12. Materials Crosscutting Research and Development

A. Technical Cost Modeling

Principal Investigator: Sujit Das
Oak Ridge National Laboratory
P.O. Box 2009; Oak Ridge, TN 37831-8048
(865) 946-1222; e-mail: dass@ornl.gov

Technology Area Development Manager: Dr. Carol Schutte
(202) 287-5371; e-mail: carol.schutte@ee.doe.gov

Field Technical Monitor: C. David Warren
(865) 574-9693; e-mail: warrencd@ornl.gov

Primary Participant: Susan Schexnayder - University of Tennessee, Knoxville

Contractor: Oak Ridge National Laboratory (ORNL)
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Objectives

- Address the economic viability of new and existing lightweight materials technologies.
- Develop technical cost models to estimate the cost of lightweight materials technologies.

Approach

- Address the economic viability of lightweight materials technologies supported by Lightweighting Materials (LM) technology area development.
- Use cost modeling to estimate specific technology improvements and major cost drivers that are detrimental to the economic viability of these new technologies.
- Derive cost estimates based on a fair representation of the technical and economic parameters of each process step.
- Provide technical cost models and/or evaluations of the "realism" of cost projections of lightweight materials projects under consideration for LM Technology Area Development funding.
- Examine technical cost models of lightweight materials technologies that include (but are not limited to) aluminum (Al) sheet; carbon-fiber (CF) precursor and precursor processing methods; fiber-reinforced polymermatrix composites (FRPMCs); and methods of producing primary Al, magnesium (Mg), and titanium and Mg alloys with adequate high-temperature properties for powertrain applications.

Accomplishments

- Completed the cost-effectiveness analysis of a 40% body and chassis weight-reduction LM goal for 2009. Carbon-FRPMC and aluminum part applications would be necessary to achieve the weight reduction goal. A significant reduction in material or fuel prices is essential to achieve the cost-effectiveness even from a life cycle cost perspective. For OEMs perspective of cost-effectiveness at the vehicle retail price level, a combination of material and fuel price reduction would be necessary.
- Completed the life-cycle analysis (LCA) of carbon-fiber reinforced polymer-matrix composites. Life cycle energy was found to be quite similar between conventional textile- and renewable lignin-based precursor carbon fibers, but with about 10% reduction in CO2 emissions in the latter case. Life cycle energy savings in the order of around 30% could be achievable with the theoretical 50-60% weight reduction potential of carbon-FRPMCs relative to conventional stamped steel.
- The Phase 1 life cycle assessment of a magnesium front end was completed and two papers were either published or accepted for publication. Large magnesium structural parts can provide both life cycle energy and environmental benefits. Additional benefits of automotive magnesium use are anticipated with improvements in Pidgeon primary magnesium production process and increased magnesium recycling with the development of sorting technologies for the efficient separation of the magnesium and aluminum rich fractions at the end-of-vehicle life.

Future Direction

- Perform the joint Ontario-DOE LCA study on natural-fiber-reinforced bioresinmatrix composites for automotive applications.
- Perform the cost-effectiveness analysis of a 50% body and chassis weight-reduction LM goal for 2010.
- Participate in the Phase II of the Canada-China-US collaborative life cycle analysis of magnesium front end research and development project with the focus on the examination of effects of advanced powertrains on vehicle lightweighting by magnesium and alternative magnesium primary production and recycling technologies.

Life Cycle Analysis (LCA) of Carbon-Fiber Reinforced Polymer Matrix Composites (carbon-FRPMCs)

A LCA of carbon-FRPMCs was completed to compare the potential energy and environmental impacts of alternative carbon-fiber precursor materials and production technologies for manufacturing a representative automotive part. In this case, the floor pan of a North American (NA) built, 4-door, large, luxury; rear-wheel-drive vehicle was selected. Although the focus is on the carbon-fiber production step using alternative precursor materials, other life-cycle stages such as part production, vehicle use, and part recycling/disposal are also considered. Conventional textile-based polyacrylonitrile (PAN) and a renewable resource material such as lignin are the two carbon fiber precursor materials considered for the analysis. Lignin is currently isolated from the chemical pulping of wood for paper production, but the byproduct generated during the cellulosic ethanol production provides an alternative, inexpensive resource which has been considered in this analysis. Sheet molding compound and powdered performing, P4, followed by compression molding in each case are the two part manufacturing technologies considered for the floor pan. End-of-life recycling of carbon-FRPMCs by the thermal treatment method developed by Argonne National Laboratory was also considered. Vinyl ester and polyester are the resin matrix materials considered for P4 and sheet molding compound technologies, respectively. For comparison purpose, hot-dipped mild steel has been considered as the baseline.

Most Life Cycle Inventory (LCI) data collection for various technologies at various life cycle stages was done by contacting directly the industry personnel involved in the development of such a technology, particularly in the case of lignin-based carbon fiber production technology. Data collection for conventional textile-based carbon-fiber production technology was based on the data available from a commercial production facility. Commercial LCA software, SimaPro, containing some of the LCI databases for commercially available processing technologies, was used for the comparative LCA of alternative carbon-FRPMC floor-pan production technologies. The LCA under investigation considered not only the positive (lightweighting vehicles for reduced energy and emissions) and negative (energy use and emission during part production) aspects of carbon-FRPMC use in light-duty vehicles but also recommendations for improved environmental impacts when using this material.

Carbon fiber production is estimated to be about 14 times more energy-intensive than conventional steel production, consistent with the earlier published results in the literature. Lignin carbon fibers have the potential to be less-energy intensive, which are estimated to require 5% less primary energy and emit 22% less CO2-equivalent greenhouse gas emissions than the conventional PAN-based textile grade acrylic fibers. A significant amount of renewable biomass use in lignin carbon fiber production causes its CO2 emissions to be significantly lower. The precursor production step contributes roughly 35% of the total energy used for carbon fiber production. Thus, any alternative energy-efficient processing technologies for the conversion of precursor into carbon fiber could significantly reduce the total carbon fiber production energy use. Since part manufacturing for both carbon-FRPMC part and conventional stamped steel part requires a small share—about 12%—of total energy, it is the higher energy content of carbon fibers in the carbon-FRPMC floor pan that results in it being about 12% more energy-intensive than conventional steel floor pan.

There exists variability in energy use based on the type of carbon fiber precursor and the manufacturing technology used. Since lignin carbon fiber and P4 are the least energy-intensive, lignin/P4 technology is estimated to be the most favorable alternative technology requiring about 312 MJ/part compared to 56 MJ/part for the conventional stamped steel. SMC technology is more energy-intensive than P4 technology not only because of the more energy-intensive SMC technology, but also because the matrix material—polyester resin—is more energy-intensive than the vinyl ester resin typically used for the P4 technology. It is to be noted that energy estimates provided here are based on primary energy and therefore may be on the high side compared to a few estimates available in the literature. For example, the 2005 paper by Suzuki and Takahashi indicates energy required for carbon-FRPMC chassis and body parts are estimated to be 234 MJ/kg and 155 MJ/kg, respectively with the assumption that energy consumption for carbon fiber production would reduce considerably to 286 MJ/kg with the increased throughput and process efficiency.

With a weight reduction potential of 17% where the objective has been to capitalize on the material's strength to optimize the crash performance rather than to reduce weight —lower than theoretically possible using random carbon fiber—for the carbon-FRPMC floor pan, life cycle primary energy use is estimated to be quite similar to the conventional steel part, especially when considering the uncertainty in LCI data that exists from using numerous sources in the literature, as shown in Figure 1. Life cycle primary energy use is estimated to be around 18,000 MJ/part. Due to the small energy difference that exists for various precursor-based carbon fibers and part manufacturing technologies and contribution they make to the total life cycle energy use in addition to assumed lower weight reduction potential, lignin/P4 technology offers the most net life cycle energy benefit of about 123 MJ/part. Two technologies among the four technology-combinations considered, i.e., PAN/SMC and lignin/SMC are about 500 MJ/part more energy-intensive than the conventional stamped steel part. Although the use life cycle stage is the dominant contributor to energy use, the energy benefits at this stage from the assumed 17% weight reduction potential are not high enough to reduce the overall life cycle energy use of carbon-FRPMC part. However, use of lower energy during the vehicle use phase in case of carbon-FRPMC floor pan, causes its CO2 emissions to be lower than the conventional steel part, i.e., about 9.5% reduction in the most favorable lignin/P4 technology case.

