5. LIGHTWEIGHT VEHICLE STRUCTURES

A. Lightweight Stainless Steel Bus Frame: Phase III

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Contractor: Autokinetics Inc.
Contract No.: 4000010114

Objectives

- Investigate and demonstrate the mass saving potential of ultra-high-strength stainless steel as applied to the structure and chassis of a full-size urban transit bus.
- Finalize design and analysis and build a full-scale prototype of the body structure and chassis.
- Investigate all of the fundamental feasibility issues related to the structure and chassis
  1. Fabricate and test large lightweight stainless steel sandwich panels
  2. Fabricate roll-formed, high-strength stainless steel sections
  3. Test feasibility of lightweight stainless steel cantilever seats
  4. Design and fabricate lightweight stainless steel independent suspension
  5. Integrate the traction motors into the suspension design

Approach

- Execute the basic body structure, including the floor and roof sandwich panels, pillar assemblies, longitudinal rails, and suspension subframes.
- Choose prototyping techniques that emulate the intended production process as closely as possible to aid in developing robust but cost-effective manufacturing techniques essential to meeting the objectives of the project.
- As computer-based design and analysis details of the bus develop, conduct hands-on physical experimentation in parallel to support the concepts and methods.

Accomplishments

- Finished the floor panel—(completed but made obsolete by enhanced design).
- Delivered the roof and floor panels—(completed but made obsolete by enhanced design).
- Fabricated subframe and wheel house components.
- Completed tooling and fixtures for the pillars and subframes.

- Completed the subframe subassemblies.
- Completed the pillar subassemblies.
- Produced a hybrid power train compatibility report.
- Produced an investigation and selection report dealing with suspension components.
- Produced an investigation and selection report dealing with traction motors.
- Developed design enhancements for suspension subframes.
- Developed design enhancements and process plan for sandwich panels.
- Fabricated a sample panel and tested it to extreme load.
- Designed and fabricated fixture and equipment for sandwich panel welding.
- Fabricated and tested all sandwich panel segments.
- Developed design for front and rear crash-energy absorbers.
- Performed analysis and testing of stainless steel, energy-absorbing tubes.
- Developed design of specialized resistance welder for joining sandwich panel segments.

Future Direction

- Complete the design and building of a segment welder for joining panel edges.
- Assemble the primary structure of the bus.
- Complete the fabrication and installation of suspension components

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Introduction

Advanced technology transit bus concepts have made significant advancements in terms of light weight and fuel economy. However, these gains have come at the expense of higher manufacturing costs. In spite of attempts to use life-cycle costs to justify their purchase, initial cost remains a major obstacle to the introduction of fuel-efficient buses.

Autokinetics was approached by the Office of Heavy Vehicle Technologies (OHVT) of DOE to attempt to solve this problem. Specifically, the OHVT asked Autokinetics to develop concepts for a lightweight urban transit bus based on the use of high-strength stainless steel. In the passenger car field, Autokinetics had developed structural and manufacturing techniques for the cost-effective use of stainless steel in spaceframes and suspensions. The OHVT wanted to determine whether this approach could be applied to transit buses as well.

The program was structured in three phases:

- Phase I – Initial Concept Development
- Phase II – Concept Verification and Initial Design
- Phase III – Final Design and Prototyping of Body and Chassis

Phase I and Phase II have been successfully completed. Phase III will result in a full-size body structure and suspension that will be tested statically and dynamically. The development of an optimized hybrid powertrain and other vehicle systems will be addressed in a separate project.

This project was unusual in that no formal mass or cost targets were given. The object was to save as much mass and cost as possible.

Pillar Subassemblies

In this reporting period, the previously roll-formed pillars were spot-welded to the attachment brackets that will connect to the edges of the floor and roof panels at final assembly. The fixturing of this pillar subassembly provides the dimensional control that will set a consistent distance between floor and roof panels in the finished vehicle. The complete set of pillar sub-assemblies for the bus is shown in Figure 1.

Figure 1. Pillar subassemblies.

Floor and Roof Sandwich Panels

Perhaps the single most important technical development in the entire bus program is the ongoing effort to successfully fabricate stainless steel sandwich panels for the floor and roof. These panels are simple in concept and potentially inexpensive to manufacture, but our experience has shown that attention to detail and proper execution are essential for success.

