance and safety goals. They include some grades and thicknesses of steel currently available but not commonly used in auto bodies. Steel is the most recycled material in the world, and all steel chosen for the ULSAB structure is recyclable.

ULSAB uses high strength steel and ultra high strength steel for more than 90 percent of the body structure to improve structural performance and save mass. And nearly half of ULSAB's mass consists of tailored blanked parts, which enable the design engineer to locate various steels within the part precisely where their attributes are most needed, thereby removing mass that does not contribute to performance.

ULSAB also features a hydroformed side roof rail, which provides an essential load path for structural performance and crash energy management. In addition to tubular hydroforming, ULSAB uses sheet hydroforming for the roof panel. The work hardening effect produces improved dent resistance in the formed part, especially in the center of the panel.

Steel sandwich material was chosen for mass reduction in the spare tire tub and dash panel.

Additionally, laser welding was used in ULSAB assembly for high static and dynamic strength of joints, for areas where access was available on only one side and for good aesthetic appearance at joint areas.

These advanced materials and processes enabled the design engineers to consolidate functions in fewer parts, resulting in mass savings and improved performance.

Manufacturing

Early involvement

Manufacturability of parts was crucial to the project's success and was contemplated throughout the design phase. Early in the design process the design engineers worked with component fabricators and steel manufacturers to optimize the design. The steel manufacturers were called upon to provide high strength and ultra high strength grades of steel for use in tailored blanks, hydroformed tubing and steel sandwich material. The project partners also used forming simulations early in the project to predict manufacturability.

Tooling

To prove manufacturing feasibility of ULSAB the consortium specified production intent standards for ULSAB parts, requiring that all parts be manufactured from tools with no manual forming. All stamping tools in this program are "soft" tools made of material such as kirksite. Due to pressure requirements, hydroforming was accomplished using hard tools. In all cases, part fabrication tolerances and quality standards were maintained the same as intended for full volume production.

Analysis

To help ensure that the part designs were feasible, the project partners performed forming simulation analysis on the most complex parts. Forming simulation was performed using finite element methods to show locations of strains and material thinning. The project partners then used this information to recommend product design and tooling adjustments accordingly.

Part validation

Upon completion of tooling, the component fabricators manufactured the parts and evaluated them using circle grid strain analysis to confirm that they were formed to full volume manufacturing standards. Confirmation was also established through measurement of key part dimensions and the use of check fixtures. Complete information to support manufacturing feasibility was documented and includes material characteristics, tooling parameters and press conditions.

Assembly

ULSAB assembly sequence is quite conventional, deviating from convention only in its two-stage body side framing. The assembly sequence includes floor complete assembly, front end assembly, body side inner assembly, underbody complete assembly, framing and final assembly. The assembly sequence, processes and tolerances were established by PES. All tooling holes and locators that would be used for production were used during the build. Porsche in Germany assembled the demonstration hardware using a flexible, modular assembly fixture system.

ULSAB employs about one-third fewer spot welds and significantly more laser welding than a conventional body structure, resulting in improved structural integrity, as well as some cost savings.

Structural performance

Physical tests show ULSAB to exceed all concept phase averages.

Performance results comparison

	ULSAB structure	Benchmark structure average	Future reference structure
Performance			
Torsion (Nm/deg)	20,800	11,531	13,000
bending (N/mm)	18,100	11,902	12,200
1st body structure mode (Hz)	60	38	40
Mass (in kg)	203*	271	250

* natural range of variation ±1 percent

Crash simulations to help predict safety indicate excellent crash behavior of the ULSAB structure in the following crash events: 35 mph frontal NCAP; 55 km/h 50 percent offset AMS frontal impact; 35 mph rear moving barrier; European side impact and roof crush. The 35 mph frontal NCAP and 35 mph rear moving barrier simulations were run at speeds that exceed mandated safety requirements by 17 percent, and the AMS frontal is widely considered one of the most severe offset crashes performed today.

Economic Analysis

Although lightweighting without sacrificing performance was ULSAB's priority, affordability was also important. Early in ULSAB's concept phase the consortium commissioned an economic analysis to establish a reference by which to compare ULSAB. IBIS Associates estimated the cost to manufacture a current, typical body structure in the same class as ULSAB at $1116 each.

In the validation phase, the cost issue was revisited more thoroughly. A Porsche-led team of analysts developed a detailed cost model that includes all aspects of fabrication and assembly. The cost model can be used to analyze ULSAB costs in comparison with other options and also to generate costs associated with alternative designs.

This model comprehends United States manufacturing costs, including investments for both plant and tooling, piece fabrication costs and assembly costs, through to the end of the body shop. The analysts used these details to generate a part-specific cost model for ULSAB. They also created assumptions about a future typical four-door sedan (Year 2000) reference structure with which to compare ULSAB. Basic economic assumptions were identical for both ULSAB and the reference structure; however, inputs about specific parts and assembly steps are not directly comparable because the Year 2000 structure represents an average of typical vehicle structures in the same class as ULSAB. For the Year 2000 structure, the study identified part groupings – instead of individual parts as with ULSAB – and assumed significantly improved fabrication and assembly techniques as compared to the concept stage benchmark.

The cost model with these inputs showed the ULSAB body structure to cost $947 each to manufacture and the Year 2000 structure to cost $979 each, demonstrating that sophisticated design of a steel body structure can achieve lightweight at no cost penalty and with potential cost savings.

Sharing knowledge

The ULSAB project employed many techniques and processes that were unique and deemed patentable by international attorneys. The consortium chose to make all patentable features along with other project results freely available to its customers and to the public. All intellectual property generated by ULSAB has been placed in the public domain.

Conclusion

The steel industry has demonstrated the viability of a lightweight, structurally superior steel auto body structure that is also affordable. ULSAB weighs less and performs better than benchmarked averages, while also providing potential cost savings.

ULSAB Design

The first objective of the UltraLight Steel Auto Body (ULSAB) consortium was to design a lightweight steel body structure that would meet increased functional and structural performance targets while remaining affordable. The consortium also specified that, while the design should be leading edge, it must also be feasible using near-reach manufacturing processes.

Benchmarking

Porsche Engineering Services, Inc. (PES) benchmarked mid-sized four door sedans to determine current performance against which to measure ULSAB. PES also established package constraints through this benchmarking process. To determine an "average base model," 32 different cars that represent varying worldwide customer requirements were selected for package benchmarking. Benchmarking considered curb weight; wheelbase; overall length and width; leg, head and shoulder room; passenger compartment; and cargo volume. Benchmarking established the following package specifications:

Package benchmark specifications

body type	4-door sedan	**headroom front/rear**	960/940 mm
wheelbase	2700 mm	**leg room front/rear**	1060/890 mm
overall length	4800 mm	**shoulder room f/r**	1420/1400 mm
overall width	1800 mm	**cargo volume**	425 liters
curb weight	1350 kg	**engine type**	V6
passenger	5	**drive**	front

For structural benchmarking (static torsion, static bending, 1st body structure mode), PES used a cross section of nine cars that represented current performance standards. These vehicles include the

- Acura Legend
- BMW 5-series

- Chevrolet Lumina
- Ford Taurus
- Honda Accord
- Lexus LS 400
- Mazda 929
- Mercedes 190 E
- Toyota Cressida

To make a direct correlation in performance among the above nine vehicles, PES adjusted the structural performance linearly to the ULSAB target wheelbase of 2700 mm. PES employed the following formula for this adjustment:

$$C_{adjusted} = C_{actual} \frac{\text{Wheelbase}_{\text{reference vehicle}}}{\text{Wheelbase}_{\text{ULSAB}}}$$

where C adjusted = adjusted stiffness of reference vehicle

and C actual = actual stiffness of reference vehicle

These vehicles were also normalized for mass by comparing the interior body volumes with the projected area (length multiplied by width). Volume of these vehicles was determined using SAE Standard 1100a, which states that the usable volume in the front (V_1) and the usable passenger compartment volume (V_2) and the usable luggage volume (V_3) add up to the entire usable volume (V_{total}) of the vehicle:

$$V_1 + V_2 + V_3 = V_{total}$$

This benchmarking exercise generated the following performance averages:

Benchmark performance

static torsional rigidity	11,531 Nm/deg
static bending rigidity	11,902 N/mm
1st body structure mode	38 Hz
mass	271 kg

This information was then used to predict a future reference vehicle with improved performance with which ULSAB must ultimately compare. Assumptions for that future reference vehicle were as follows:

Future reference structure performance

static torsional rigidity	13,000 Nm/deg
static bending rigidity	12,200 N/mm
1^{st} body structure mode	40 Hz
mass	250 kg

Design philosophy and architecture

PES determined to employ an holistic philosophy toward design early in the design process. This holistic approach treats the body structure as an integrated system rather than an assembly of individual components, emphasizing total body analysis. Through each iterative step, sophisticated computer re-analysis confirms the effectiveness of the latest optimizations. The holistic approach also allows evaluation of how other areas are affected by these changes and where future optimization opportunities exist. This approach promotes weight savings and improved structural integrity by enabling engineers to reduce weight in certain areas while strengthening strategic locations. The net effect is the creation of a more efficient structure.