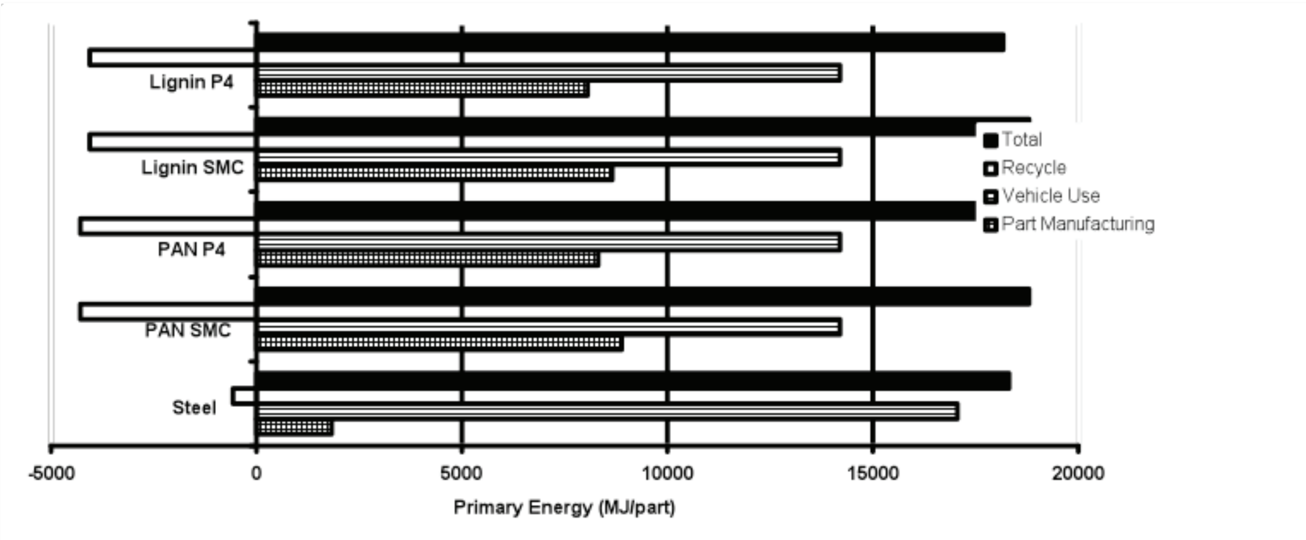

Figure 1. Life cycle primary energy estimates four competing carbon-FRPMC and conventional stamped steel floor pan manufacturing technologies.

It is likely that the use of carbon fibers in automotive applications would make economic sense when actual weight reduction approaches the theoretically possible weight reduction of 50-60% relative to conventional stamped steel. It also has been found from the life cycle energy perspective that, with a higher weight reduction potential of 43% with the use of carbon fabric compared to 17% weight reduction achieved with random carbon fiber, life cycle energy savings in the order of around 30% could be achievable. This savings would be obtained before the end-of-life vehicle unlike under the 17% part weight reduction case. An undated life cycle energy analysis of intense carbon-FRPMC application of numerous body and chassis components of a vehicle with assumed weight savings potential of 65-70% by Suzuki et al indicates a vehicle life cycle energy savings potential of 17-25%. Due to the dominance of energy use at the use phase life cycle stage, life cycle energy-effectiveness can only be achieved with increase in vehicle application areas so that higher fuel economy can be achieved with reduced weight. Another potential life cycle energy reduction strategy considered in this study is the efficient energy use during conversion of renewable lignin precursor into carbon fiber. This appears to be less effective not only due to the fact that the part manufacturing is not the largest contributor of life cycle energy use, but the net part manufacturing energy benefit is reduced since less energy is recovered at the recycle step. Depending on the carbon fiber content, recycling of carbon fibers helps in reducing more than 45% total energy content of the manufactured part.

Cost-Effectiveness of a 40% Body and Chassis Weight-Reduction Goal in LightDuty Vehicles

The Lightweighting Materials (LM) component of the DOE Vehicle Technologies Program has a 50% weight-reduction goal for passenger vehicle body and chassis systems with safety, performance, and recyclability comparable to 2002 vehicles. To achieve this long-term weightreduction goal, LM has set annual intermediate weight-reduction goals, starting with

10% in FY 2007 and finally achieving 50% by FY 2010. The focus of the current work was on the 40% body and chassis weightreduction goal of FY 2009, with emphasis on assessment of the cost-effectiveness of this goal.

Cost-effectiveness of the LM 2009 body and chassis weight-reduction goal of 40% in light-duty vehicles was assessed based on the use of lightweight material options for various body and chassis components under a plausible mid-size vehicle scenario, focusing on carbon-fiber reinforced polymer matrix composites (carbon-FRPMC) for body components in order to meet a significantly high weight reduction goal. Specific body systems considered for carbon-FRPMC include body-in-white, panels, and front/rear bumpers. In addition, aluminum was selected for several chassis components, i.e., cradle, corner suspension, and forged wheels in order to achieve the total 40% weight reduction in body and chassis systems. The analysis also considered the effect of primary weight savings of 40% on other vehicle components that can be resized while maintaining the same level of vehicle performance with the reduced vehicle weight. These weight savings are known as secondary weight savings. Due to consideration of secondary weight savings, total body and chassis weight savings is estimated to be 45%, whereas final vehicle weight savings is estimated to be 28%. The cost-effectiveness of the 40% body and chassis weightreduction goal is estimated in terms of both vehicle retail price and life-cycle cost using the detailed 35+ component level automotive system cost model developed by ORNL and Ibis Associates, Inc. Cost data of components considered for lightweight material substitution are collected from recent major studies, thereby reflecting the latest technology developments and material prices.

Even with the consideration of powertrain resizing and secondary body and chassis mass savings, carbon-FRPMC lightweight material vehicle option is not cost-effective in meeting the ALM 40% body and chassis weight savings goal from the life cycle cost perspective if the recent low gasoline price trend continues, as shown in Figure 2. The higher cost results mainly from using the carbon-FRPMC body system which is $2,200 more expensive than the baseline system. The higher cost is not offset during the vehicle operation stage. The higher vehicle retail price also affects some of the operation cost categories such as financing, insurance, and local fees which are functions of vehicle retail price. The vehicle retail price is estimated to be $1,492 higher than baseline. The life cycle cost is $1,102 higher.

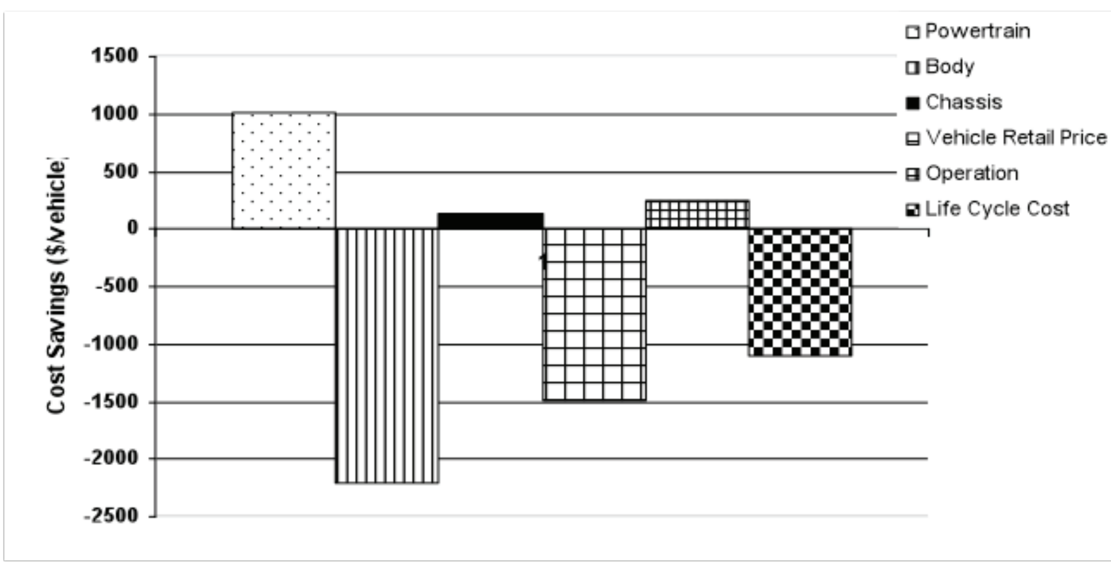

Figure 2. Estimated cost savings of 40% body and chassis weight reduction scenario.