The decision to use corrugated cores as opposed to honeycomb cores was made early in the program. The small loss of structural efficiency is more than offset by the substantial cost savings. Corrugated cores can readily be roll-formed in large quantities, and can be attached to the face sheets by welding rather than bonding or brazing. A literature search revealed that at least two types of welding had been used to make this type of sandwich panel. Resistance welding techniques were developed first, followed by laser welding. A supplier experienced in making both types of panel was contacted. It was jointly decided to make the panels for the bus using laser welding.

Laser Welded Panels

The fabrication of laser-welded sandwich panels was begun in FY 2002. The completion of a full set of 4 × 8 ft panel segments has been reported on previously. The final butt-welding of the floor- and roof-panel assemblies was delayed. This was the result of the poor fit-up between the individual panel segments, making laser butt-welding of the as-fabricated panel segments impossible. After initial unsuccessful attempts to TIG-weld the joints resulted in excessive distortion, the supplier attempted to weld the panels together using a hybrid laser/MIG welding technique. This also resulted in excessive distortion. In an effort to salvage the existing hardware, the panel segments were sent to an outside supplier to have all the mating edges laser trimmed to produce an accurate enough fit to allow the laser butt-welding. This solution required a deviation from Autokinetics' design intent. After trimming, one-half of the face sheet butt-welds were in an unsupported location. To overcome this, T-shaped backup bars were added to provide the support required to clamp and weld the seams between subsections. This stopgap measure added approximately 300 pounds to the weight of the finished panels.

To implement the welding procedure, the supplier completed the design, fabrication, and installation of a specialized fixture for clamping and supporting the floor and roof panels because the edges of the individual panel segments are laser butt-welded together. This fixture was used in conjunction with the panel transporter (supplied by Autokinetics and described below) to perform the final assembly welding of the floor and roof panels.

The degree of difficulty and potential for damage associated with handling and transporting the very large corrugated panels seemed to justify the construction of a special panel transporter. The primary objectives were to protect the edges of the panels and provide enough support to prevent the panels from buckling. This could be accomplished by clamping a channel-like structure along the edges of the panels. Additionally, such a device may be useful to hold and align the panels during final assembly, as it provided a continuous full-length straight edge. A design was developed to assist final panel assembly as well as ensure the integrity of the panels during transport. The design consisted of standard 6-in. steel channel around the periphery of the panels. The large surfaces (top and bottom of the transporter) were spanned by plywood.

The procedure was to stand the transporter on edge and incrementally feed the panels in through the removable ends as the subsections were welded together. Once complete, the finished panel was secured in place by tightening the wedge-like clamping blocks between it and the inside of the channel section. The transporter was designed to be compatible with the Autokinetics lifting rig so the entire unit could be lifted by crane from a single point. Additionally, a hand maneuverability method was developed to move the transporter through tight quarters. This consists of a specially designed "trailer" axle and dolly.

A set of laser-welded floor and roof panels was delivered by the supplier to Autokinetics in February 2003, more than 8 months behind schedule. The finished panels consisted of 17 segments that had been butt-welded together to form a one-piece roof and a three-piece floor (designed to be joined to the suspension subframes to complete the floor assembly). Initial inspection of the panels revealed that many of the laser welds were unattached. This raised a concern about the integrity of the remaining welds. A sample section was sent to Oak Ridge National Laboratory (ORNL) for inspection with a new non-destructive, infrared imaging technique. The images showed minimal attachment in most of the welds examined. At this point, destructive testing was considered appropriate, and it was found that most of the welds could be popped apart quite easily with a screwdriver, showing a dramatic lack of penetration. The reason for the poor weld integrity has not been explained by the supplier, but it is likely the result of incorrect weld parameters, or inconsistent clamping, because earlier samples had shown the material to be quite weldable. With no viable plan to repair the defective welds or inspect the quality of the remaining welds, the panels were deemed not usable and therefore had to be rejected.

