ULSAB-AVC

Engineering Report
October 2001

The design, materials, manufacturing,
performance and economic analysis of
ULSAB-AVC (Advanced Vehicle Concepts)

Prepared by Porsche Engineering Services, Inc.

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Preface

ULSAB-AVC is the most recent addition to the global steel industry's series of initiatives offering steel solutions to the challenges facing automakers around the world to increase the fuel efficiency of automobiles, while improving safety, performance and maintaining affordability.

This program follows the UltraLight Steel Auto Body (ULSAB) program (results announced worldwide in 1998) and the Ultralight Steel Auto Closures (ULSAC) program (results announced worldwide in 2000). The ULSAB-AVC Consortium has once again commissioned Porsche Engineering Services, Inc. (PES) Troy, Mich. USA, to provide program design and engineering management for ULSAB-AVC, as with the ULSAB and ULSAC programs.

In the ULSAB-AVC program, PES takes a holistic approach to the concept development of a new vehicle architecture that offers steel-intensive solutions to mass reduction problems.

The concept development focused on the achievement of future crash and safety requirements coupled with the demonstration of low CO_2 emissions and affordability of steel intensive vehicle concepts. Advanced high strength steels and manufacturing processes, which reflected state of the art or future trends were primary design considerations.

Two vehicle concepts were developed – one representing the European C-Class and one representing the North American Midsize-Class, which is the target for the Partnership for a New Generation of Vehicles (PNGV) program. The C-Class vehicle was developed as a 5-seat, 2-door hatchback, whereas the PNGV-Class vehicle was a 5-seat, 4-door sedan. Each vehicle class had both a diesel and gasoline engine variant.

Executive Summary

ULSAB-AVC Program Background

The objective of the ULSAB-AVC Program was to demonstrate and communicate the capabilities of steel to help fulfill society's demands for safe, affordable and environmentally responsible vehicles for the 21st Century. Porsche Engineering Services, Inc. (PES) conducted this study on behalf of the ULSAB-AVC Consortium.

The ULSAB-AVC Program concentrated on the conceptual design of two lightweight steel-intensive vehicles (C-Class and PNGV-Class). An important factor for the success of this Program was the combination of advanced vehicle design, exploiting the properties of a range of new steels together with suitable advanced, as well as traditional manufacturing and assembly processes, to achieve significant mass reduction for the body structure and the total vehicle.

ULSAB-AVC Program Targets

Benchmarking and Target Setting were the ULSAB-AVC Program's first steps in building a foundation and giving direction for work to follow. Benchmarking data from current production C-Class and PNGV-Class (North American Midsize Class) vehicles, as well as vehicles with a curb mass in the 900 kg range was collected. Based on benchmarking results, Program Targets were set and mutually agreed upon with the ULSAB-AVC Consortium.

Various factors had to be taken into consideration during the establishment of targets. First the program targets were prioritized in the following order

- Meet anticipated safety requirements for the year 2004
- Mass reduction of main components in steel to aid achievement of emissions requirements
- Mass reduction of complete vehicle
- Cost is the final priority, the goal was to minimize cost increase.

Due to differences in size and performance requirements of the two vehicle classes, two sets of targets, one for the C-Class and one for the PNGV-Class were established for:

- Mass of total vehicle
- Mass of subsytems and components

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- Vehicle dimensions
- Vehicle performance (US standard and European standard)
  - ⇒ CO_2 emissions
  - ⇒ Acceleration
- Vehicle equipment
  - ⇒ Safety
  - ⇒ Comfort (e.g. air conditioning, audio system, electronic seats)
- Crashworthiness (i.e. anticipated 2004 safety requirements)
- Structural performances of body structure
  - ⇒ Torsional rigidity
  - ⇒ Bending rigidity
  - ⇒ Normal mode frequencies
- Aerodynamic Drag
- Affordability (i.e. from none to limited or nominal cost increase)

Concept Considerations

Based on the targets set for safety/crashworthiness, mass, structural performance, dimensions and the component material definition, the main influencing factors in the package for a successful program were:

- Platform approach for both C-Class and PNGV-Class
- Safety targets for crashworthiness
- Steel intensive vehicle at low mass
- Vehicle dimensions
- Modular design/assembly approach

The main drivers for the concept development were the attainment of future crash and safety requirements coupled with demonstration of low CO_2 emissions and affordability of steel intensive vehicles in 2004 and beyond.

The closure design utilized the findings from the UltraLight Steel Auto Closures (ULSAC) Program – both concept study and validation phase. The objective was to integrate the frameless ULSAC door concept and the other ULSAC closure concepts into this program.