From the life cycle cost perspective, either a change in material price or fuel price would be necessary to achieve the cost-effectiveness goal. Aluminum and carbon fiber prices need to be at $2.20/kg and $6.60/kg, respectively, whereas fuel price needs to be $4.25/gallon for the lightweight vehicle to be cost effective. It is likely that a combination of material and fuel prices would be necessary to achieve the cost-effectiveness at the level of vehicle retail price, which is the primary consideration of OEMs for determining the viability of any new vehicle technology. The extent of the necessary price changes would depend on the extent of secondary mass savings considered, with this analysis employing a conservative estimate of secondary mass savings. In contrast to this conservative estimate, General Motors 1992 Ultralite carbon body structure weigh 191 kg (compared to the 171 kg body structure in this analysis) demonstrated a super-lean 635 kg curb weight concept car—considerably lower than our estimated curb weight of 1102 kg.

Findings in this analysis are consistent with the earlier findings that carbon-FRPMC is too expensive for large scale application in light-duty vehicles today. Composite monocoque BIW designs considered in the past several studies indicate cost to be in the range of 41-73% higher than the steel unibody, depending on the type of tooling used based on the Mascarin et al. 1995 study. The technology is suited for mainly low annual production volume, and a reduction in carbon fiber price would help to a large extent in improving its viability. Vehicle platforming considerations which allow low annual production volumes would facilitate the competitiveness of carbon-FRPMC body structure. Lightweighting also improves the cost-effectiveness of advanced technology vehicles by lowering the expensive powertrain cost while maintaining the performance based as discussed in the recent 2008Aluminum Association and Das 2005 studies. Consideration of powertrain resizing, secondary mass savings, and life cycle cost perspectives would therefore be important to maximize the fuel economy gains from a lightweight structure and eventual successful market penetration of lightweight vehicles in the future. With a higher lightweighting goal, reduced material cost become more critical because it is such a large share of the total part costs particularly in low production volume production manufacturing processes. Accordingly, a current focus of DOE's lightweight materials program is the development low cost carbon fibers from alternative cheap renewable resources and high-volume processing of composites.

A Comparative Life Cycle Assessment of Magnesium Front End

The Canada-China-U.S. collaborative life cycle analysis of magnesium front-end research and development project continued with the completion of the final Phase 1 report by presentation of its results at the annual Minerals, Metals & Materials Society conference in February 2008 and SETAC North America Annual Meeting held in November 2008. In addition, a paper was accepted for the upcoming SAE 2010 Annual Congress. Verification of the life cycle inventory data for the Chinese Pidgeon process was completed and the sensitivity analyses of major parameters were undertaken. Since the vehicle use phase dominates the life cycle energy use, improved fuel economy due to lightweight is one of the most determining factors in the estimation of breakeven point for lightweight materials. The two major factors, i.e., secondary weight savings and the correlation between changes in fuel economy with change in vehicle weight have been considered for the sensitivity analysis of the vehicle use phase. Other plausible sensitivity analysis scenarios considered were based on the primary magnesium production technology, i.e., mix of Pidgeon vs. electrolytic process and improved Pidgeon process; and end-of-life magnesium recycling processes. In addition for comparison purpose, the LCA analysis of aluminum front end was also considered in these analyses.

Life cycle energy and CO2 emissions comparisons were made in terms of breakeven distance. Compared to conventional steel front end design, alternative lightweight magnesium and aluminum front end designs would achieve energy breakeven point at 33,774 km and 128,798 km, respectively. Because of extensive use of coal in primary magnesium production, the breakeven distance for GHG emissions is estimated to be higher, i.e., at 144,461 km than from the energy perspective. Due to relatively smaller component weight contribution to the overall vehicle weight, the sensitivity of various vehicle use phase parameters was not high about 1000 km from both energy use and GHG emissions perspectives for magnesium. The sensitivity results for aluminum are similar to that for magnesium, but aluminum remains more favourable than magnesium from both energy and GHG emissions perspectives. A 100% use of Pidgeon process for primary magnesium production instead of current 80% use of that process would increase total primary energy use and global warming by 5% and 8%, respectively. On the other hand, global warming will be decreased by 13% as a result of the ongoing technological improvements in the Pidgeon process. With the development of lightweight metal separation technologies resulting from the increased automotive magnesium use in the near future, magnesium recovery would increase by 11% resulting in a decrease in both life cycle primary energy use and global warming by around 5%.

Conclusions

Carbon-FRPMCs offer significant potential for reducing vehicle weight while maintaining strength and stiffness. These composites are up to 30% lighter than Al and 50% lighter than steel and can reduce the overall weight of a vehicle up to 10%. Carbon-fiber production is one of the most energy-intensive production steps in the manufacturing of carbon-FRPMCs; its CO2 emissions are estimated to be 15 times more than conventional steel on a weight basis. Low-cost and renewable precursor materials such as lignin offer significant energy and emission reduction potential in the manufacturing of these materials. A life-cycle assessment of this material has been completed to compare the potential energy and environmental impacts of manufacturing a representative automotive part, the floor pan, with a focus on comparison of conventional vs. lignin-based precursor materials technologies for carbon-fiber production. Carbon fiber production is estimated to be about 14 times more energy-intensive than conventional steel production, but lignin carbon fibers have the potential to be less-energy intensive requiring 4% less primary energy and 22% less CO2-equivalent greenhouse gas emissions than the conventional PAN-based textile grade acrylic fibers. Lignin carbon fibers would be even more favorable when no energy requirements for the production of precursor material black liquor is assumed since that by-product is currently being unused.

With a weight reduction potential of 17%—lower than theoretically possible using random carbon fiber—for the carbon-FRPMC floor pan, life cycle primary energy use is estimated to be quite similar to the conventional steel part, especially when considering the uncertainty in LCI data that exists from using numerous sources in the literature. It is likely that the use of carbon fibers in automotive applications would make economic sense when actual weight reduction approaches the theoretically possible weight reduction of 50-60% relative to conventional stamped steel. It also has been found from the life cycle energy perspective here that, with a higher weight reduction potential of 43% with the use of carbon fabric compared to 17% weight reduction achieved with random carbon fiber, life cycle energy savings in the order of around 30% could be achievable. This savings would be obtained before the end-of-life vehicle unlike under the 17% part weight reduction case.

The specific goal of LM is to develop material and manufacturing technologies by 2010 that, if implemented in high volume, could cost effectively reduce the weight of vehicle body and chassis systems by 50% with safety, performance, and recyclability comparable to 2002 vehicles. The intermediate body and chassis weightreduction goal of 40% in 2009 can be met through the use of carbon-FRPMCs in major body components in addition to the use of aluminum in some chassis components. With the consideration of secondary weight savings, a higher body and chassis weight reduction of 45% than the 40% weight-reduction goal will be achieved. Cost-effectiveness of the weight reduction goal was estimated both at the retail price and lifecycle cost levels.

Even with the consideration of powertrain resizing and secondary weight savings, cost-effectiveness of the 40% weight reduction goal wouldn't be achievable from the life-cycle cost perspective. A change in material prices of aluminum and carbon fiber or fuel would be essential. It is likely that a combination of material and fuel prices would be necessary to achieve the cost-effectiveness at the level of vehicle retail price, which is the primary consideration of OEMs for determining the viability of any new vehicle technology. Consideration of powertrain resizing, secondary mass savings, and life cycle cost perspectives would therefore be important to maximize the fuel economy gains from a lightweight structure and eventual successful market penetration of lightweight vehicles in the future.