Resistance Welded Panels

Based on the lessons learned, Autokinetics began investigating the resistance welding alternative. It was felt that this approach may be better suited than laser welding for low-volume series production, which is characteristic of bus manufacturing. In addition, parts holding, fixturing, and process/quality control were all identified as areas in need of improvement. This was considered of significant added value to the project and received the approval of DOE project management. AK Steel, a partner in the project, generously offered to contribute additional custom-rolled stainless steel and brake-formed corrugated cores for the fabrication of the new panels. To investigate the potential quality and strength of resistance-welded panels, a sample roof panel measuring 2 × 8 ft was made and tested by Autokinetics. As is seen in Figure 2, the flatness and quality of this panel is far superior to that of the laser-welded roof panel on which it is resting. A static load test rig was designed and constructed to apply a uniformly distributed bending load to the

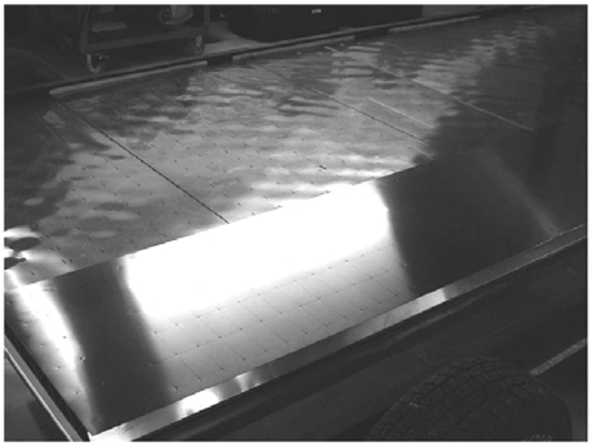

Figure 2. Sample resistance welded roof panel on top of laser welded roof.

Figure 3. Panel static proof load test rig.

face of the panel. The load is applied by four hydraulic cylinders through a set of distribution beams. The hydraulic pressure is measured to calculate load. This arrangement is shown in Figure 3. The sample panel easily supported the load required by the Altoona Bus Research and Testing Center with no permanent deformation. The applied load was progressively increased to more than five times the Altoona required load. The permanent deformation was only on the order of 1/32 in. No weld failures occurred at any point in the testing. The magnitude of this safety margin indicates that the sandwich panels may be over-designed, and future additional weight savings may be possible.

The floor and roof panels were redesigned with a different edge configuration to facilitate the joining of the segments using resistance welding. Initial tests indicate the resulting joints will be robust, with little or no distortion. A process plan was developed for the series production of sandwich panels. A key element of this plan is a concept for a pair of automated spot-welding fixtures capable of maintaining flatness and alignment of the elements of the sandwich as they are being welded. These fixtures would use multiple electrodes and transformers to perform a full row of spot-welds simultaneously. With this plan as a guide, a prototype nonautomated welding fixture was designed, which simulates the production process fairly closely. The prototype panel welding fixture is shown in Figure 4. A standard single-point welding gun was modified by extending and reinforcing the arms so that the center of a 4 × 8 ft panel could be reached. Locating features on the fixture and on the welding tips aided the rapid and accurate placement of each weld. After this simple manual fixture was set up, a full set of floor and roof segment panels was completed in about 2 weeks. The flatness, alignment, and lack of distortion in this set of panels were far superior to those of the earlier laser-welded panels. This will greatly facilitate the final assembly of the bus structure.

To ensure weld integrity, the static loading fixture, which was used for the sample panel, was employed to apply a proof load to every floor- and roof-panel segment. The applied loads were equivalent to three times the Altoona requirement for the floor and four times the Altoona requirement for the roof. No weld failures or permanent deformations were observed. This simple and quick nondestructive quality control test is a practical enough procedure to be used in production.

Figure 4. Prototype panel welding fixture.

Suspension Subframes

The suspension subframes also were extensively redesigned to improve the structural efficiency, simplify the fabrication, and make the floor-panel fabrication easier. Instead of welding each subframe to the bottom of the floor panel, the new subframe design replaces a section of the floor panel. This has the benefit of breaking the floor panel into three more manageable subassemblies, and it eliminates the trimming operation around the wheelhouses. It also has the functional benefits of increasing the ground clearance and improving underbody aerodynamics. This effort was not a specific deliverable of the project, but was considered important for the success of the program. The design for the prototype that was built is shown in Figure 5.