Use of advanced high strength steels and manufacturing processes that reflect state of the art or future trends were primary design considerations. The body structure design analysis was run with high strain rate properties of advanced high strength steels. Fabrication and assembly processes (such as tailored blanks, hydroformed tubes, and laser assembly welding) were also basic considerations for these vehicle concepts.

Package

The package of the ULSAB-AVC vehicles (C-Class 2-door hatchback design, PNGV-Class 4-door sedan) was iterated several times during the continuous design optimization and ongoing component design process.

The main drivers for the package were the considerations to achieve the crashworthiness and component mass targets, as well as the target for total vehicle mass.

Early consideration in the package development were pedestrian head injury and frontal crash event performance (US-NCAP and Euro-NCAP) along with a reduced front vehicle overhang for mass reduction reasons with the optimization for dynamic vehicle crash length. It was also decided that both vehicle variants would be front-wheel drive front engine vehicles, which is typical for state of the art vehicles in both classes and preferred by customers.

The engine bay package was developed considering safety requirements, vehicle mass distribution, body structure mass, package space and wheelbase. This unique engine arrangement positioned the engine almost flat with the crankshaft in transverse direction and the cylinder head facing rearwards into the tunnel and the transmission forward of the engine.

Once a fixed front seating concept was decided upon for enhanced side impact crashworthiness, several measures to assure ergonomic compliance were necessary to make this concept feasible. An adjustable pedal system along with an adjustable steering wheel column were chosen to account for various sized drivers.

Executive Summary

Styling

The overall goal of styling for the ULSAB-AVC Program was to visualize a family of vehicles that would be suitable for the year 2004 and beyond without detracting from the program focus of technology and steel. The styling highlights the ability to develop a family appearance from one platform, consider material use, safety (Star-Rating) and enhanced aerodynamics.

Styling was developed using Computer Aided Styling (CAS). For the body structure, closure and upper surface related parts, surface models of the two vehicle concepts were developed based on the styling sketches. Interior styling began as a series of sketches to develop a main styling direction, and culminated in an interior styling of the cockpit module integrating the rear view mirror displays with the desire to show steel features merged into module components that are lightweight in appearance.

Body-in-White Concepts

Based on the philosophy that the structural performance in one region of a vehicle may, or will influence that of another, a holistic approach was used for the development of the ULSAB-AVC body structure architecture.

The first priority was frontal crashworthiness performance, thereby establishing the general design and arrangement of the front-end structure load paths for the selected powertrain package. Considering the stringent side impact crash demands, the focus of attention was then set on the passenger compartment environment and next, the rear end structure.

Two different vehicle classes (C-Class and PNGV-Class) were developed, while at the same time, integrating as much common structure, individual parts, joints, or complete sub-assemblies into both structure variants. Thus, achieving cost related benefits such as reduced parts manufacturing, body assembly and vehicle assembly costs. The percentage of common parts in relation to their body structure mass is 23% (C-Class) and 21% (PNGV-Class).

As a result of the suspension design, an upper longitudinal load path could be eliminated. The most distinct aspect of the upper structure in both vehicle variants is the two tubular hydroformed body side members designed to transfer loads between the hinge pillar and the rear longitudinal rails. These tubes incorporate the A-pillar, side roof rail and partially, the C-pillar structure.

Much attention was given to the B-pillar design with the design criteria including crashworthiness for side impact crash events and the roof crush crash event. Unlike the PNGV-Class structure, the absence of a rear door presented a different challenge for the C-Class design. With unique design features, such as the kick-up crossmember extension and the seat crossmember extension passing through the rocker in horizontal transverse direction, the mass increase associated with the crashworthiness for the side impact events, could be minimized.

The closure structures were designed utilizing the findings of the UltraLight Steel Auto Closure (ULSAC) studies and successfully applied to the ULSAB-AVC vehicle concepts.

Chassis and Suspension Concepts

Although the ULSAB-AVC Program involves the development of two vehicle concepts, with either a diesel or gasoline engine variation, it was necessary to develop similar suspensions for both C-Class and PNGV-Class vehicles. Tuning components such as springs and dampers would have to be specific to each vehicle to accommodate the range of wheel loads in conjunction with vehicle mass.

The emphasis on safety was, in some respects, a principle driver of the concept design of the body structure. This decision required significant deformable distance be achieved between the vehicle skin and the shock tower location under the hood and influenced the shock and spring location.

The double wishbone with transverse leaf spring front suspension concept was selected after investigation of several alternative suspension concepts. This concept showed the most potential for packaging and it was the most promising front suspension concept for the overall vehicle concept.