Overall, large magnesium structural parts such as front end considered in the Canada-China-US collaborative life cycle project, can provide environmental benefits in terms of energy use and GHG emissions compared to conventional steel part within the expected vehicle life. But, overall, the aluminum design is still better in achieving the breakeven distance from energy use and GHG emissions perspectives at a less vehicle driving distance and within the vehicle life. The magnesium autopart manufacturing is more energy intensive than the equivalent part made of steel and aluminum due to the high reactivity of magnesium. Improvements in the Pidgeon process and the higher share electrolytic process use for primary magnesium production can decrease the energy requirements and the associated GHG emissions. The assumed weight reduction of 45 kg of the magnesium front end compared to the baseline steel part will provide a vehicle lifetime fuel savings of 507 liters, compared to 289 liters for aluminum part. An improvement in the sorting technology of the magnesium and aluminum rich fractions with the increase in the automotive magnesium applications would provide both life cycle primary energy and global warming savings of about 5%.

Presentations/Publications/Patents

S. Das, A. Dubreuil, L. Bushi, and A. Tharumarajah. "A Life Cycle Assessment of a Magnesium Front End," Proceedings of the 138th TMS 2009 Annual Meeting and Exposition, held on Feb. 15-19 in San Francisco, CA, Magnesium Technology 2009, pp. 179–184 (2009).

A. Dubreuil, L. Bushi, S. Das, and A. Tharumarajah. "A Comparative Life Cycle Assessment of Magnesium Front End Auto parts," paper accepted for presentation and publication at SAE 2010 Annual Congress, to be held in Detroit, MI on Apr. 13-15, 2010.

B. K-12 Outreach Program in the Southern Regional Center for Lightweight Innovative Designs

Principal Investigator: Mark F. Horstemeyer
Center for Advanced Vehicular Systems (CAVS) Chair in Solid Mechanics & Professor, Mechanical Engineering, MSST
206 Carpenter Bldg., PO Box ME
Mississippi State, MS 39762
(662) 325-7308; e-mail: mfhorst@me.msstate.edu

Participants: R. C. Cuicchi, P. M. Cuicchi

Technology Area Development Manager: Dr. Carol Schutte
(202) 287-5371; e-mail:carol.schutte@ee.doe.gov

Project Manager: Magda Rivera
(304) 285-1359; e-mail: magda.rivera@netl.doe.gov

Contractor: Mississippi State University
Contract No.: DE-FC-26-06NT42755

Objective

- The Mission Eggcellence Project is designed to develop a commitment from CAVS to the children of Mississippi through curriculum instruction and competitions dealing with the design of a vehicle bumper and/or seatbelt for passenger safety.
- This instruction and student competitions will create an awareness of the importance of design in safety implications and of the real-world applications of mathematics, science, and engineering problem-solving skills.
- Mission Eggcellence will create awareness among the Mississippi school age population of future job opportunities in the State of Mississippi as well as college majors associated with these jobs.

Approach including industrial partner/collaborator and path to technology transfer and commercialization

- Create a grade appropriate curriculum with experiments and problems associated with the physics of car crashes for grades K-2, 3-5, 6-8, and 9-12. (Objective 1)
- Develop a Teacher Workshop for grades K-2, 3-5, 6-8, 9-12 teachers for training in use of the grade appropriate curriculum in the regular classroom. Equipment necessary to conduct the experiments and compete in the competitions is given to each teacher participant. (Objective 1)
- Design a competition for grades K-2, 3-5, 6-8, and 9-12 incorporating bumper design for passenger safety. (Objective 2)
- Design a competition for grades K-2, 3-5, 6-8, and 9-12 incorporating car design for passenger safety. (Objective 2)

- Publish a book containing the experiments, illustrations, competitions, and safety chapter. An electronic version will be included with the book and will contain videos of the teacher training and competitions. (Objective 3)

Milestone, Metrics and Accomplishments

- The grade appropriate curriculum is complete for K-2, 3-5, 6-8, and 9-12 grades. (Objective 1)
- The teacher workshops are designed. (Objective 1)
- The bumper design for passenger safety competition is designed. (Objective 2)
- The car design for passenger safety competition is designed. (Objective 2)

Future Direction

- Teachers from thirty-three school districts in nineteen counties have been trained. Goal is to train teachers from each of the 185 school districts in eighty-one counties in the state of Mississippi.
- Expand the competitions to regional semifinals and state finals.
- Publish a book containing the experiments, illustrations, competitions, and safety chapter. An electronic version will be included with the book and will contain videos of the teacher training and competitions.

Introduction

The Center for Advanced Vehicular Systems (CAVS) at Mississippi State University (MSU) is teaming with the local school districts and the Mississippi Children's Museum to develop a sophisticated Science & Technology area in the form of workshops in the museum with teachers to inspire young minds to explore the worlds of math, science, and engineering. We will create powerful interactive learning/teaching kits for K-12 students with a program based upon materials design, which will be supported by the American Society of Metals (ASM). It is worth explaining the Mission Eggcellence notion further as illustrative of our other ideas.

Mission Eggcellence provides students with a hands-on introduction into vehicular crashworthiness through applying basic concepts of physics (students are provided with simple definitions from physics such as mass, velocity, momentum, and energy, and how they are used during a crash), explanations of what actually happens during a crash (using the physics terms and defining what is necessary to enable passengers to survive a crash), and examples of safety devices (explanations and examples of some devices such as bumpers, seatbelts, airbags, and safety cages, used in cars and trucks, with simulations to demonstrate how they work). Other explanations provided will include manufacturer goals (creating a vehicle that is lightweight for the cheapest price possible, creating a vehicle that demonstrates good fuel efficiency, creating a vehicle that is aesthetically pleasing in appearance) versus consumer goals (a vehicle that is strong enough to protect passengers from impact, a vehicle that is light enough to provide economical fuel consumption, a vehicle that has a pleasing appearance, a vehicle that has a memory of its shape and can be repaired faster, cheaper, and easier) and the difficulties involved in balancing these requirements.

Vehicles, materials, eggs, workbooks/worksheets, and instructions will be provided to the students with which they must design a safety barrier for each team's vehicle that will prevent the egg from breaking upon impact during an impact competition. The vehicles are released upon a ramp, which is elevated to a higher degree of angle, from 15 degrees to 70 degrees, at each step of the impact competition, and the vehicle(s) in which the eggs do not break can win. The winners are determined by the lightweight designs. Competitions are expected to be state wide. Undergraduates and graduate students will play a large role in communicating the principles and overseeing the activities. They will also be used to help monitor the tournaments and mentor some of the K-12 students

Each curriculum consists of eight grade-appropriate experiments for the physics concepts of velocity, acceleration, Newton's Third Law, momentum, impulse, elastic, and inelastic collisions. These experiments include a bumper design and a car design. In the bumper design competitions for grades K-2, 3-5, 6-8, and 9-12, the bumper is tested by rolling a wooden car, with the bumper attached, down a ramp using a raw egg as the passenger. The winner is the one that can endure the steepest incline without cracking the egg. The tie breaker is the lightest mass. In the K-2 and 3-5 car design competitions, a car is designed using K' NEX pieces from a kit. The 6-8 and 9-12 car design competitions use a car designed from balsa wood. Winner is steepest incline with egg intact. The tie breaker again is the lightest mass.

Academic/Research Excellence Basis

An overarching theme of multidisciplinary design integration motivates our research as well as our multilevel educational activities in K-PhD and continuing education. Our educational approach is structured to overcome the knowledge compartmentalization and overspecialization of traditional technical education that stand as barriers to the implementation and dissemination of science-based engineering. Core university collaborations seek to empower a broad range of students, through a fusion of exciting new science-based tools with design habits of mind, team creativity, and effective multidisciplinary communication. Our Mission Eggcellence design project work will be enhanced by the emerging technology of a distributed web-based collaborative environment. We have a clear education accountability structure administered by the CAVS Chair Professor, Mark Horstemeyer. In addition, MSU CAVS has a strong extension/outreach center in which quick implementation of research is plausible.

Contributions to the long-term and sustainable engagement of the team/unit

MSU is developing an "Automotive Experience" strategic program that includes K-12, undergraduate work, and graduate level work. A new course and certificate are being developed in real time for this endeavor. For MSU to have an excellent PhD pool, we need to have aligned in the pipeline K-12 students. We are viewing these grant funds as start-up funds only, but the program will continue long into the future.

From the DOE-SRCLID Statement of Program Objectives, the transfer of knowledge obtained from the leading-edge research to K-12 educational programs is a core requirement: CAVS is required to develop an educational program to integrate lightweighting design concepts with crashworthiness into student curricula. Hence, the K-12 program is key for the K-PhD program that is progressing at CAVS for crashworthiness and safety.