All of the stainless steel components for the front and rear subframes and wheelhouses were laser cut and brake formed by 3-Dimensional Services in only 10 days. The quality and workmanship were outstanding. During this time, Autokinetics completed the rather minimal fixturing for the subframes. The subframes were designed to be somewhat self-fixturing using precision, laser-cut gage holes. The subframe and wheelhouse components were delivered to Autokinetics where they were welded together using a combination of spot welding and TIG welding.

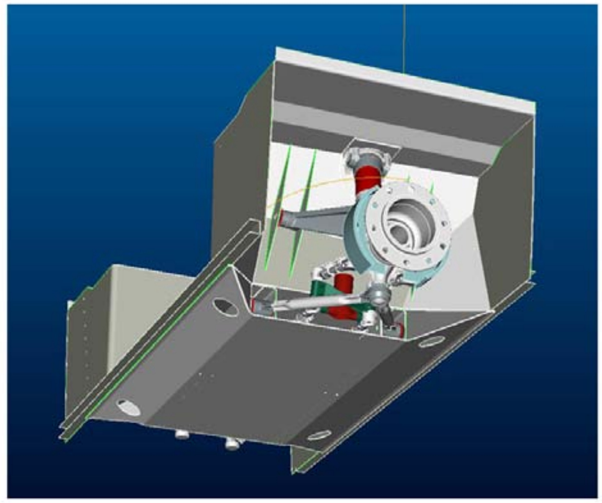

Figure 5. Suspension subframe design.

Suspension / Driveline

An important aspect of the design strategy for this bus is to develop a versatile platform that can accommodate a wide variety of advanced propulsion systems. To support this strategy, Autokinetics completed an investigation into the compatibility of the new bus design with various potential combinations of advanced propulsion components. Viable packaging solutions were found for all of the configurations studied. These included small diesel engine/generators, microturbine generators, and fuel cells.

The traction motors and controllers were ordered from PreMag. This involved considerable interaction with PreMag to specify a suitable mounting interface and to accommodate the somewhat enlarged cooling provisions. As of the date of this report, the motors and controllers have not been received and are seriously behind schedule. PreMag claims to have had difficulty with the molding of the stators. If PreMag is unable to deliver in a reasonable amount of time, an alternate motor supplier will be used.

The initial bearings selected during suspension concept development were reviewed by Timken, who found them to be undersized. A new bearing was selected and the rear suspension successfully repackaged around it. The front suspension has not yet been updated, but no serious difficulties are anticipated.

Crash Energy Management System

Autokinetics has independently developed a unique crash energy management system for passenger vehicles based on the inversion of stainless steel tubes. This concept was adapted for use on this bus project. As can be seen in Figure 6, the front bumper of the bus is supported by a

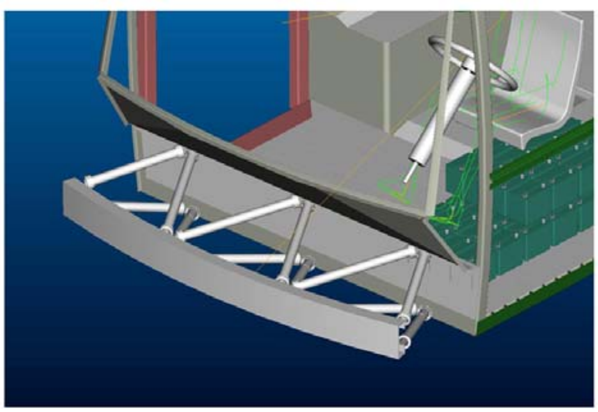

Figure 6. Crash energy management structure.

set of 12 round tubes in a triangulated arrangement. Each tube is attached at both ends by a bendable "plastic" hinge (not shown in the illustration), which limits the amount of bending moment that is applied to the tube. On impact, the tube is driven onto a forming device that turns the tube inside-out, thus absorbing large amounts of energy.

The energy-absorbing tubes have been tested by Autokinetics, AK Steel Research, and General Motors Research. A force vs. displacement curve indicates that the E/A tube very closely approaches an ideal constant force device. Drop-tower testing performed at GM Research indicates that very little strain rate effect is associated with this material. It is hoped that future testing at the High Strain Rate Facility at ORNL will more accurately quantify this finding.