PES investigated various concepts to develop the optimum ULSAB body structure. Some of these included full frame, space frame, unibody and hybrid solutions. Criteria for the structures under consideration were significant weight savings potential, opportunity to achieve performance targets and assembly possibilities in future full volume production body shops.

Early in the project PES engineers eliminated the full frame concept because it offered no significant mass saving opportunities. They also doubted that the full frame would meet ULSAB's structural performance criteria and were concerned about high investment costs for assembly. Although a spaceframe was considered, it was ultimately eliminated because it is not considered as mass efficient as other approaches. The PES team ultimately narrowed its investigation to two structures—a unibody and a hydroform-intensive body structure—finally settling on creating a unibody or monocoque vehicle with key hydroformed parts.

Packaging

The first step in packaging was to define the vehicle concept type, exterior and interior dimensions and main components. With these package definitions, package drawings were created and structural hard points defined. ULSAB did not save mass through downsizing: its wheelbase is 2700 mm; vehicle width is 1819 mm; and vehicle length is 4714 mm.

Package specifications for ULSAB are:

ULSAB package

body type	4-door sedan	**headroom front/rear**	994/932 mm
wheelbase	2700 mm	**leg room front/rear**	1043/894 mm
overall length	4714 mm	**shoulder room f/r**	1512/1522 mm
overall width	1819 mm	**cargo volume**	490 liters
curb weight	1350 kg	**engine type**	3 liter V6
passenger	5	**drive**	front
radiator size	0.252 m^2	**exhaust system**	single routing
battery (in mm)	280 X 170 X 170	**suspension front**	McPherson
suspension rear	twist beam	**tire size (f & r)**	195/60R15
spare tire	space saver	**fuel tank volume**	65 liters
steering	rack & pinion		

The ULSAB package drawings comprehend all essential parts of the structure interior. Criteria for interior design included visibility, obscuration by the pillars, head clearance and seat belt anchors. In the engine compartment, the engine, gearbox, exhaust system, radiator and battery were used to define space for the structural members of the front body structure.

Styling

The ULSAB project also comprehended styling issues. Exterior styling of ULSAB was used to create surfaces for design. Styling also gave it a look that is easily recognized and afforded the opportunity to conduct closure design studies, the results of which will be made available in the future.

Demonstrating exterior styling posed certain challenges. The styling had to follow precisely the engineering design of ULSAB. And, while not attempting to provide leading-edge styling, the results had to illustrate the highest quality surfaces typical of steel-skinned vehicles, which global audiences have come to expect.

ULSAB styling was entirely computer-aided using ALIAS Studio Paint Software for the creation of two-dimensional sketches and Pro-Designer for renderings and three-dimensional modeling. CATIA was used for the final surfacing on the 'A' class surfaces. In the studio, the CATIA package data was imported into a three-dimensional concept modeling software called CDRS, and a side view outline drawing was developed for sketching purposes.

Material selection

The selection of appropriate materials was based on considerations of mass, performance, and crash requirements. In its effort to optimize the best attributes of steel in this project, PES engineers specified unusually large percentages of high and ultra high strength steels, tailored blanks and steel sandwich material. The materials for the body were chosen to meet mass and performance targets and include some grades and thicknesses of steel currently available but not commonly used in auto bodies.

ULSAB uses high strength steel and ultra high strength steel for more than 90 percent of the body structure to improve structural performance and save mass.

Nearly half of ULSAB's mass consists of tailored blanked parts, which enable the design engineer to locate various steels within the part precisely where their attributes are most needed, thereby removing mass that does not contribute to performance.

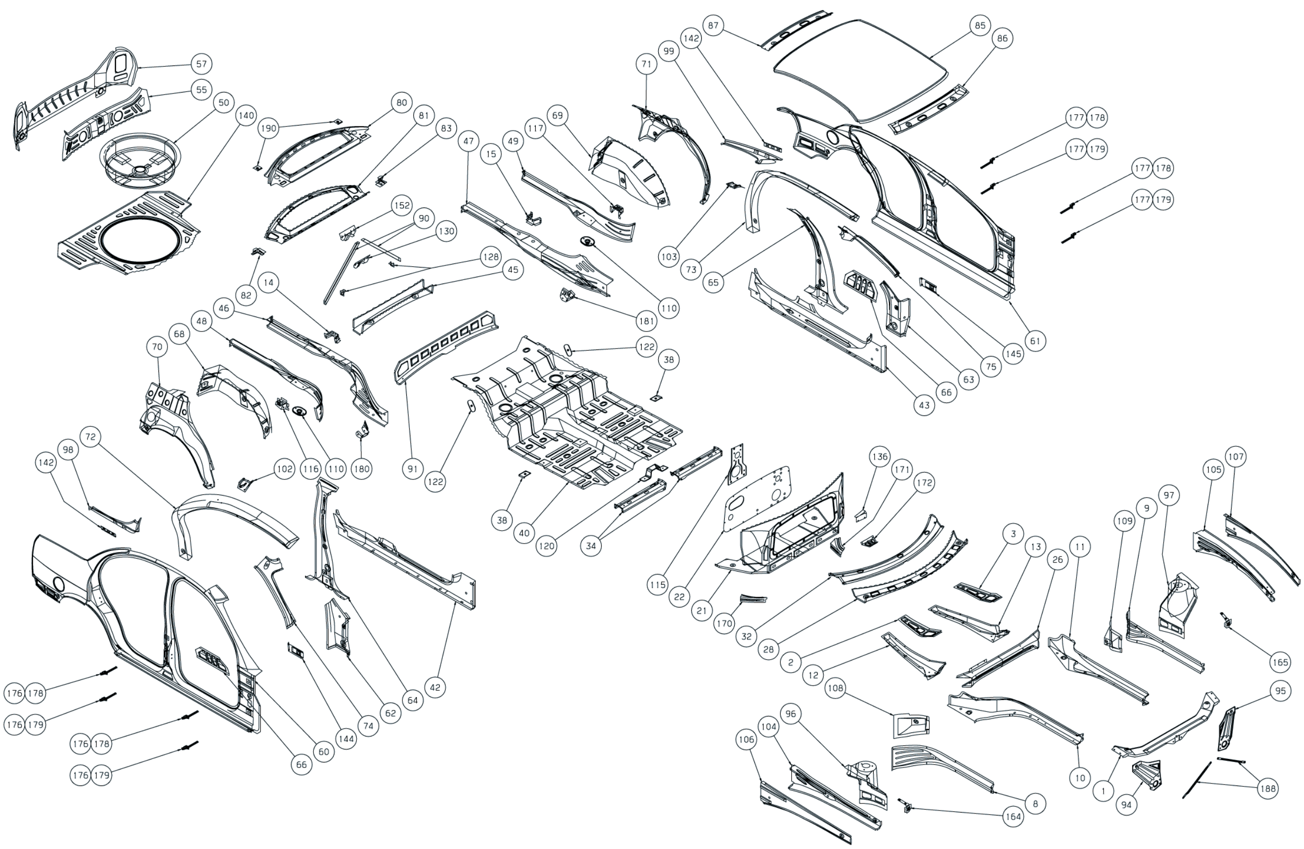
ULSAB also features a hydroformed side roof rail, which provides an essential load path for structural performance and crash energy management from the top of the 'A' pillar along the roof, into the 'B' and 'C' pillars and into the rear of the structure. In addition to tubular hydroforming, ULSAB uses sheet hydroforming for the roof panel. The work hardening effect produces improved dent resistance in the formed part, especially in the center of the panel.

Steel sandwich material was chose for mass reduction in the spare tire tub and dash panel.

These advanced materials and processes enabled the design engineers to consolidate functions in fewer parts, reducing ULSAB's part count to 94 major parts and 158 total parts, as compared with more than 200 total parts for an existing typical body structure in the same class. Reduced part count leads to reduced tooling and assembly costs. This function consolidation also leads to mass savings and improved structural performance.

ULSAB in detail

Below is an exploded view of the ULSAB structure with numbers and corresponding parts list:



Part drawings, typical sections and design highlights are included in the ULSAB Electronic Report, available through consortium members.