Specific subtasks include:

- Develop crash kits for K-2, 3-5, 6-8, and 9-12.

- Develop competitions with crash kits for Mississippi wide contests.
- Publish a resource book with experiments, competitions, and video directions.
- Assist in the development of modules for Mississippi Children's Museum.

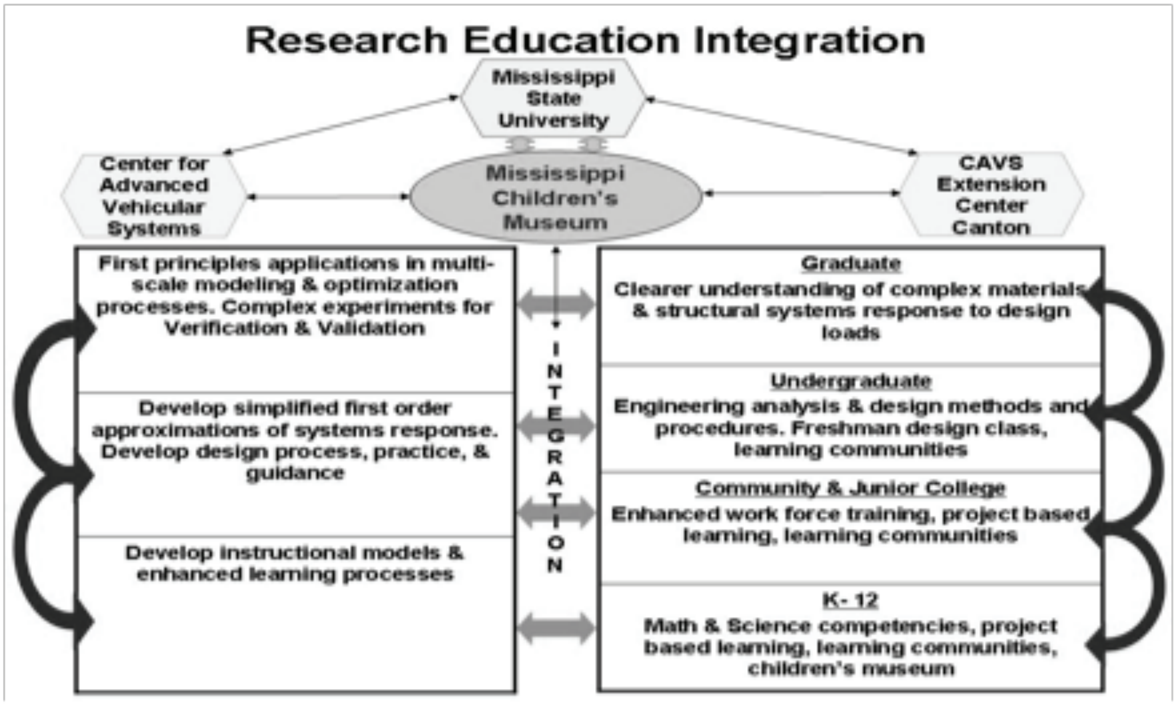

Figure 1. The schematic represents the integration of education, industry, and outreach as they will be applied in technology transfer to the children via the Mississippi Children's Museum.

The Center for Advanced Vehicular Systems (CAVS) will design materials kits and crash kits with their associated documentation (student and instructor) and provide engineering specialists as keynote speakers, trainers, and lecturers. Rosemary Cuicchi (retired teacher – 32 years experience) and Dr. Paul Cuicchi (Starkville High Physics teacher and MS Teacher of the Year 2002) is involved in developing the program. We are planning on including ASM to broaden the program further. Nissan North America (Canton, MS) and Vista Engineering Inc. have both donated in-kind contributions to the SRCLID program with specific interest in the educational development aspects of the program.

The Mississippi Children's Museum administrators and staff will be involved in designing and setting up the exhibits within the museum, as well as establishing agendas for exhibit changes. Dr. Mark Horstemeyer is helping design the regions within the children's museum to help explain the math, science, and engineering aspects.

Evaluation

The program will be evaluated both internally by MSU staff and externally by partnering organizations, committee members, and visitor surveys. External evaluations will be completed through a teacher and a student evaluation form. In addition, staff will track the number of the following:

- Individuals who participated in the special events, workshops, and programming;
- Number of events we will participate in during the next year.

Making a difference within the community and the university

University metrics will demonstrate the effectiveness of the program by showing increases in students coming to MSU, and other colleges and universities, in the fields of math, science and engineering. Within the community, we expect to see a higher rate of students becoming involved in math, science, and engineering, and in the long run, we expect to see more high-tech companies moving into the state as a result of this program. That is, if we increase the rates of students in math, science, and engineering, indicating a more highly educated future work force, the number of incoming high-tech companies will increase.

Priorities and Intended Outcomes

The priorities of this project are thoroughly integrated within the mission and vision of CAVS, especially as defined by the DOE-SRCLID Statement of Program Objectives (SOPO). Specifically, the transfer of knowledge obtained from the leading-edge research to K-12 educational programs via developing an educational program to integrate lightweighting design concepts with crashworthiness into student curricula will be accomplished by developing crash kits for appropriate educational levels and by fostering state and regional tournaments to further interest in the technology and resultant designs. The intended outcome will be increased numbers of students at all educational levels who will have a deeper understanding of math, science, and engineering, as well as an appreciation of these fields of study in real-world applications.

Inputs - The Center for Advanced Vehicular Systems (CAVS), MSU, the CAVS Extension (Canton), and the community will integrate into a synergistic teaming effort to provide staff, volunteers, time, money, basic research, materials, equipment, technology, and partners to ensure the success of this program

Outputs – What Will We Do? Personnel from the core facilities mentioned above will conduct workshops and meetings, will deliver services, will develop products and curriculum, will provide resources, will provide training, will provide counseling, will assess the program and its effectiveness, will work with the partnering organizations, and will work with media to ensure proper dissemination of information to the public.

Who Will We Reach? We will reach participants (children, parents, and teachers), providing satisfaction feedback.

Outcomes – Impacts – Short Term: We anticipate an increased interest by students in math, science, and engineering as demonstrated by improved learning, awareness, knowledge, attitudes, skills, opinions, and motivations, all a result of student participation in the workshops and so forth.

Outcomes – Impacts – Medium Term: We anticipate seeing an increase in museum student participation (Actions), an increase in classroom participation (Practice), an increase in understanding, and application of lessons-learned by students in their respective schools (Decision-making), an increase in awareness of potential impacts upon society of vehicle lightweighting and crashworthiness (Social Action), and an increase in students interested in math, science, and engineering.

Outcomes – Impacts – Long Term: We anticipate students graduating from their respective schools and entering colleges and universities to pursue degrees in math, science, and engineering who will have a stronger working knowledge and understanding of math, science, and engineering as they relate to societal/behavioral, economic, civic and environmental impacts. We also anticipate seeing an increase in the number of high-tech companies moving to Mississippi, as a result of having a more informed and more highly educated student labor based from which future employees can be selected.

Evaluation - The effectiveness of this program will be determined by follow-up investigations and over time to collect data, to analyze and to interpret the data, and to report on the increase in students who enroll in institutions of higher learning in the fields of math, science, and engineering.

Conclusions

The Mission Eggcellence Program has been developed for the grades K-2, 3-5, 6-8, and 9-12. The Teacher Workshop for these grades has been very successful. Thirty-three school districts in 22 counties have had 127 teachers participate in the teacher workshops. Five hundred sixty-four students have competed in the student competitions. Seventy-five percent of the teachers who attended the workshop had students compete in both the bumper design and car design competitions. Feedback was excellent.