Non-linear finite element analysis of the tube inversion process has been performed by Autokinetics using ALGOR software. The mesh size has been considerably refined compared to earlier analysis, and it shows fairly good correlation with test data. The analysis tool will continue to be used to investigate changes in material properties, wall thickness, tube diameter, and inverter radius.

Design of Specialized Segment Welder

Preliminary welding tests indicate that the panel segments can be successfully joined together using resistance welding. It is expected that this method will result in far less distortion than MIG, TIG, or laser welding. It will also be faster and more consistent.

A specialized spot-weld gun will be required to reach at least halfway across the floor and roof. This welder, along with its support stand, has been designed and is being built. Completion is expected by mid-November. This equipment is not a specific deliverable of the project but is being built at Autokinetics' expense. After the welder is operational, the final assembly of the bus body structure will begin. An illustration of the framing assembly sequence is shown in Figure 7.

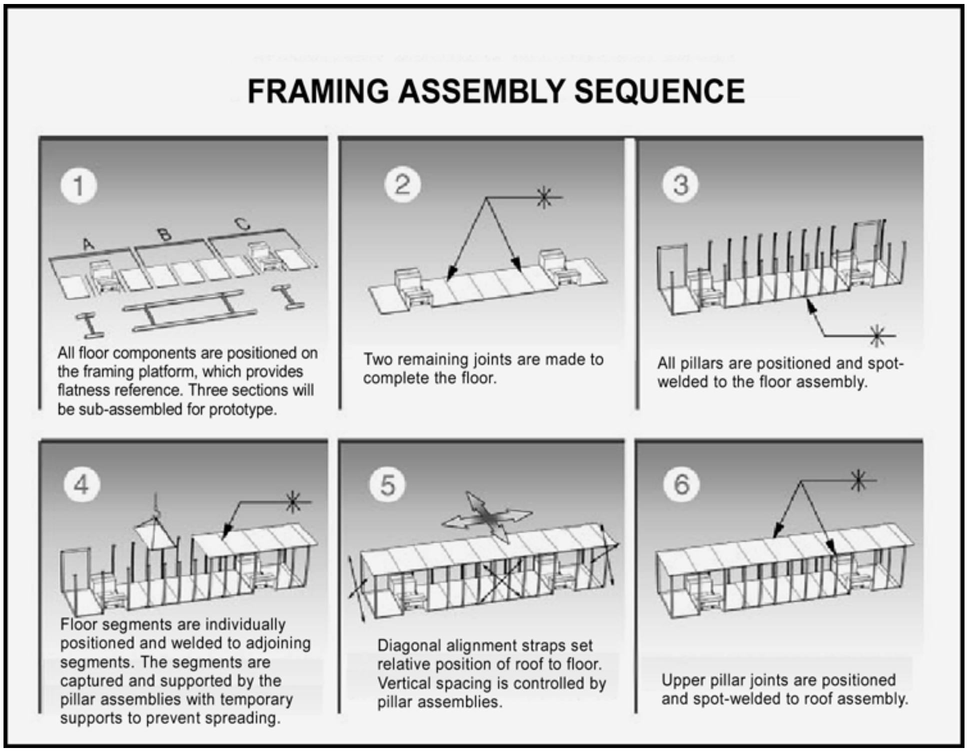

Figure 7. Framing assembly sequence.

Dissemination and Commercialization

11/5/02—JBE presentation to WestStart/Calstart—Technical Assessment Committee. Response was very favorable, and WestStart support was recommended.

11/5/02—Meeting with GET to discuss commercialization in Japan. Ray Geddes and Koichi Okuda attended. (Ray Geddes has since passed away. The status of the GET effort is currently unknown).

11/7/02—JBE attended WestStart Advanced Transportation Industry Conference in Los Angeles.

2/19/03 thru 2/21/03—JBE attended "Clean Heavy Duty Vehicles for the 21st Century" Conference sponsored by WestStart in Tempe, Arizona.

10/01/02, and 1/09/03—Meetings and continuing communication with John Friedl, entrepreneur, who is developing a business plan to manufacture commercial delivery vans using Autokinetics' structure technology.