ULSAB parts list

Part No		Part Name		Material Grade (MPa)	Material Thickness (mm)
001		Assy Reinf Radiator Support Upper	(Bolted on)	350	1.00
002		Reinf Front Rail Extension RH		350	1.00
003		Reinf Front Rail Extension LH		350	1.00
008	A	Assy Rail Front Outer RH		350	1.50
	B	*(Tailor Blank)*		350	1.60
	C			350	2.00
009	A	Assy Rail Front Outer LH		350	1.50
	B	*(Tailor Blank)*		350	1.60
	C			350	2.00

Part No		Part Name	Material Grade (MPa)	Material Thickness (mm)
010	A	Assy Rail Front Inner RH	350	1.50
	B	*(Tailor Blank)*	350	1.60
	C		350	1.80
011	A	Assy Rail Front Inner LH	350	1.50
	B	*(Tailor Blank)*	350	1.60
	C		350	1.80
012		Rail Front Extension RH	350	1.40
013		Rail Front Extension LH	350	1.40
014		Bracket Roof Rail Mount Lower RH	350	1.20
015		Bracket Roof Rail Mount Lower LH	350	1.20
021		Panel Dash	210	0.70
022		Panel Dash Insert (Bolted on)	Sandwich	0.95
026		Member Dash Front	600	1.20
028		Panel Cowl Lower	210	0.70
032		Panel Cowl Upper	210	0.70
034		Assy Member Front Floor Support (2-Req'd)	800	0.70
038		Assy Reinf Floor Front Seat Rear Outer (2-Req'd)	280	0.80
040		Pan Front Floor	210	0.70
042	A	Panel Rocker Inner RH	350	1.30
	B	*(Tailor Blank)*	350	1.70
043	A	Panel Rocker Inner LH	350	1.30
	B	*(Tailor Blank)*	350	1.70
045		Member Rear Suspension	280	0.70
046	A	Assy Rail Rear Inner RH	350	1.00
	B	*(Tailor Blank)*	350	1.30
	C		350	1.60
047	A	Assy Rail Rear Inner LH	350	1.00
	B	*(Tailor Blank)*	350	1.30
	C		350	1.60
048	A	Assy Rail Rear Outer RH	350	1.00
	B	*(Tailor Blank)*	350	1.30
	C		350	1.60
049	A	Assy Rail Rear Outer LH	350	1.00
	B	*(Tailor Blank)*	350	1.30
	C		350	1.60
050		Panel Spare Tire Tub (Bonded on)	Sandwich	0.96
055		Member Panel Back	210	0.65
057		Panel Back	140	0.65
060	A	Panel Body Side Outer RH	210	0.70
	B	*(Tailor Blank)*	280	0.90
	C		280	1.30
	D		350	1.50
	E		350	1.70
061	A	Panel Body Side Outer LH	210	0.70
	B	*(Tailor Blank)*	280	0.90
	C		280	1.30
	D		350	1.50
	E		350	1.70
062		Panel A-Pillar Inner Lower RH	350	1.00
063		Panel A-Pillar Inner Lower LH	350	1.00
064		Panel B-Pillar Inner RH	350	1.50
065		Panel B-Pillar Inner LH	350	1.50
066		Reinf B-Pillar Lower (2-Req'd)	350	0.90
068		Panel Wheelhouse Inner RH	210	0.65
069		Panel Wheelhouse Inner LH	210	0.65
070	A	Panel Wheelhouse Outer RH	140	0.65
	B	*(Tailor Blank)*	210	0.80
071	A	Panel Wheelhouse Outer LH	140	0.65
	B	*(Tailor Blank)*	210	0.80
072		Rail Side Roof RH	280	1.00

Part No	Part Name		Material Grade (MPa)	Material Thickness (mm)
073	Rail Side Roof LH		280	1.00
074	Panel A-Pillar Inner Upper RH		350	1.50
075	Panel A-Pillar Inner Upper LH		350	1.50
080	Panel Package Tray Upper		210	0.65
081	Panel Package Tray Lower		210	0.65
082	Support Package Tray RH		280	0.80
083	Support Package Tray LH		280	0.80
085	Panel Roof		210	0.70
086	Panel Front Header		280	0.70
087	Panel Rear Header		140	0.70
090	Member Pass Through (2-Req'd)		140	0.65
091	Member Kick Up		800	0.70
094	Reinf Radiator Rail Closeout RH	(Bolted on)	350	1.00
095	Reinf Radiator Rail Closeout LH	(Bolted on)	350	1.00
096 A	Panel Skirt RH		140	2.00
B	*(Tailor Blank)*		140	1.60
097 A	Panel Skirt LH		140	2.00
B	*(Tailor Blank)*		140	1.60
098	Panel Gutter Decklid RH		140	0.65
099	Panel Gutter Decklid LH		140	0.65
102	Support Panel Rear Header RH		140	0.70
103	Support Panel Rear Header LH		140	0.70
104	Rail Fender Support Inner RH		420	1.20
105	Rail Fender Support Inner LH		420	1.20
106	Rail Fender Support Outer RH		350	0.90
107	Rail Fender Support Outer LH		350	0.90
108	Reinf Front Rail RH		350	1.00
109	Reinf Front Rail LH		350	1.00
110	Plate Rear Spring Upper (2-Req'd)		350	2.00
115	Reinf Panel Dash Brake Booster	(Bolted on)	350	1.00
116	Assy Bracket Rear Shock Absorber Mount RH		350	2.00
117	Assy Bracket Rear Shock Absorber Mount LH		350	2.00
120	Reinf Floor Front Seat Rear Center		350	1.20
122	Assy Reinf Rear Seat Inner Belt Mount (2-Req'd)		350	2.00
128	Bracket Member Pass Through Lower (2-Req'd)		350	1.00
130	Bracket Member Pass Through Upper Front		350	1.00
136	Reinf Panel Dash Upper		350	1.00
140	Pan Rear Floor		210	0.70
142	Assy Reinf Hinge Decklid (2-Req'd)		350	1.50
144	Reinf A-Pillar RH		350	1.50
145	Reinf A-Pillar LH		350	1.50
152	Bracket Member Pass Through Upper Rear		350	1.00
164	Assy Closeout Fender Support Rail RH		350	1.00
165	Assy Closeout Fender Support Rail LH		350	1.00
170	Reinf Rail Dash RH		350	1.30
171	Reinf Rail Dash LH		350	1.30
172	Assy Reinf Cowl Lower		350	1.00
176	Hinge Base RH (4-Req'd)		280	-
177	Hinge Base LH (4-Req'd)		280	-
178	Hinge Stem 119 (4-Req'd)		280	2.00
179	Hinge Stem 141 (4-Req'd)		280	2.00
180	Bracket Trailing Arm Mount RH		350	2.00
181	Bracket Trailing Arm Mount LH		350	2.00
188	Brace Radiator (2-Req'd)	(Bolted on)	350	0.80
190	Assy Reinf Seat Belt Retractor Rear (2-Req'd)		350	1.20

ULSAB Manufacturing

Early involvement

Manufacturability of parts was crucial to the ULSAB's success and was contemplated throughout the design phase of the project. Early in the design process the design engineers worked with component fabricators and steel manufacturers to optimize the design. The steel manufacturers were called upon to provide high strength and ultra high strength grades of steel for use in tailored blanks, hydroformed tubing and steel sandwich material. The project partners also used forming simulations early in the project to predict manufacturability.

Tooling

To prove manufacturing feasibility of ULSAB, the Consortium specified production intent standards for ULSAB parts, requiring that all parts be manufactured from tools with no manual forming. All stamping tools in this program are "soft" tools made of material such as kirksite. Due to pressure requirements, hydroforming, was accomplished using hard tools. In all cases, part fabrication tolerances and quality standards were maintained the same as intended for full volume production. Tool development logs and coordinate measuring machine (CMM) reports were compiled for the most critical and complex parts, listed below. These documents are available for inspection.

- Floor pan
- Rocker inner
- B pillar inner
- Rear rail inner
- Rear rail outer
- Wheelhouse outer
- Body side outer
- Dash member front
- Skirt and shock tower
- Rail front inner
- Rail front extension
- Panel dash
- Member kick up
- Spare tire tub
- Side roof rail
- Panel roof

Analysis

To help ensure that the part designs were feasible, the project partners performed forming simulation analysis on the most complex parts. Forming simulation was performed using finite element methods to predict locations of strains and material thinning. The project partners then used this information to recommend product design and tooling adjustments accordingly. Simulation reports on the parts listed below are available for inspection upon request.

- Floor pan
- Rocker inner
- B pillar inner
- Rear rail inner
- Rear rail outer
- Body side outer
- Side roof rail
- Panel roof

Part validation

Upon completion of tooling, the component fabricators manufactured the parts and evaluated them using circle grid strain analysis to confirm that they were formed to full volume manufacturing standards. Confirmation was also established through measurement of key part dimensions and the use of check fixtures. Complete information to support part manufacturing feasibility was documented and includes material characteristics, press conditions, forming limit diagrams, process sheets and tolerance measurements. These reports comprehend all parts listed under section "Tooling" in this report and are available for inspection upon request.

Assembly

Sequence

ULSAB assembly sequence uses two-stage body side framing in which all inner parts of the body side are assembled to the body structure and the body side outer is subsequently attached. This approach enables better attachment of inner pieces and improves structural integrity by eliminating unnecessary weld access holes.

ULSAB employs about one-third fewer spot welds and significantly more laser welding than a conventional body structure, resulting in improved structural integrity, as well as some cost savings. Assembly of the structure includes 18,286 mm of laser welding, 2,206 spotwelds and 1,500 mm of MIG welding, the majority of which is used to attach through pillar door hinges.

Assembly requires joining the following subassemblies, as described:

Floor complete assembly: the rear rail outer, right and left are attached to the assembly floor inner

Front end assembly: the assembly dash is attached to the assembly front ladder complete

Body side inner assembly: the side roof rail is attached to the assembly rocker inner; the 'B' pillar inner and assembly wheelhouse are then attached to that structure

Underbody complete assembly: the assembly cowl lower is attached to the assembly front end and brought to the assembly floor complete

aFraming: to the underbody assembly complete is attached the assembly front rails outer right and left and the cowl panel upper. Then attached are the assembly member pass through and the assembly body side inner right and left. From the back the assembly package tray lower is inserted and then the front and rear headers are dropped on.