C. Multi-Material Vehicle Research and Development Initiative

Principal Investigator: John K Catterall
Global Technology Engineering
30200 Mound Rd
Warren, MI 48090
(586) 218-9376; e-mail: john.1.catterall@gm.com

Technology Area Development Manager: Dr. Carol Schutte
(202) 287-5371; e-mail:carol.schutte@ee.doe.gov

Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objective

The Multi-Material Vehicle Research and Development (MMV R&D) Initiative is an umbrella focal project established in FY2006 to connect and relate the USAMP's Auto-Steel Partnership (A-SP), Automotive Composites Consortium (ACC), Automotive Metals Division (AMD), and Non-Destructive Evaluation (NDE) projects together in a "multi-materials vehicle" so that USAMP projects address vehicle level material integration issues as well as bulk materials issues. The overarching goals of MMV R&D are aligned with those of the FreedomCAR Program. It focuses on collaborative, pre-competitive, high-risk research to develop the component technologies and direct R&D in materials and processes that enable the high volume production of vehicles that are half the mass, as affordable, more recyclable, and of equal or better quality and durability than vehicles that are currently available.

The project's main near-term objective is to define new opportunities across USAMP that bridge lightweight materials R&D to applications on a donor vehicle and potential future production implementation, as well as addressing integration, joining and assembly, testing and validation, and advanced vehicle design/architectures.

The MMV R&D Initiative deliverables include:

- Vehicle Technical Specifications (crash performance, dynamic stiffness, durability, etc.) for donor vehicle for alignment of other USAMP projects
- CAD and CAE models for the baseline donor vehicle for alignment of other USAMP projects
- Baseline cost estimates for steel donor vehicle for alignment of other USAMP projects
- Gap/Needs analysis to identify inhibitors to production and manufacturing
- Attribute performance, mass reduction and cost implications for multi-material vehicle components, sub-assemblies and systems
- Promoting dissimilar material joining projects

Approach

The MMV R&D Initiative defines new opportunities across USAMP that bridge light weighting materials R&D to applications on a donor vehicles, addressing integration, joining and assembly, testing and validation, and advanced vehicle design/architectures to accommodate alternative energy powertrains. It is anticipated that the MMV will help motivate USAMP's partner organizations (suppliers, academia, and national laboratories) to accelerate research in areas of importance.

- An MMV R&D Steering Committee consisting of two representatives per OEM was formed to assess the current USAMP project portfolio, identify technology gaps, and to advocate, "bubble-up" and transition new projects in joining, integration, and assembly technologies to individual consortia or project teams across USAMP.
- Donor vehicle platforms have formed the baseline for affecting the light weighting technology improvements. The focus for the three initial technology projects addressing major light weighting initiatives is: A/SP's Future Generation Passenger Compartment (FGPC), AMD's Magnesium Front End Design and Development (MFEDD), and ACC's Composite Underbody (ACCU).
- Results from demonstration of the three initial projects on a large Rear Wheel Drive (RWD) passenger vehicle platform will be extrapolated to address light weighting strategies for other vehicle architectures.

Accomplishments

During the period October 2008 through September 2009, MMV accomplishments primarily surround either initiating or trying to initiate efforts and continuing alignment of the three USAMP body subassembly projects.

- Helped projects teams complete the donor vehicle systems-level manufacturing and assembly baseline cost modeling project.
- Continued to guarantee alignment between all three projects.
- Supported the technical and business case for a new multi-material joining R&D projects by engaging with experts in joining technologies. One new joining R&D concept feasibility project was selected for sponsorship and support – MMV704 Multi-Material Metallurgical Bond Joining to Steel, this project is now complete.
- Developed a proposal for a Lightweight 7+ Passenger Vehicle Study (L7) with the goals of; developing a generic lightweight 7+ passenger vehicle concept to demonstrate application of mixed material technologies and mass compounding towards the creation of a lightweight, cost effective vehicle to achieve at least a 40% increase in EPA combined fuel economy with no sacrifice in safety, comfort, features, utility, or performance. Phase 1 of the project was approved by the USAMP Steering Committee and is currently in the early stage of execution, as of yet there are no results to report.

Future Direction

The MMV R&D initiative will continue to help close out the three USAMP MMV projects, and remain opportunistic in attracting new project ideas from USAMP in areas such as multi-material joining technologies.

MMV will complete Phase 1 of the L7 project in the second quarter of CY 2010, present the results to the USAMP Steering Committee, and determine with the Committee whether further work in this area is warranted.

Introduction

The MMV R&D Initiative is a USAMP umbrella focal project, supporting FreedomCAR goals and timeline, with the primary objective of investigating vehicle weight reduction opportunities and issues associated with incorporating multiple materials in multiple locations.

The MMV R&D portfolio emphasizes design, joining, corrosion, energy management, manufacturing processes, and other technologies that facilitate mixed material systems that can support delivery of FreedomCAR goals by 2015.

In its first year since charter in FY 2006, the MMV team was directed by the USAMP to focus on standardization of analytical, design, cost modeling and benchmarking studies supporting the three technology projects. Longer term focus of MMV R&D will be on integration and joining/assembly technologies as well as new vehicle architectures utilizing lightweight materials and associated processes developed for manufacturing discrete parts and sub-assemblies in high-volume.

Recent significant accomplishments in program standardization are reported below under each sub-task heading.

Baseline MMV Vehicle

Previously the MMV team identified a common baseline vehicle, the GM unibody (body-frame-integral) rear wheel drive vehicle. This provided a single focus vehicle for each of the following three initial projects:

- AMD603/604 Magnesium Front End project,
- ACC Composite Underbody, and
- A/SP (Advanced High Strength Steel) Future Generation Passenger Compartment.

Figures 1 – 3 illustrate baseline modules being researched within USAMP and being held to engineering performance targets set by MMV.

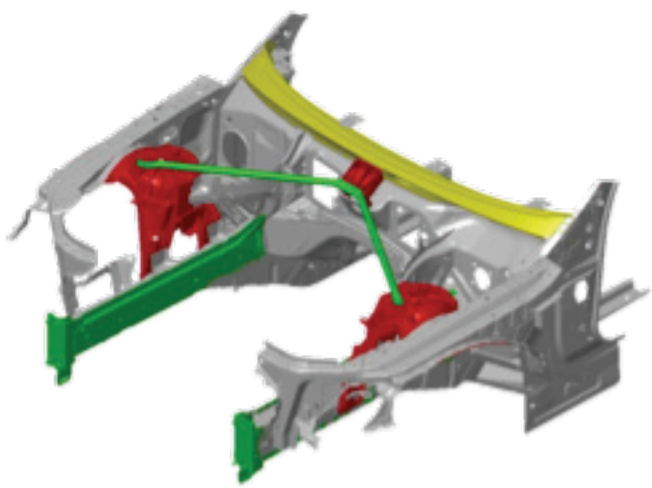

Figure 1. AMD Magnesium Front End project, (picture is the benchmark BMW aluminum front end).

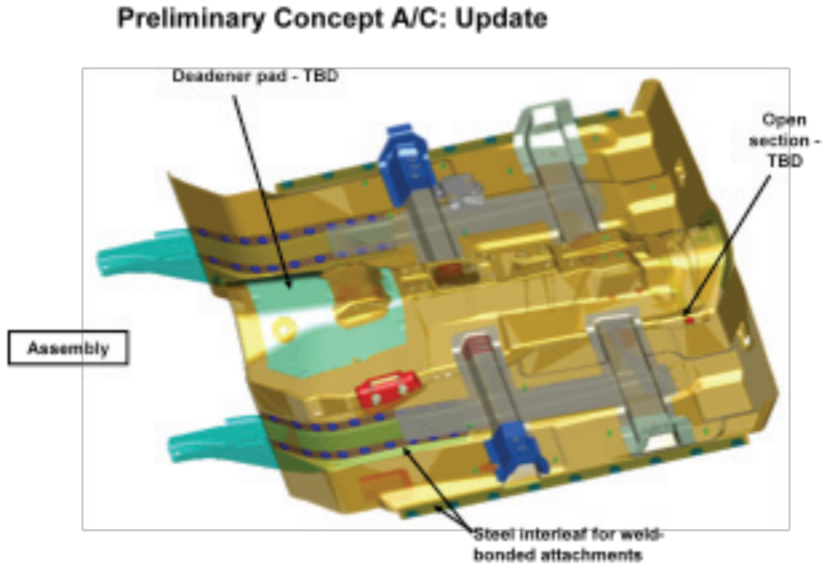

Figure 2. ACC Composite Underbody.