Conclusions

Over the course of the past year, Autokinetics has become increasingly confident that high-strength stainless steel has the potential to achieve mass reductions of bus structures on the order of 60%. It also appears that this can be achieved in a practical and cost-effective manufacturing system, using existing processing technology. The ability to form, cut, weld, and cast stainless steel into strong, lightweight structures has now been well demonstrated. Almost all of the major body structure components have now been fabricated, so little if any schedule slippage is expected in the mass prediction for the body structure.

B. Large Castings for Advanced Cab Structures

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Contractor: Pacific Northwest National Laboratory
Contract No.: DE-AC06-76RL01830

Objective

- Develop the design for a prototype cast structural component for use in an advanced heavy truck cab design.
- Evaluate cast structure performance and durability under simulated vehicle service conditions.

Approach

- Contract with the Alcoa Automotive products group to assist in the detailed design and manufacturing assessment tasks associated with the effort.
- Collaborate with Freightliner to conduct in-kind design development and manufacturing process studies to determine the economic and technical feasibility of the large casting process for cab structural components.

Accomplishments

- Completed the design of a large one-piece cast cab component that will replace the fabricated multipiece cab component.
- Conducted finite element modeling analyses, which showed that the redesigned cast component meets simulated durability and crashworthiness requirements.
- Completed evaluating the use of self-piercing rivets for joining cast-to-wrought aluminum materials under static and dynamic loading conditions.
- Completed the final report for the project, detailing the design features and overall performance.
- Held a final project review at Freightliner to review the design and cost models.

- Determined that if a large casting capability becomes available, large cast components can be cost and performance competitive with more conventional fabricated assemblies in Class 8 heavy truck applications.

Introduction

Current manufacturing methods used for lightweight aluminum truck cabs typically involve the assembly of numerous simple detail parts and assemblies using rivets and mechanical fasteners. Although cost-effective and durable, this materials and manufacturing approach often limits part shape and complexity; it dictates the use of constant sheet or extrusion wall thickness, and it requires labor-intensive assembly. Developments in casting technologies for large casting size and reduced wall thickness offer the opportunity to design and manufacture complex, highly shaped components using relatively inexpensive tooling and casting process technology. The purpose of this project was to explore the potential of using large aluminum castings in selected truck cab structural component applications.

Project Approach

The project involved the selection of a large, complex cab component that was suitable for redesign into a large casting. Design development and structural analysis of the component led to a final large casting design. Under contract to Pacific Northwest National Laboratory (PNNL), Alcoa Automotive Engineering was tasked with development of the large casting design. Alcoa, PNNL, and Freightliner staff met several times to select a design for a component that was suitable for the ultra-large casting process being developed in parallel by Alcoa. PNNL investigated the issue of joining wrought to cast aluminum materials using self-piercing rivets, and the component design was engineered so that self-piercing rivets could penetrate through the casting and into the wrought material. Following component selection, Alcoa developed a design for an optimized large casting that incorporated variable wall thickness, cast features for pass-through and mounting brackets, and the incorporation of multiple fabricated parts into a single casting envelope. All casting design features were selected to be compatible with the Alcoa ultra-large casting process.

After development of the digital component design, Freightliner staff conducted static and dynamic structural and crash analyses of the component using existing cab models. These analyses resulted in several design modifications prior to finalizing the design. As part of the final design report, Alcoa completed a cost model for the casting for the component at two different production volumes. In both cases, the cast component was found to be competitive with the existing fabricated parts, assuming that the large casting equipment had sufficient casting work (other components) to keep the facility fully utilized.

As a result of Alcoa's decision not to complete commercialization development of the ultra-large casting process, the PNNL/Freightliner team determined that there was not sufficient reason to continue with the proposed prototype stage of the project. The project is now considered complete.

Conclusions

The project studying large casting for cab structures was completed with the development and analysis of a large cast component design. The final design resulted in a 27% reduction in weight and a 70% reduction in part count. Under typical production assumptions, it appears that a large casting is cost competitive with the baseline fabricated component.

C. New-Generation Frame for Pickup/Sport Utility Vehicle Application

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Contractor: Pacific Northwest National Laboratory
Contract No. DE-AC06-76RLO 1830

Objective

- Evaluate the design of an optimized hybrid materials frame that represents a new generation of pickup/sport utility vehicle (PU/SUV) frame applications and vehicle architecture.