Final assembly: the assembly package tray upper drops onto the package tray lower; the assembly panel back attaches to the back of the floor complete; the body side outer assembly is brought onto the side of the body; the fender rails support outer are attached; and, finally, the roof panel is dropped on.

After the body structure leaves the body shop, the assembly radiator support upper is attached to the front end; the assembly dash insert is attached to the dash panel; and the spare tire tub (spare tire in place) is dropped into the rear trunk area.

Adhesive bonding

Steel sandwich material cannot be welded, so the ULSAB parts made of steel sandwich material employed adhesive bonding as the joining technology. Adhesive bonding provides structure as well as a seal. The bonding material is a two-component, non-conductive, high modulus, high viscous, chemically curing polyurethane adhesive / sealant that cures virtually independent of temperature and moisture.

The parts to be joined must be held securely in place while the adhesive bonding cures. The steel sandwich dash panel insert was secured with adhesive bonding and then bolted in place.

Adhesive bonding technical data

Basis	polyurethane prepolymer
Processing temperature	10° to 35° C
Working time	about 10 minutes at 23° C / 50 % relative humidity
Ultimate tensile strength	>5.5Mpa
Percentage elongation	>200%
G-modulus	>2.5 MPa

The assembly sequence, processes and tolerances were established by PES. Porsche in Germany assembled the body structures using a flexible, modular assembly fixture system that was developed in CATIA, a computer-aided design system. All tooling holes and locators that would be used for production were used during the build.

The final assembled body structures were checked by coordinate measuring machines (CMM) to guarantee their dimensional integrity, and this data is available for inspection upon request.

ULSAB Materials and Processes

The UltraLight Steel Auto Body (ULSAB) design called for the application of some steel thicknesses and grades currently available but not commonly used in automotive bodies, as well as the use of advanced manufacturing processes. Steel is the most recycled material in the world, and all steel chosen for the ULSAB structure is recyclable. Steel specifications for the body were chosen to meet mass, performance and safety goals.

In their effort to optimize the best attributes of steel in this project, PES engineers specified unusually large percentages of high and ultra high strength steels and steel sandwich material. They also called for the use of hydroforming and tailored blanking.

These materials and advanced processes enabled the design engineers to consolidate functions in fewer parts, resulting in mass savings and improved performance.

Materials

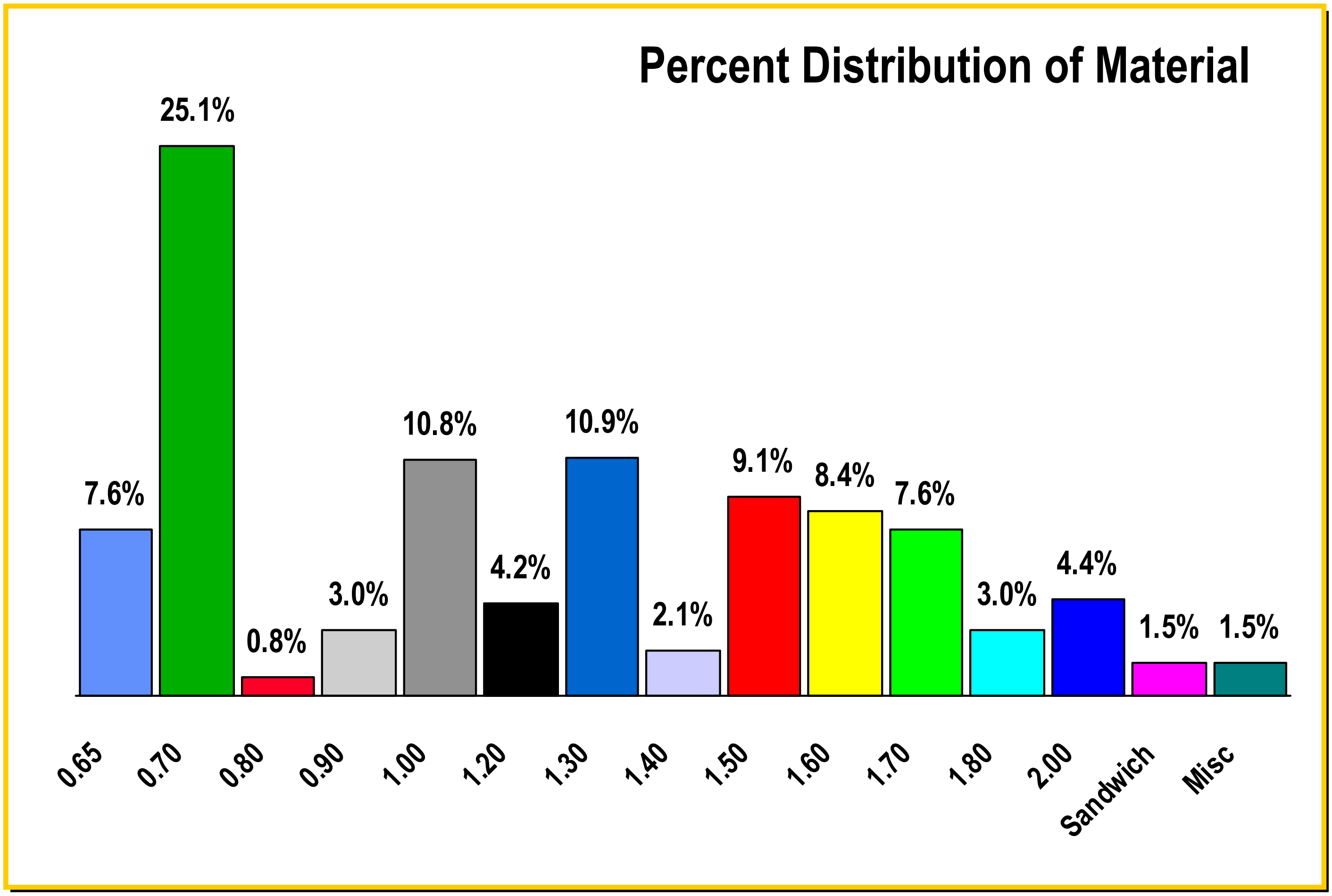
High strength steel

ULSAB uses high strength steel and ultra high strength steel for more than 90 percent of the body structure. ULSAB defines high strength steel as yield strength 210 through 550 MPa and ultra high strength steel as yield strength above 550 MPa. Material thicknesses range from 0.65 mm to 2.0 mm.

High and ultra high strength steels were used where the design required certain crash and strength characteristics. For high and ultra high strength steel parts, ULSAB uses phosphor-alloyed steels, bake-hardened steels, isotropic steels, high-strength IF steels, transformation induced plasticity steels and dual phase steels. Ultra high strength steel was used for most of the lower crossmembers.

One challenge posed by these steels is that they form differently from the mild steel to which many component fabricators are accustomed. High strength steel has greater springback and requires different draw angles so each different grade must be treated by the design engineer and manufacturing engineer as a unique material.

Thickness usage in ULSAB is illustrated in the chart below.



Tailored blanks

Nearly half of ULSAB's mass consists of tailored blanked parts, which promote smooth load flow, reducing structural discontinuities and allowing for the combination of thicker and higher strength materials within the same part. Tailored blanking enables the design engineer to accurately situate the steel within the part precisely where its attributes are most needed. While this benefit results in improved crash performance, it also leads to weight reduction because it allows the design engineer to remove mass that does not contribute to performance.

Tailored blanks also reduce the total number of parts, which leads to the reduction of dies needed for part stamping and the reduction of costs associated with those dies. Likewise, they reduce the number of spot welds and promote improved dimensional accuracy due to reduction in assembly steps.

ULSAB's body side outer is one of several parts that employs a fully laser welded tailored blank with different thicknesses and grades of steels. The body side outer panel uses a laser welded tailor blank and employs a one-piece design which includes the complete body side ring as well as the rear quarter. This part was designed for weight savings — through elimination of reinforcements in the body side assembly — and structural performance. It provides exact door fit and also leads to cost savings.

Careful placement of the seams in the tailored blank was critical for minimizing weight and facilitating forming. This consideration was especially important in the body side outer because of its complexity, its size, its use of high strength steels and the inclusion of a class A surface quarter panel. Nearly half of the ULSAB mass consists of tailored blank parts.

Tailored blank usage

Part	Material grade (yield strength) in MPa	Material thickness (mm)
rail front outer (r&l)	350	1.5 - 2.0
rail front inner (r&l)	350	1.5 - 1.8
panel rocker inner (r&l)	350	1.3, 1.7
rear rail inner and outer (r&l)	350	1.0 - 1.6
panel body side outer (r&l)	210 - 350	.7 - 1.7
panel wheelhouse outer (r&l)	140, 210	.65, .8
panel skirt	140	1.6, 2.0

Steel sandwich

Steel sandwich material consists of a thermoplastic (polypropylene) core sandwiched between two thin steel skins. This material can be up to 50 percent lighter than a comparable sheet of homogeneous steel without compromising performance. It is favored where bending stiffness is the design criterion. The thermoplastic core acts as a spacer between the two outer sheets, separating the outer surfaces from the neutral axis when a bending load is applied. It shares many of the same processing possibilities — deep drawing, shear cutting, laser cutting, drilling, adhesive bonding and riveting — with sheet steel but cannot be welded.