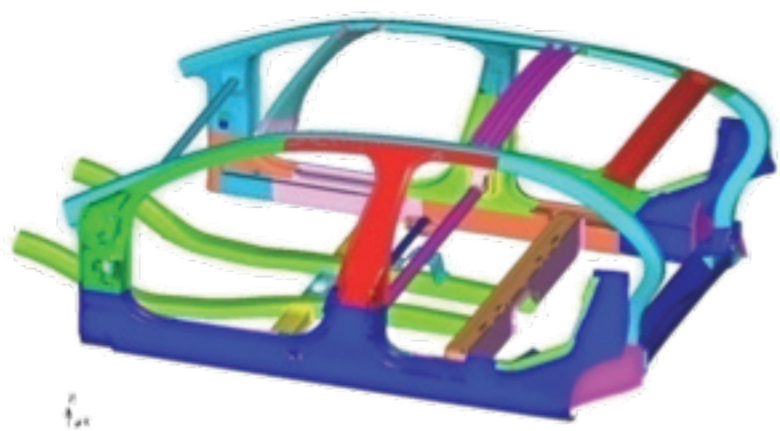

Figure 3. - A/SP Future Generation Passenger Compartment.

Common MMV Technical Specification

The MMV began FY 2007 by developing a consensus technical specification for comparisons and validation of vehicle performance modeling with respect to the large rear-wheel drive passenger donor vehicle data contributed by GM. The MMV specification was updated by team members to incorporate new FMVSS requirements and was then disseminated to all three USAMP teams overseeing the three core MMV projects. The MMV specification has been used to drive design and lightweight materials and manufacturing technology developments across the initial three projects that would be compliant to the specification.

Engineering Performance Targets

Previously MMV established the engineering targets and manufacturing goals for each of the three projects to meet anticipated 2015 functional requirements or match the baseline production vehicle performance. A tracking mechanism for assessing progress in design maturity towards meeting these targets was also established, a detailed spreadsheet is being maintained by

Multimatic (lead design vendor for the ACCU project) under contract to the MMV, and involves the regular participation and input of the other two project leaders and their respective lead design vendors.

The specific MMV engineering targets relate to:

- Structural Performance (stiffness, dynamic frequencies, mode shapes)
- Manufacturability (cycle time, paint issues, repair procedures in-plant and in-service)
- Safety (front, side, rear, roof, restraints, cargo retention, bumper requirements)
- Durability and Target Life
- Ride and Handling
- Towing and Trailer

In addition, the three projects are proposing new module designs incorporating lightweight materials which must also identify how the designs could be integrated into a full vehicle manufacturing scenario capable of producing 100,000 units per year at an affordable cost.

MMV Baseline Cost Model Development

The MMV Baseline Cost Model development has been executed by Camanoe Associates with close oversight and input from the MMV team. Camanoe has estimated the target piece costs and assembly cost for the donor vehicle and for each of the subassemblies for the three projects, the A/SP Future Generation Passenger Compartment, the ACC Composite Underbody, and the AMD Magnesium Front End. Having the cost model and estimate as a single project through MMV minimizes the work and costs to each of the three projects. Also, this effort has provided many inputs for the cost models for each of the three projects.

The results include cost estimates for the stamped steel baseline donor vehicle. The cost of each individual part has been estimated based on the material and manufacturing technique, i.e. typical stamping operations. Additionally, the cost of assembly for the full vehicle structure has been estimated based on the donor vehicle assembly process. Finally, the assembly cost of the three subassemblies matching the three projects, passenger compartment, underbody, and front end has been estimated.

Identification of Critical R&D Gaps

In parallel, the MMV team also identifies new strategies for promoting mass savings across the USAMP project portfolio including coordination with the FreedomCAR Materials Tech Team. The MMV team also resolves design/analytical information discrepancies, as well as assessing critical technology gaps and R&D needs across these three projects.

The highest priority technology development identified was in multi-material joining technology relevant to the assembly needs of the projects. A project on “Multi-Material Metallurgical Bond Joining to Steel” was completed with ORNL studying concept feasibility of using ultrasonic excitation during the casting process to create a metallurgical bond between steel inserts and aluminum or magnesium castings. This project created test criteria and identified potential production applications in order to evaluate castings made at ORNL as to their capabilities to meet the specified goals.

Conclusion

The USAMP Multi-Materials Vehicle Research and Development Initiative (USAMP701) has continued successfully building on the baseline vehicle identification, engineering, and manufacturing performance targets establishment and maintaining a consistent source for baseline design, models, and engineering performance analysis. In addition, MMV has started Phase 1 of a project to develop a Lightweight 7+ Passenger Vehicle. MMV will review the results of Phase 1 with the USAMP Steering Committee to determine if further work in this area is warranted.

D. Lightweighting Materials, Designs and Manufacturing Processes for Light Duty Vehicles

Principal Investigators: Jacky Prucz and S. Shoukry
Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, WV 26506-6106
(304) 293-3131; email: Jacky.Prucz@mail.wvu.edu

Technology Area Development Manager: Carol Schutte
(202) 287.5371; e-mail: carol.schutte@ee.doe.gov

Contractor: West Virginia University
Contract No.: DE-FC26-08NT02353

Objective

Develop, analyze and validate data, methodologies and tools that support widespread applications of lightweighting technologies for light-duty vehicles.

Approach

- Leverage experience that has been accumulated during the last six years at West Virginia University (WVU) in the areas of design, joining, and durability predictions of lightweight structures for heavy-duty, long-haul trailers and energy-dense hydrogen storage tanks.
- Identify a pilot project for a case study that demonstrates the potential for weight savings at affordable costs through integrated material-structural lightweight design, prototyping, and testing of a selected automotive component or sub-system.
- Conduct a three-dimensional finite element analysis of a 2007 Chevrolet Silverado in order to explore the mass distribution in such a vehicle and identify the most suitable structural component or assembly for showcasing the weight savings that could be, potentially, achieved through its integrated deterministic design by using lightweight composite materials.
- Develop and analyze cost-effective joining concepts for assembling lightweight automotive components, such as sandwich panels, made of fiber-reinforced composites or dissimilar materials.
- Develop a phenomenological model for plasticity and damage evolution to failure to predict the durability of fiber-reinforced, unidirectional composite materials in various application scenarios to light-duty vehicles.

Milestone, Metrics and Accomplishments

- The chassis/floor pan assembly of a Chevy Silverado has been selected to be the main case study for investigating and demonstrating through this project the cost-benefit tradeoffs associated with selected design and prototyping methodologies for structural weight reductions.

- A three-dimensional phenomenological model for plasticity and damage evolution to failure has been developed to predict the durability of fiber-reinforced composite materials in applications to light-duty vehicles.

Future Direction

- Use the theoretical results of analyzing the Chevy Silverado model to showcase through prototyping and testing the commercial/economical viability of the lightweighting approaches developed and implemented at WVU, most likely in partnership with an industrial company.

Introduction

The class of light-duty vehicles consists of cars and light trucks, minivans, sport utility vehicles (SUV's), and trucks with a gross vehicle weight lower than 8,500 pounds [1]. Gasoline-powered vehicles dominate this class in the United States. Recently, fuel economy has become a major area of public and government concern as light-duty vehicles account for approximately 40 percent of all U.S. oil consumption, and much of this oil is imported. Furthermore, light-duty vehicles contribute about 20 percent of all U.S. carbon dioxide emissions [2]. Bandivadekar et al. [3] showed that a reduction in vehicle weight and size could significantly reduce fuel consumption and greenhouse gas emissions. Direct weight reductions can be achieved through the substitution of heavy structural materials by lightweight materials, as well as through basic changes in the vehicle design, which maximize the interior volume for a given vehicle length and width. The benefits resulting from direct weight savings enable secondary weight reductions, as other vehicle components can now be appropriately downsized.

The reduction in vehicle body mass is considered to offer the greatest opportunity for achieving near-term, cost-effective reductions in fuel consumption. This led the US Department of Energy and U.S. Council for Automotive Research (USCAR) to continue and expand their research and development efforts for devising practical means to reduce the body mass of light-duty vehicles. The common approach is to substitute new materials, such as advanced high-strength steel, aluminum, magnesium, and fiber-reinforced composites, for the current materials and especially heavy structural steel. The materials industry is also investing intensive research and development efforts to advance the availability and commercialization of new, lightweight materials (such efforts are coordinated, for example, through the Auto-Steel Partnership, the Aluminum Association, and the American Chemistry Council). The application of lighter and stronger materials in place of the conventional ones in light-duty vehicles is associated, unfortunately, with higher costs resulting from either the cost of the materials themselves or the costs of component fabrication and joining.