The package studies highlighted the benefits of a front end module including subframe with engine, wishbones, steering knuckle and damper, steering gearbox and tie rods, transverse leaf spring and the cooling system. This front end module allows ease of assembly during vehicle manufacture, as well as disassembly for maintenance and repair over the vehicle life.

Gathered benchmarking data showed the twist beam rear suspension concept to be one of the lightest among the possible alternative systems such as multi-link, double wishbone, de Dion and twist beam. An advantage of the twist beam rear suspension is reduced number of parts compared to an alternative multi-link concept. Additionally, the design did not add mass to the body structure for brackets, cross-members and reinforcements, which are needed for other suspension concepts.

The suspension components were optimized using FEM calculation and supported with forming simulations to assess part manufacturing feasibility.

Chassis components such as lightweight steel wheels, electrical parking brake, electro-hydraulic brake system, tailor welded blanks and wishbones utilizing high strength steels have contributed to surpassing the mass reduction target.

Engine and Transmission Concepts

One of the program targets for ULSAB-AVC was CO_2 emissions (<140 g/km) therefore, the selection of the powertrain (engine and transmission) was one of the most important tasks. In order to fulfill program requirements, another important task was to include options for both diesel and gasoline engines.

To achieve the total vehicle performance of acceleration and top speed, both concepts needed to provide sufficient power and torque. The selection of engine displacement was based on program targets with the CO_2 emissions calculated according to NEDC 2000 driving cycle requirements.

The engine type was determined based on the calculated engine displacement and the engine bay concept considerations. To reduce the engine width and optimize available package space, the VR principle for locating the cylinders in a 15 degree angle with one common cylinder head was chosen.

The transmission also had to fit within the defined package space and was therefore designed in a way that it would provide the possibility for a primary drive chain connection with the engine. For ULSAB-AVC, it was decided to use a manual transmission with an automatic gearshift actuator to achieve the lower CO_2 emissions and additionally, to reduce the number of parts with the elimination of a gear shifter and clutch pedal. The driver changes gears by simply pressing a button on the steering wheel or has the option to use an automatic shift mode.

Materials and Processes

The goals for the ULSAB-AVC Program are focused on the development of steel-intensive concepts that could be introduced from 2004. Therefore, it was appropriate to consider, to a large extent, the application of new types of high strength steels, the so-called "Advanced High Strength Steels" (AHSS). These grades, exhibit higher rates of work hardening than conventional steels and therefore, have the potential for higher crash energy absorption. In combination with their good press formability these steels grades can contribute significantly to project objectives.

Since ULSAB-AVC is a concept program, the portfolio of steels available for selection was expanded to include those steels that are currently under development and will be commercially available by 2004. Additionally, because the program required high strain rate properties for conducting crash simulation, steels grades considered were further limited to those for which these properties were available.

The initial steel selection was made by PES based upon static strength requirements and experience. Then, using a Simultaneous Engineering Approach, the ULSAB-AVC Consortium's Material Working Group determined the ultimate grade of steel to best satisfy manufacturing feasibility and performance requirements of each component. For the more complex components, forming feasibility was assessed through the use of one-step forming simulations. The formability of some of the more challenging parts, which were designed to use tailor welded blanks or hydroforming, and all outer panels, were subjected to incremental FEA simulations. During all these assessments, opportunities to utilize higher strength, lower thickness and/or lower costs were continuously assessed.

In the ULSAB-AVC body structure, the AHSS grades represent approximately

82% of the body structure mass, of which 74% are DP grades, 4% are TRIP and the grades with the highest strengths available – CP and martensite steels – account for the remaining 4%.

Tailor welded blanks were used extensively in the ULSAB-AVC Program (> 30%). The advantages of this type of design are well accepted by the automotive industry. The Active Hydromechanical (AHM) sheet hydroforming process was considered as an alternative to conventional stamping for the manufacture of the closure panels for mass reduction reasons.

ULSAB-AVC relies on established arc-, spot-, and laser-welding technologies. Laser welding assembly became essential for joining hydroformed parts or other close sections with the vehicle structure.

CAE Analysis Results

Computer Aided Engineering (CAE) techniques were used in the ULSAB-AVC concept design program as a tool to evaluate the structural concepts.