Approach

- Apply high-risk manufacturing and design methods to the PU/SUV frame to reduce mass while meeting cost goals consistent with a high-production vehicle.

Accomplishments

- Completed vehicle testing by DaimlerChrysler at the DCX Proving Grounds using a PU/SUV platform equipped with the hybrid frame.
- Proved through accelerated testing that (1) the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements, and (2) the frame was probably somewhat overbuilt and heavier than required, even with a substantial weight reduction.
- Established performance, packaging, and weight targets for the second iteration of the new-generation frame “the next-generation frame” (NGF).
- Created a design for the NGF that projects a greater weight reduction and a decrease in the number of parts compared with the current steel baseline frame.
- Created a computer-aided engineering (CAE) model of the NGF to evaluate impact; noise, vibration, and harshness (NVH); and durability of the NGF.
- Made CAE and design iterations for attachments based on the early findings of the durability analysis.

Future Direction

- Complete the CAE/design iterations. Data generated from the CAE model results and the characteristics of the high-risk manufacturing methods chosen for the NGF will be used to establish a test plan.
- Validate the CAE analysis by DCX using a dynamic sled test of the front section of the frame.
- Evaluate challenging attachment sections of the frame by laboratory testing at Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL).

Introduction

Increased consumer demand for PUs/SUVs has resulted in increased fleet fuel consumption. The trend toward consumer demand for PUs/SUVs has been predicted to increase. By 2005 the fuel demand for this class of vehicle will exceed that for passenger automobiles.[1, 2] The objective of this project is to explore manufacturing methods and materials to reduce the mass of the SUV/PU frame, thereby reducing fuel consumption for this class of vehicle.

During the second quarter of FY 2003, DaimlerChrysler completed vehicle testing at the DCX Proving Grounds using an SUV/PU platform equipped with a hybrid frame. Results of the accelerated testing have proved that (1) the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements, and (2) the frame was probably somewhat overbuilt and heavier than required even with a substantial weight savings from the current baseline steel frame.

The next phase of the project will evaluate the use of a lighter frame, the NGF. The NGF uses a CAE approach and higher-risk manufacturing technologies. The projected weight for the NGF, shown in Figure 1, is lighter than the previously tested new-generation frame and requires 35% fewer components.

Approach

The successful accelerated testing of the next-generation hybrid frame indicates that further road testing as an evaluation tool will not be required, and the CAE design will be validated by dynamic "sled" tests of full-size front-ends and high-strain-rate mechanical testing of critical components at ORNL. Strain rates used for the dynamic tests will be determined by the CAE impact simulation, and results will be compared with results from the sled tests.

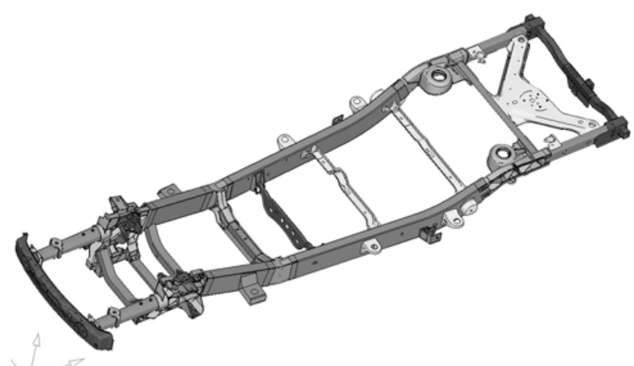

Figure 1. Next-generation frame design.

Progress

Preliminary CAE results indicate that there are no major structural design faults in the NGF and that minor adjustments to attachment points will be required to lower the predicted stress in all areas of the frame to desired levels. Differences were observed in the NVH response of the NGF and of the baseline steel frame. The complete NVH analysis is performed using an entire vehicle model to predict driver and passenger comfort level. Initial review of the NVH data indicates that the response can be tuned to match the baseline frame by re-design of attachment brackets, which would have minor effects on the frame design.

Future Direction

The CAE/design iterations shall be completed. Data generated from the CAE model results and the characteristics of the high-risk manufacturing methods chosen for the NGF will be used to establish a test plan. The CAE analysis will be validated by DCX using a dynamic sled test of the front section of the frame. Challenging attachment sections of the frame will be evaluated by laboratory testing at PNNL and ORNL.

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