Steel sandwich material was chosen for mass reduction and was used for the spare tire tub and the dash panel. The steel yield strength for the spare tire tub is 240 MPa with a width of 1050 mm and a thickness of .14 mm. Its core has a thickness of .65 mm. For the dash panel, the steel yield strength is 140 MPa with thickness of .12. Its core is .65 mm.

Processes

Hydroforming

Tubular hydroforming and its cold working effect produces high dimensional stability and increases effective yield strength in any component. The part making process incorporates four steps: 1) making the tube; 2) bending the tube; 3) pre-forming the pre-bent tube; and 4) hydroforming the pre-formed tube into the final component shape.

ULSAB's hydroformed side roof rail provides an essential load path for structural performance and crash energy management from the top of the 'A' pillar along the roof, into the 'B' and 'C' pillars and into the rear of the structure. The hydroformed side roof rail reduces the total number of parts and maximizes section size, allowing for both mass and cost savings.

The raw material for the side roof rail is a welded, high strength steel tube of thickness 1 mm and outside diameter of 96 mm. The yield strength is 280 MPa.

Sheet hydroforming was chosen for the roof panel for weight reduction. This process provided the opportunity to manufacture the roof panel at a thinner gauge and still achieve a work-hardening effect, especially in the center area where the degree of stretch is normally minimal. Typically, additional thickness is needed to meet dent resistance requirements there.

With sheet hydroforming, the work-hardening effect is achieved by using fluid pressure to stretch the blanks in the opposite direction towards the punch. This plastic elongation causes a work-hardening effect in the center area of the blank. In the second step, the punch forms the panel towards controlled fluid pressure achieving excellent part quality because there is no metal-to-metal contact on the outer part surface. The roof panel is manufactured in 0.7 mm high strength isotropic steel with a yield strength of 210 Mpa.

Assembly laser welding

Laser welding was used in ULSAB to improve static and dynamic strength of joints, for areas where access was available on only one side and for good aesthetic appearance at joint areas. Laser welding also has the benefit of small a heat-affected zone, which reduces dimensional distortion and material property changes. Total length of laser welding in ULSAB is 18,286 mm.

The laser welding and laser cutting cabin was equipped with a KUKA KR 125 robot to which the laser heads were attached. The maximum load was 125 kg with a working range of 2410 mm. The laser source was a Rofin Sinar CW 025 Nd:YAG Laser. The maximum output of 2500 watts was transferred through a switching device with two outlets via two 15 m glass fiber cables of 0.6 mm diameter to the laser optic. In addition to the laser cutting head, two types of laser welding heads were used: Laser picker and single roller. Welding requires contact between the surfaces that are being joined, and each of these laser heads employs a different method by which they help ensure zero gap prior to welding.

ULSAB Structural Performance

Satisfactory performance of any body structure is critical to its success. Performance includes measures of static torsional rigidity, static bending rigidity, body structure modes and safety.

Static torsional and bending rigidity refer to body stiffness, and the body structure modes refer to the shapes the body assumes at its natural frequencies, which are related to noise, vibration and harshness (NVH). These factors affect the ride and handling and structural feel of an automobile and have a direct impact on ride satisfaction. Safety refers to the body structure's ability to withstand impacts and meet specific crash criteria.

A stiff auto body is preferred to a pliant one because it handles better and resists excitement (vibration) produced by road inputs, which are created when the tires strike bumps or potholes. When excited by outside forces such as a bump in the road, an auto body vibrates at a particular frequency, called its natural frequency, and in a particular manner, called its mode shape. Components attached to the car body — such as the suspension and the powertrain — also vibrate at individual natural frequencies.

It is important to design structural systems with vibration frequencies that do not excite each other, or "couple." Coupling creates dissonance and unpleasant vibration and is caused when two major systems resonate at similar natural frequencies.

Validation

Two methods have been used to validate ULSAB's performance: **Computer-aided engineering** (CAE) and **physical testing**. Both analyses yield information on static bending, static torsion, normal modes and mass. CAE analysis is predictive of physical test results and is performed through computer simulation. Physical testing is used to validate CAE analysis and is performed by loading the physical structure after it has been built. For ULSAB, no physical crash tests were performed because they are destructive and they require crashing a full running vehicle (not merely the body structure). Only CAE was used to predict ULSAB crash results.

CAE analysis

ULSAB analysis employed a fully surfaced body structure that includes all exterior styling surfaces. All surfaces were generated from CAE CATIA design software. That design data was used to create finite element analysis static and crash models. The models were comprehensive, the largest requiring approximately 178,000 elements (1 million degrees of freedom) and the use of a supercomputer to analyze.

Static and modal analysis

Static analysis included static torsion and static bending and free-free normal mode (as if the structure were floating in space). Static models were run and optimized using NASTRAN, a linear static analysis code. Half-models symmetric about the centerline were used and constrained accordingly at all nodes on the centerline. All spot welds were represented using a rigid element placed in the middle of the weld flange with an average spacing of 50 mm. A free node exists between welds. Urethane glass adhesive was simulated for the windshield and backlite using spring elements with stiffness in three directions, x, y and z. The mesh was created accordingly.

Crash analysis

ULSAB was subjected to crash simulations using LS Dyna-3D, an explicit finite element analysis code, and exhibited acceptable crash behavior. The models were created using industry accepted methods. For realistic crash behavior in the simulation, all spot welds and laser welded areas were considered in the model, and the following relevant components were added to the model:

- Wheels with tire model
- Engine and gearbox
- Steering system
- Chassis system with subframe
- Fuel tank
- Bumper system including crushbox
- Radiator with fan
- Battery
- Spare tire
- Brake booster, ABS box and cylinder

All simulations were run to their completion. Test and full vehicle mass was assumed to be 1612 kg, which included luggage at 113 kg and occupants at 149 kg.

Analysis was performed with models of the following size:

Model definition

	Static half model	front impact and offset	side impact	rear impact half model	roof crush
Number of elements	54,521	178,386	181,963	90,105	119,226
Nodes	53,460	174,532	179,918	88,769	117,053

ULSAB was designed to meet five crash requirements:

35 MPH NCAP 0 DEGREE FRONTAL (FMVSS 208)

The conditions for the front crash analysis are based on several requirements. In the ULSAB project, the focus was on progressive crush of the upper and lower load path; sequential stack up of the bumper, radiator and powertrain; integrity between individual components; 'A' pillar displacement; definition of the door opening; uniform distribution of the load; toe pan intrusion; and passenger compartment residual space. These requirements contribute to occupant safety and reflect the United States Federal Motor Vehicle Safety Standard, FMVSS 208.

Analysis was set up as shown. The maximum deformation image shows the deformed structure at event completion, which occurred at 67 msec. The crash pulse can be seen in the graph below. The table below lists the major events that occur during the simulation. Maximum footwell intrusion was 94 mm. Peak deceleration was approximately 31 gs. Maximum dynamic crush was approximately 620 mm.

35 mph NCAP simulation behavior

TIME (MS)	EVENTS
12	initial folding of longitudinal
16	initial folding of subframe
21	1st buckling of rails upper in front of shock tower
35	engine contacts barrier
37	buckling rear of subframe at fixture on extension longitudinals
50	rear end of longitudinals start to buckle behind reinforcements
51	wheels contact barrier
67	maximum dynamic deformation

This analysis illustrates good progressive crush of the upper and lower structure and subframe. It shows peak deceleration of 31 gs, which is satisfactory considering that this structure is designed with stiffer body sides to meet 50 % AMS offset crash requirements.

The pulse graph is sympathetic to current occupant restraint systems. It shows a consistent rise to the peak of 31 gs then a smooth ride down to zero, indicating that the occupant would experience controlled restraint. The initial, early peak should trigger airbag systems. Low intrusion at the footwell indicates that leg damage is unlikely.

55 KM/H 50% AMS FRONTAL OFFSET

The aim of the AMS offset crash is to secure the passenger compartment residual space. For this requirement, a stiff passenger compartment and good energy absorption in the front structure is needed.

The offset barrier is a block with a 15 degree rotated contact area, including two anti-slide devices mounted on the contact surface. The left side of the car hits the barrier with an overlap of 50 percent.

Analysis was set up as shown below. The maximum deformation image shows the deformed structure at event completion, which occurred at 88 msec. The crash pulse can be seen in the graph below. The table below lists the major events that occur during the simulation. Maximum footwell intrusion was 146 mm. Peak deceleration was approximately 35 gs. Maximum dynamic crush was approximately 740 mm.