The following load cases were analyzed to predict the structural performance of the ULSAB-AVC C-Class and PNGV-Class vehicle concept structures:

- Static Torsional Rigidity
- Static Bending Rigidity
- Normal Modes

The following impact events were analyzed to predict crashworthiness of the ULSAB-AVC structure:

- US-NCAP - 100% frontal crash at 35 mph (56 km/h) into rigid barrier
- Euro-NCAP front crash - 40% overlap offset frontal crash at 64 km/h into deformable barrier
- US-SINCAP - US side impact barrier impact at 38.5 mph (61.6 km/h)
- Side Pole Impact - side impact into rigid pole at 20 mph (32 km/h)
- Rear impact - moving barrier crash at 35 mph (56 km/h)
- Roof crush/Rollover
- Low speed impact - 100% front crash at 15 km/h into rigid barrier

A good compromise has been achieved between the US-NCAP front impact event and the Euro-NCAP offset frontal impact. The final structures demonstrate crash pulses, which are comparable to Four-Star and Five-Star US-NCAP vehicles at the same time having stable occupant compartments and reasonable levels of footwell intrusion for the Euro-NCAP offset frontal impact.

The C-Class and PNGV-Class concepts demonstrate good structural characteristics for the US-SINCAP and Side Pole Impact events. Low levels of intrusion velocity have been achieved for the US-SINCAP. These results are comparable to Five-Star SINCAP vehicles.

The rear crash performance for both ULSAB-AVC designs show good results for fuel system integrity and deformation in the rear seat area. The ULSAB-AVC structures also demonstrate good performance for the Roof Crush/Rollover condition.

Aerodynamic Drag Assessment

Computer Fluid Dynamic (CFD) analysis was done for the ULSAB-AVC Program as a method to evaluate the aerodynamic concept of the C-Class and PNGV-Class vehicles from the very beginning of vehicle concepts, where no hardware models were available.

The results from the initial study of aerodynamic performance of both the C-Class and PNGV-Class vehicle confirm the potential to achieve the target c_w of 0.25.

Subsystems

The ULSAB-AVC vehicles incorporate subsystems, which have been chosen for mass reduction potential with particular attention to packaging and advanced design. The front set structure design concept features a modular design based on a single cross-car beam, to which the entire seat structure and trim components are attached prior to vehicle installation. The rear seat structure design is based on a 2-seat 60/40 split. This concept provides additional cargo space by means of tilt-and-stowage of the rear seats.

The instrument panel structure was designed for stiffness to support the steering column with a DP 350/600 straight tube. The 40 L capacity fuel tank is made of two stampings of Mild steel 140/270 and shares the same fuel filler routing for both vehicle classes.

An adjustable pedal system was developed as a result of the decision to utilize a fixed seating concept. The pedal system was developed to integrate functions and combines the attachment of accelerator and brake pedal, the electric hydraulic brake unit, foot rest and guide rail housing. Drivers can find their ideal pedal position by unlocking the gas strut and manually pushing the system forward.

The front fascia module consists of fascia, bumper beam with crash box, radiator intake, duct and radiator closeout module. The radiator closeout module is a hybrid design combining nylon and steel.

The engine cover module integrates the HVAC system, intake air filter, engine service module and is pre-assembled prior to delivery to the final trim line. The engine cover hybrid module is made of nylon with a steel reinforcement, also integrating the function of lower HVAC unit housing and wheelhouse cover rear.

Considerations for development of the wiring system on ULSAB-AVC included replacement of conventional wiring with Controller Area Network (CAN), utilization of load free switches, integration of switches into electronic modules, use of smart power switches in control units, placement of control switches near the actuators and diagnostic information using CAN.

NVH

In the ULSAB-AVC Program, the basis for good NVH characteristics for the vehicles has been established by surpassing the global mode targets. The next step for NVH optimization was to determine the measures and their mass to achieve good NVH performance overall. The body structure design concepts and the package (location of engine, exhaust, etc.) were reviewed and the measures to be taken were specified using engineering judgement.

The areas of optimization were identified as

- Airborne noise absorption

- Anti-booming measures
- Bypass noise sealing
- Interior components

Final Trim Line Assembly

The ULSAB-AVC vehicle incorporates modular component subassemblies into the vehicle design. Therefore, having these modules preassembled, and supplied trackside by approved suppliers can reduce the assembly process. Current practices do not usually incorporate such modular approaches and typically most subassemblies would be built trackside which would increase the overall time and area required for vehicle assembly. The closure panels are delivered trackside from the paint shop, where they are sub-assembled into modules where required, and attached to the vehicle. The assembly process was then reviewed for the best utilization of manpower and robots, based on the volume requirements.