AMS offset simulation behavior

TIME (MS)	EVENTS
12	Initial folding of longitudinal left hand side
16	Initial folding of subframe
18	1st buckling of upper rails in front of shock tower
36	Wheels left hand side contact barrier
40	Engine contacts barrier; start of vehicle rotation around Z axis
44	Subframe front totally deformed; left hand longitudinal rail moves rearward, causing deformation in front floor; buckling of longitudinal rail in area of shock tower
48	2nd buckling of upper rails left hand side behind shock tower
52	Buckling of rear end of subframe at fixture on extension longitudinals
60	buckling of brace cowl to shock tower left hand side; engine hits steering gear
68	gearbox mounting contacts brake booster
70	wheel left hand side contacts hinge pillar
88	maximum dynamic deformation

This analysis shows good progressive crush on the barrier side (left), as well as crush on the right, indicating transfer of load to the right side of the structure. This transfer means that the barrier side is not relied upon solely to manage the crash event.

This transfer also contributes to the preservation of the occupant compartment. The intrusion of 146 mm into the footwell is minimal given the severity of this event.

The initial, early peak shown in the pulse graph should trigger airbag systems.

Peak deceleration of approximately 35 gs, a good result considering the severity of this event.

35 MPH REAR MOVING BARRIER (FMVSS 301)

The conditions for rear impact analysis are based on United States Rear Moving Barrier test FMVSS 301. The test specifically addresses fuel system integrity during rear impact. Automotive companies also specify goals for structural integrity and passenger compartment volume.

The impacting barrier is designed to represent a rigid body with a mass of 1830 kg that contacts the vehicle at zero degrees relative to the vehicle longitudinal axis. FMVSS 301 specifies the velocity of the rear moving barrier to be 30 mph at the time of impact. ULSAB ran its analysis at a velocity of 35 mph, which represents 36 percent more kinetic energy.

Analysis was set up as shown below. The maximum deformation image shows the deformed structure at event completion, which occurred at 86 msec. The crash pulse can be seen in the graph below. The table below lists the major events that occur during the simulation. Maximum intrusion into rear passenger compartment was 120 mm. Peak acceleration of the vehicle was approximately 14 gs. Maximum dynamic crush was approximately 650 mm.

Rear moving barrier simulation behavior

TIME (MS)	EVENTS
4	Initial folding of longitudinals rear
20	Spare tire contacts barrier
35	First buckling of crossmember rear suspension
40	Spare tire contacts crossmember rear suspension
48	Buckling of rear end rocker at connection to longitudinal rear
44	Buckling of crossemember rear suspension
52	Collapse of crossmember rear suspension
56	Buckling of front end of longitudinal rear
86	Maximum dynamic deformation

This analysis shows that the structural integrity of fuel tank and fuel filler was maintained during the event, so no fuel leakage is expected. The spare tire tub rides up during impact, avoiding contact with the tank.

Rear passenger compartment intrusion was restricted to rear most portion of the passenger compartment, largely in the area behind right rear seat. This result is due to good progressive crush exhibited by the rear rail.

50 KM/H EUROPEAN SIDE IMPACT (96/27 EG, WITH DEFORMABLE BARRIER)

The conditions of the side impact analysis are based on a European Side Moving Barrier test that addresses injury criterion gathered from EUROSID side impact crash dummies. Automotive companies also specify goals for structural integrity and passenger compartment volume.

The impacting barrier has a mass of 950 kg and contacts the vehicle at ninety degrees relative to the vehicle longitudinal axis. The velocity of the barrier is 50 km/hr at the time of impact.

Analysis was set up as shown below. The maximum deformation image shows the deformed structure at event completion, which occurred at 64 msec. Side impact velocity versus intrusion can be seen in the graph below. The table below lists the major events that occur during the simulation. Maximum dynamic inboard displacement was 248 mm at the rear of the front door. Maximum velocity of the intruding structure was 8 m/sec.

Side impact simulation behavior

TIME (MS)	EVENTS
16	Buckling of rocker in front of B pillar
28	Buckling of floor
35	Buckling of roof
40	Buckling of roof frame at b-pillar
44	Buckling of member kick up
48	Buckling of brace tunnel
64	Maximum dynamic deformation

The body side ring and doors maintained their integrity with only 248 mm of intrusion. The velocity of the intruding structure was tracked to determine the degree of injury an occupant may sustain. The maximum velocity was only 8 meters per second. The event is considered complete when the deformable barrier and vehicle reach the same velocity, in this case 64 msec.

The conditions for the roof crush analysis are based on United States Federal Motor Vehicle Standard, FMVSS 216. This requirement is designed to protect the occupants in the event of a rollover. The surface and angle of impact represent impact on the front corner of the roof.

The federal standard requires roof deformation to be limited to 127 mm of crush. The roof structure must support 1.5 times the vehicle weight or 5,000 pounds, whichever is less. For testing, the complete body structure is assembled and clamped at the lower edge of the rocker. The roof crush uses a quasi-static force versus displacement arrangement.

Analysis was set up as shown below. The maximum deformation image shows the deformed structure at event completion, which is 127 mm of crush. The force versus displacement curve can be seen in graph below. Peak load was approximately 36 kN at 75 mm of crush versus the requirement of 22.25 kN.

Analysis showed that 22.25 kN was reached within 30 mm of crush. The structure resisted the applied load all the way up its peak of 36 kN and continued to maintained it quite well even after peak, when it dropped to about 28 kN at 127 mm. The load was well distributed through the ‘A,’ ‘B’ and ‘C’ pillars and down into the rear rail.

Physical testing

Physical tests were used to validate static torsion, static bending and normal modes. Normal mode testing was performed by suspending the body structure on a test rack with rubber straps while exciting it at all four corners using electrodynamic shakers. To validate mass, the ULSAB structure was weighed.

Static torsion test

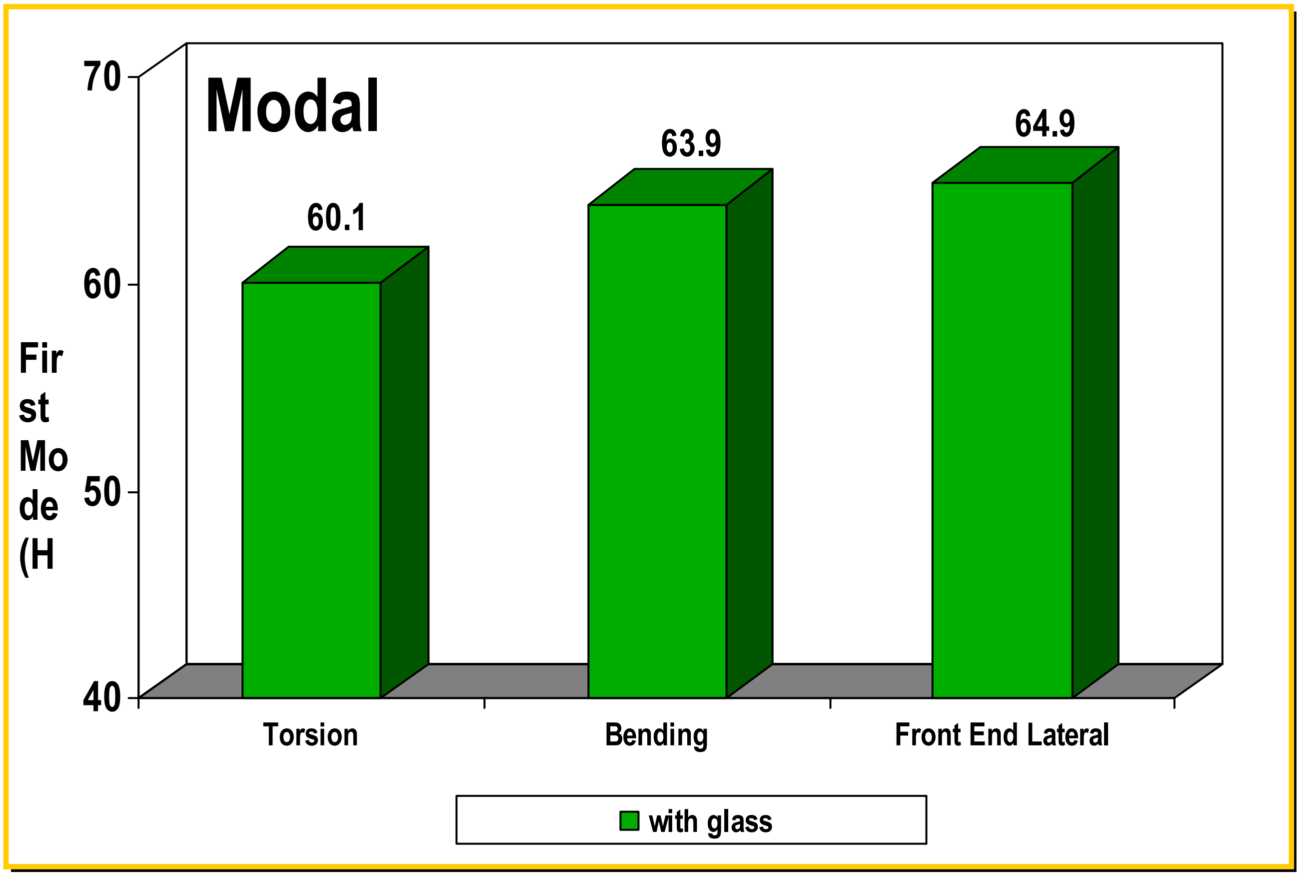
The static torsion test yielded a stiffness of 20,800 Nm/deg. The displacement along the length of the body structure can be seen in the graph below. The plot shows excellent structural continuity with a local increase in stiffness between x=3800 and 4200 due to the member pass through.

Static bending test

The bending test yielded a stiffness of 18,100 N/mm. The displacement along the length of the body structure can be seen in the graph below. The plot shows excellent continuity with a local increase in stiffness between x=3500 and 4200. This result indicates a stiff joint between rocker and rear rails.

Modal test

The first three major body structure modes with and without glass are shown in the graph below. The ULSAB body structure shows good dynamic rigidity, as indicated previously by the static test. The following graph shows the natural frequencies of the body structure.



Results and prediction

CAE was employed in the design and manufacture process to predict physical confirmation and ensure that the concept would meet established performance targets. Physical testing following development was used to validate results generated earlier in the process by CAE. In ULSAB's case, CAE results were, in most cases, predictive of the physical tests, as shown below.

Static analysis

	torsional rigidity (Nm/deg)	bending rigidity (N/mm)	1st body structure mode (Hz)	Mass (kg)
CAE	20,347	20,543	60.3	212
Physical	20,800	18,100	60.1	203*

* natural range of variation ±1 percent

The reliable correlation demonstrated (above) between CAE and physical results for static analysis indicates that a similar correlation would exist between CAE and physical crash results. The disparity in the mass numbers exists because the CAE model assumed constant thickness within each part; however, actual stamped parts — thinned in the stamping process — exhibit varying degrees of thickness throughout. Constant material thickness assumed in the CAE model yielded mass numbers that are higher than actual.

Structural performance

Physical tests and CAE results show ULSAB to exceed all concept phase benchmarked averages.

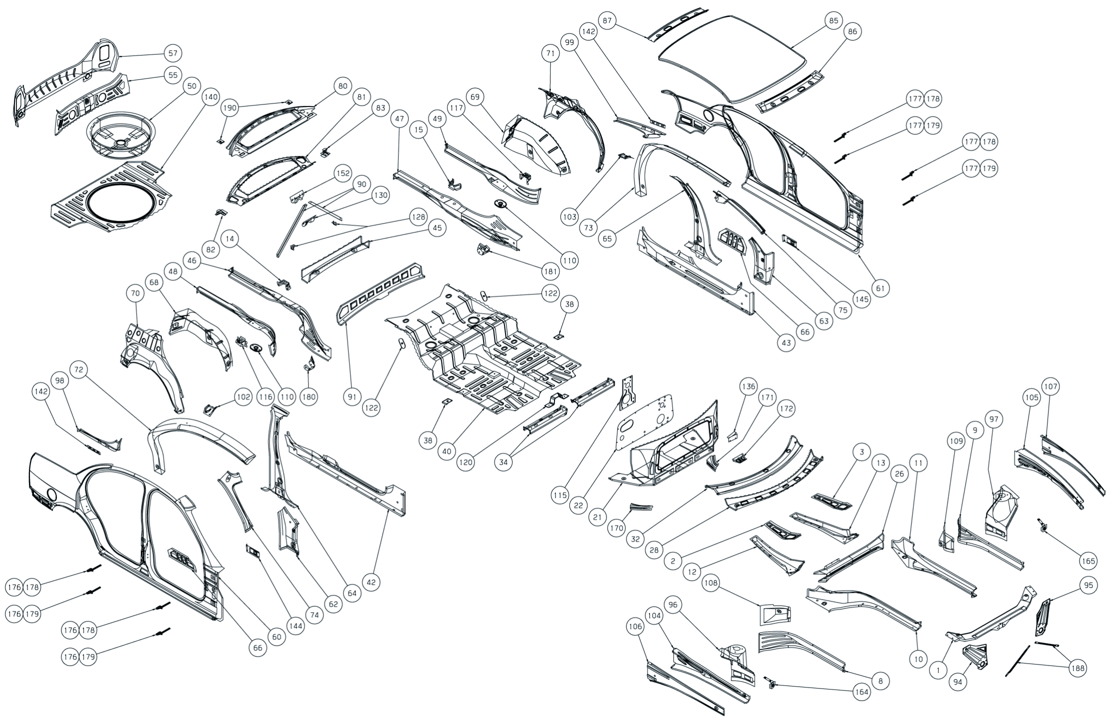
Structural performance comparison

	ULSAB structure	benchmark structure average	Future reference structure
Performance			
torsion (Nm/deg)	20,800	11,531	13,000
bending (N/mm)	18,100	11,902	12,200
1^{st} body structure mode (Hz)	60	38	40
Mass (in kg)	203*	271	250

* natural range of variation ±1 percent

Body structure

The body structure consists of 94 major parts plus 31 reinforcements (not manufactured) — such as the hood hinge, steering rack assembly mounting, deck lid latch support and gearshift mounting — as well as 22 brackets (not manufactured) — such as the battery tray and the spare tire mounting. The exploded view of the body structure shown below represents the parts that were included in the measured body.



ULSAB Economic Analysis

Although lightweighting without sacrificing performance was ULSAB's priority, affordability was also important. Early in ULSAB's concept phase the Consortium commissioned an economic analysis to establish a reference by which to compare ULSAB. At that time, IBIS Associates estimated a cost of $1116 each to manufacture current, typical body structures for vehicles in the same class as ULSAB. The North American manufacturing costs calculated during the concept phase of the project represent the estimated cost to manufacture a typical body structure in the same class as ULSAB at the time of the project's inception in 1994.

In the validation phase, the cost issue was revisited more thoroughly. The ULSAB Consortium's primary objective was to provide a cost model that automotive customers could use to analyze ULSAB costs in comparison with other options and could also be used to generate costs associated with alternative designs. The cost model should allow auto companies to use their own manufacturing and business environment assumptions to compare with the assumptions used for ULSAB. This cost estimation tool should permit the user to easily adapt various input parameters, allowing cost investigations for any design on a consistent basis.

A Porsche-led team of analysts developed the detailed cost model that includes all aspects of fabrication and assembly. This model comprehends United States manufacturing costs, including investments for both plant and tooling, piece fabrication costs and assembly costs, through to the end of the body shop. The analysts used these details to generate a part-specific cost model for ULSAB. This particular analysis showed part manufacturing and assembly costs for the ULSAB body structure to be $947 each.

Using the same cost model, the team also created assumptions about a future typical four-door sedan (Year 2000) reference body structure with which to compare ULSAB. Basic economic assumptions were identical for both ULSAB and the Year 2000 structure; however, inputs about specific parts and assembly steps are not directly comparable because the Year 2000 structure represents an average of typical vehicle structures in the same class as ULSAB. For the Year 2000 structure, the study identified part groupings – instead of individual parts as with ULSAB – and assumed significantly improved fabrication and assembly techniques as compared to the concept stage reference. The cost model with these inputs showed part manufacturing and assembly costs for the Year 2000 structure to be $979 each.

The team began analysis by establishing **general inputs** or assumptions for the cost model. Then they established **production costs**, which include part fabrication and assembly. And finally they created the **model scope**, which comprehends direct manufacturing costs. The cost model examines the 158-part, 203 kg ULSAB structure and a 200-part, 250kg Year 2000 structure.

General inputs

The first step in economic analysis began with the formulation of general inputs that may vary for different locations. Inputs used for this project are as follows:

General inputs

	Input
Production volume	60 jobs per hour (225,000 vehicles per year)
Working days per year	240 (2 shifts)
Production location	mid-west USA
Wage including benefits	$44.00 per hour
Interest rate	12%
Production life	5 years
Equipment life	20 years
Building life	25 years

Production costs

Production costs comprise **fabrication** and **assembly** of ULSAB's 158 parts, which include brackets and reinforcements.

Fabrication

To calculate costs for part fabrication, the team established a press line time requirement based on the machine clean running rate, line downtimes, part reject rates and total annual production volume. They then used that press line time requirement to calculate the total number of each press line type needed to produce ULSAB. This calculation specified 15 press lines and five blanking lines to produce all necessary parts and blanks.

Assembly

Assembly costs include equipment and tooling investments, assembly plant area and labor force. Additional assembly inputs consider material, energy, overhead labor and maintenance. The assembly line was designed for a net line rate of 60 jobs per hour, as well as a specific number of spot and length of laser welds. Any change in practice of these two operations necessitates a change in the investment inputs for accurate estimates at other production volumes. Also, because the line was designed for one line speed, the model cannot adjust the investment based on different rates.

Model scope

This cost model accounts for economic and technical processes used in the manufacture and assembly of the body structure. Data for stamping include blanking, welding of tailored blanks and stamping for all parts; data for hydroforming include bending, pre-forming and final hydroforming; and data for assembly include spot welding, MIG welding, laser welding and adhesive bonding.

This model is limited to direct manufacturing costs, which include fabrication and assembly of the body structure. Indirect manufacturing costs – executive salaries, marketing and sales, shipping and purchasing, research and development, profits – are not considered.

Cost is assigned to each unit operation from a process flow diagram and then those operations are separated into individual elements. Fixed cost elements include equipment, tooling, building maintenance, overhead labor and cost of capital; variable cost elements include materials, labor and energy.