For the purpose of this report, the vehicle assembly has been categorized into the following subassemblies:

- Underbody Installation
- System Installation
- Interior Trim Installation
- Miscellaneous Installation
- Vehicle Hookup
- Closures and Glazing
- Miscellaneous Installation
- Vehicle Testing and Preparation for Shipping

CO_2 Emissions and Vehicle Performance

Based on the total vehicle mass and other CO_2 emission influencing parameters calculated for the C-Class and PNGV-Class vehicles with both engine variants (diesel and gasoline), the CO_2 emissions and vehicle performances were calculated in accordance to the New European Driving Cycle (NEDC 2000) and the US Combined driving cycle.

The calculations for the C-Class vehicle in both vehicle variants for both automatic and manual shift mode showed in each configuration, the target of less than 140 g/km has been surpassed. The C-Class diesel variant showed significantly lower CO_2 emissions than the targets.

The calculations for the PNGV-Class vehicle in both vehicle variants for both automatic and manual shift mode showed in each configuration, the target of less than 140 g/km has been surpassed. The PNGV-Class diesel variant showed significantly lower CO_2 emissions than the targets.

The achievement of the EU4 Exhaust Emissions targets by 2005 are dependent upon developments being undertaken by automotive companies and their suppliers. The results achieved by the ULSAB-AVC Program provide an excellent basis for such related developments.

Program Achievement Summary

In comparison with the C-Class average benchmark body structure mass of 243 kg, the ULSAB-AVC C-Class has achieved a mass reduction of 41.22 kg. In comparison with the PNGV-Class average benchmark body structure mass of 263 kg, the ULSAB-AVC PNGV-Class has achieved a mass reduction of 44.76 kg.

Both the C-Class and PNGV-Class closure structures, which were designed utilizing the findings of the ULSAC studies, have surpassed the targets with the C-Class closures (including structure and assembly parts) achieving 55.200 kg and the PNGV-Class closures (including structure and assembly parts) 60.762 kg.

Chassis and suspension components also surpassed their target, achieving a 182.053 kg. The front suspension including subframe surpassed its target by more than 6 kg, whereas the rear suspension by more than 16 kg. A lightweight steel wheel concept was integrated into ULSAB-AVC achieving a 16.208 kg mass.

In comparison with the program targets, the total vehicle masses have been significantly surpassed with the C-Class diesel vehicle achieving 966.263 kg, the C-Class gasoline vehicle achieving 932.963 kg, the PNGV-Class diesel achieving 1030.893 kg and the PNGV-Class gasoline achieving 997.593 kg.

Economic Analysis

Part of the ULSAB-AVC Program was a cost assessment to estimate the manufacturing cost without logistic cost of both the ULSAB-AVC vehicles concepts (C-Class and PNGV-Class).

Due to the different degree of detail design for the vehicle components in this concept phase and the great variety of different fabrication methods, several cost assessment methods were used to establish the manufacturing cost of both ULSAB-AVC designs:

- Technical Cost Modeling
- Supplier Cost Assessments
- Expert Judgements

The following cost elements were considered and included in the manufacturing cost definition of the ULSAB-AVC Program:

- Fabrication costs of all vehicle parts (including tooling)
- Press shop, body shop, paint shop and final trim line cost elements were considered including material, direct labor, energy, equipment, tooling, building, maintenance, overhead labor (indirect labor directly connected to the manufacturing process)

Process data for stamping, tailor welded blanks and sheet hydroforming were determined and used as fabrication input data for body-in-white parts, which were assessed in the technical cost modeling approach.

Purchased parts were defined with the vehicle broken into subsystem modules and parts. For these subsystems, suppliers provided cost assessments.

Based on assembly sequences and joining specifications of body structure, liftgate, decklid and hatch, body-in-white assembly costs were estimated.

A final trim line model with the final trim line sequence was developed to establish the best utilization of manpower and robots.

The ULSAB-AVC cost model provides a platform for understanding the costs of all aspects of manufacturing an entire vehicle. The model tracks the costs of all parts in the vehicle, production of subassemblies and the final assembly process. Emphasis is placed on understanding the costs of metal fabrication and assembly processes, which are modeled in considerable detail.

The manufacturing costs of all ULSAB-AVC designs were assessed by using different methods of cost estimation. Therefore, an error estimation of the approach to calculate an idea of accuracy was done. An exemplary calculation for the PNGV-Class gasoline version showed that with a desired confidence level of 80%, the manufacturing costs will be within a bandwidth of approximately ±6% relative to the cost assessment.

Sensitivities analysis were performed to demonstrate the effects of changing key process variables and assumptions on the cost results and include sensitivity of the overall vehicle cost, the cost of the assembled body-in-white and an analysis of different process cycle times for those parts fabricated using sheet hydroforming.