ULSAB results

Manufacturing costs for the ULSAB structure are $666 for parts fabrication and $281 for assembly. Of the 158 total parts, 94 major stamped parts represent the largest cost element at $584. Total fixed costs account for 43 percent of the total.

ULSAB results

	ULSAB cost in $US	% of Total
PARTS FABRICATION	**584**	**62**
material	351	37
labor	36	4
energy	6	1
fixed costs	191	20
HYDROFORMING	**41**	**4**
PURCHASED COMPONENTS	**41**	**4**

ASSEMBLY	**281**	**30**
Variable	55	6
fixed	226	24
TOTAL COST	**947**	**100**

Fabrication breakdown

Total fabrication costs can be broken down further. Major stamped components account for $584; the hydroformed side roof rail accounts for $41.

Fabrication breakdown

Breakdown for stamped parts	Cost per structure in $US
material	351
labor	36
energy	6
TOTAL VARIABLE	**393**
equipment	89
tooling	51
overhead labor	27
building	8
maintenance	15
working capital	1
TOTAL FIXED	**191**
TOTAL COST	**584**

Assembly breakdown

Assembly accounts for less than one-third of the overall cost. Largest single items are labor and assembly line equipment.

Assembly breakdown

Breakdown for assembly	cost per vehicle in $US
material	0
labor	45
energy	10
TOTAL VARIABLE	**55**
equipment	50
tooling	23
overhead labor	125
building	18
maintenance	9
working capital	1
TOTAL FIXED	**226**
TOTAL COST	**281**

Investments

Investments for the assembly line and related tooling and building expenses account for approximately one-third of the total investment. Press lines represent nearly half of the total investment. Weld line investments for tailored blanks are also significant, despite the fact that there are only 16 tailor welded blank parts in the vehicle. Investments are comprehended in the ULSAB results and are represented in the table below.

Investments

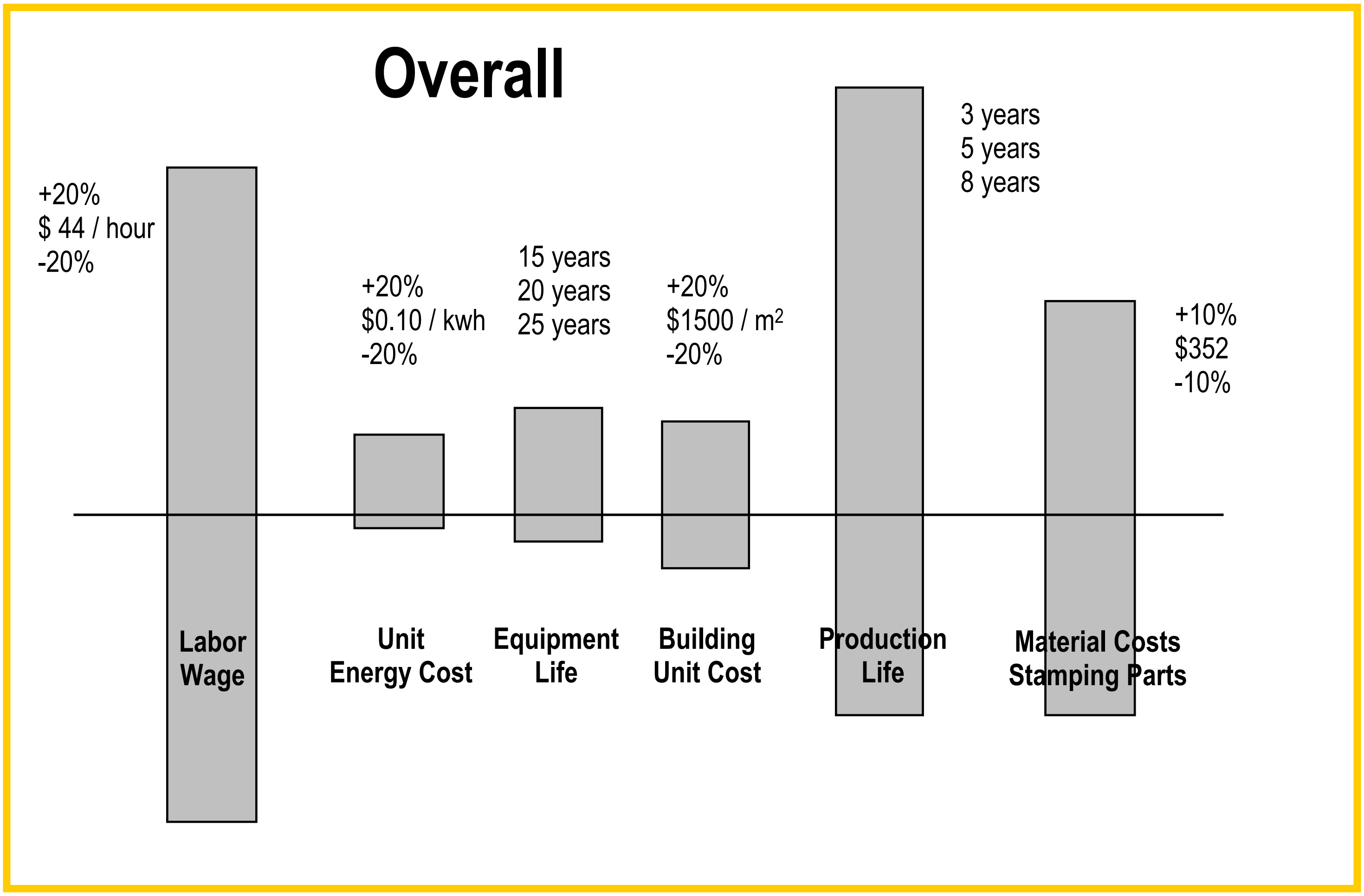
Investments	ULSAB ($US M)	% of total
Blanking tooling	4.4	1.4
Blanking lines	10.1	3.2

Blanking build	1.2	0.4
Welding line	37.2	11.9
Welding building	5.9	1.9
Stamping tooling	37.1	11.8
Stamping lines	102.9	32.8
Stamping building	6.1	1.9
Hydroforming tooling	1.3	0.4
Hydroform lines	16.3	5.2
Hydroform building	0.5	0.2
Assembly tooling	19.0	6.0
Assembly equipment	40.4	12.9
Assembly building	31.4	10.0
TOTAL INVESTMENTS	**313.8**	**100**

Sensitivity analysis

A key element of economic analysis is to determine potential cost movements as a result of sensitivity analysis and other scenarios that could impact cost. It includes investigation of labor wage, unit energy costs, equipment life, building unit cost, production life and material costs. As the use of new technologies such as tailored blanking, hydroforming and laser welding increases, so should efficiency, resulting in further cost reductions.

The sensitivity analysis, shown in the graph below, illustrates that the factors that most affect body structure cost are labor wage, production life and material costs. Factors of least influence on total cost are unit energy cost, equipment life and building unit cost.



Comparison

For comparison purposes, this economic analysis calculated the cost of manufacturing a future reference (Year 2000) structure in addition to ULSAB. This reference is a hypothetical construct intended to represent an averaging of typical mid-sized four-door sedans in the same class as ULSAB. The model inputs assume significantly improved fabrication and assembly techniques in year 2000 body structure manufacturing in the United States, including a lower part count, double attachments, and completely automated assembly.

Because no design details were assigned to the Year 2000 structure, the study identified part groupings instead of individual parts, as with ULSAB. The groupings are based on part size and complexity as well as assembly operations grouped by levels of automation and size.

The comparison below represents a single run of the cost model based on United States inputs.

Comparison of ULSAB with Year 2000 structure

			ULSAB	Year 2000
Body Structure Mass:				
	Net weight (kg)		203	250
		Stampings	184	230
		Hydroformings	10	0
		Purchased parts	9	20
	Material utilization		49	55
Parts Fabrication:				
	Direct labor		59	79
	Indirect labor		47	36
	Parts count:		158	200
		Large stampings	11	6
		Medium stampings	39	79
		Small stampings	44	50
		Hydroformings	2	0
		Purchased parts	62	65
	Die sets:		61	109
		Transfer	14	20
		Tandem	27	59
		Progressive	18	30
		Hydroform	2	0
	Hits per die set:			
		Transfer	4.1	3.8
		Tandem	3.6	3.2
	Hits per part:			
		Transfer/tandem combined	2.5	2.5
Assembly:				
	Direct labor		64	80
	Indirect labor		178	210
	Number of spot welds		2206	3250
	Length (mm) laser weld		18286	0
	Number of robots		136	200
	Number of laser welders		13	0
	Number of assbly stations		114	130
	Assembly bldg. area (m2)		20925	30000
Cost: (in $US)				
	Stamped parts		584	609
	Hydroformed rail		41	0
	Purchased parts		41	41
	Assembly		281	329
	TOTAL COST		**$947**	**$979**

Conclusion

Achieving lightweight and superior performance in a steel body structure can be done at no cost penalty. In fact, it can be less expensive than structures that do not have its benefits. ULSAB demonstrates that reduced weight and superior performance are achievable and affordable.