A midsize-car body with closure panels (no trim or glass) can weigh roughly 800 lb, which is about 25% of the total vehicle weight. It is estimated that every 10 percent reduction in vehicle weight will result in an approximately 7 percent saving in fuel [4]. Vehicle testing has confirmed the reductions in fuel consumption associated with reductions in vehicle mass [5].

Estimates of the body-mass reduction that can be achieved in the near term vary from 10% (with mostly conventional and high-strength steels) to 50% (with a mostly aluminum structure). Adopting advanced materials such as carbon fibers and polymer matrix composites could produce weight reductions of 25-70%, while improved methods of manufacturing and using high strength steel can reduce vehicle weight by 15-25%. Even greater weight reductions in light-duty vehicles are feasible, but they require expensive high-performance materials or component manufacturing and assembly methods.

Vehicle interiors offer, as well, opportunities to reduce vehicle mass. Some changes can be implemented for little cost, while others at a higher cost. For example, composite-intensive instrument panels, recycled seating materials, and lighter-weight trim panels can reduce mass by tens of pounds at virtually no cost. However, those options tend to affect vehicle character, and additional costs may be incurred in offsetting negative aesthetics.

Definition of a Practical Case Study

The objective of this task is to identify specific components or systems of a light duty vehicle, as well as specific engineering materials, which are most likely to demonstrate the feasibility of drastic reductions of structural weight at affordable manufacturing costs and without compromising safety and durability.

Possible collaboration was sought with various automotive companies, such as Ford and Toyota, through the National Center for Manufacturing Sciences (NCMS), for selecting a pilot project that was as realistic and complete as possible, in terms of practical, real-life specifications, manufacturing and testing. Most automotive manufacturers appear to accept and employ structural components made of either lightweight fiber reinforced composite materials or ultra high strength steel. However, they showed no interest in employing titanium as a lightweight, high strength material, mainly because it is extremely difficult to machine. Unfortunately, no formal partnership could be established so far with an industrial company because of the economic down turn and its negative impact on the automotive industry, as well as because various concerns regarding the disclosure and handling of proprietary information.

A detailed three-dimensional finite element (FE) model of a 2007 Chevrolet Silverado, as shown in Figure 1, has been obtained for use as the base of the case study. This model was developed at the National Crash Analysis Center (NCAC) by using the LS-DYNA commercial software and was publically released in summer 2009. The model has been validated by conducting a frontal rigid barrier test. The total vehicle mass calculated from the FE model is 2,337 kg, which is 2.86% higher than the mass of the physical vehicle. The material data used for developing the FE model were derived from coupon testing [6]. The model contains 679 parts, 942,677 nodes and the total number of elements is 929,131. The mass distribution is being analyzed by using this model in order to identify components with the highest potential of weight reductions. Assuming that these will be the chassis/floor pan assembly, as expected, they will be redesigned and optimized through an integrated material-structural design approach to reduce their weight without affecting structural integrity and safety.

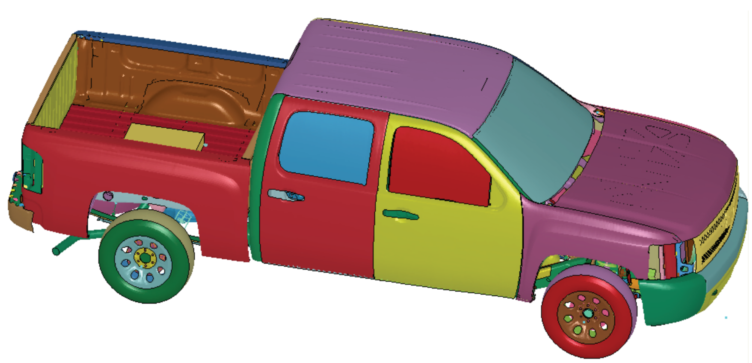

Figure 1. NCAC FE Model of 2007 Chevrolet Silverado

A comprehensive review of the pertinent literature reveals that intensive research efforts are underway to develop lightweight components for light-duty vehicles. Three main categories of advance materials appear to be pursued, as described below, as the most promising candidates for significant structural weight reductions in future light-duty vehicles.

1. Superplastically formed aluminum

Superplastically formed 5083 aluminum has been widely used in the past in aerospace applications and has been more recently introduced by General Motors, in a modified form, for selected aluminum automotive components [7]. The advantages of superplastic forming include low-cost tooling, the ability to form complex shapes, simplified die design as compared with traditional stamping, low noise and environmental impacts, and the opportunity for significant part count consolidation [8]. Although SPF is traditionally viewed as a slow-forming process, recent advances in aluminum alloys and forming process procedures have reduced typical forming times to the point where SPF appears well suited for the volumes of automotive production. However, a number of technical barriers remain, including the ability to form Class A surfaces, the availability of suitable SPF sheet materials for large components, and the field performance of SPF components and structures in automotive applications.

2. High Strength Steel

Realizing that most cars and trucks have been getting progressively heavier over the last three decades, the Research and Development arm of the Mazda Company managed to reduce the weight of a mid-size car by over 200 pounds as compared to the previous generation car. This was achieved by utilizing high-strength steels to optimize the design of the whole body to reduce the weight while improving the rigidity and crash resistance. Sixty percent of such weight savings came from engineering solutions, including optimizing the structure of the body shell while using high and ultra-high tensile steels for lower weight, higher rigidity and better crash resistance. Another 20 percent of vehicle weight was saved by adjusting certain features of the vehicle, while 20 percent of the weight was saved by decreasing the length of the vehicle by 40 mm and its height by 55 mm. These remarkable weight-saving measures make the new Mazda light-duty car a trendsetter for fuel efficiency and low carbon dioxide emissions [9].

The Materials, Manufacturing and Concepts Center of the Daimler-Chrysler Corporation has reported recently that the flexible roll forming of high-strength steel allows the production of deep-drawn parts that can achieve the tolerances required in automotive design quickly and with high precision. Additionally, the wall thickness of various body panels could be further reduced by using super high-strength steels and, therefore, achieving lightweight constructions. This in turn makes it possible to cut the weight by up to 1.5 kilograms per part [10].

3. Lightweight Composite Materials

Knouff et al. [11] have led recently a research and development effort for the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles. Class 8 tractor lateral braces were selected for such study as they offer an opportunity for significant weight savings and represent a large hurdle in terms of composite applications and market acceptance. The mass reduction target is 50% and the minimum requirement is 30%. Finite element analysis was utilized to investigate the failure mechanisms with progressive failure analysis.

In 2003, the Daimler-Chrysler Corporation completed vehicle testing that provided grounds for using an SUV/Pickup platform equipped with a hybrid frame. The results of an accelerated testing program have proven that the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements. Even though the frame of the vehicle was probably somewhat overbuilt and heavier than necessary, substantial weight savings were achieved through the hybrid configuration, as compared to the baseline of a current steel frame [12].

Durability Modeling and Predictions

A three-dimensional phenomenological model has been developed to predict the plasticity and the damage evolution to failure of unidirectional reinforced composites for automotive applications. As a first stage, classical thermodynamic and continuum mechanics principles were used to simulate all the thermomechanic conditions that govern the accumulation of failure in terms of a set of internal variables. Currently, the model is based on the small strain theory and assumes local dissipation where no heat conduction is included.

Two different types of failure mechanisms, namely plastic strain and damage evolution, have been included so far in the model, by assuming that they are independent of each other. The term "damage" is used only in the context of failure mechanisms associated with fracture, which is assumed to be always associated with a certain level of degradation in the stiffness of the material.

Three specific Helmholtz free energy potentials were formulated in order to model linear elastic, plastic, and damage accumulation types of behavior. All three were considered independent from each other, so that the total potential is expressed as their sum. The internal state variables for the elastic potential, as deduced from the strain energy density, are the total strain, plastic strain, and damage level. An isotropic hardening plasticity and isotropic damage hardening were used as internal variables for the plastic and damage potentials.

By employing the thermomechanic principles, all the needed thermodynamic forces, thermodynamic force rates, state variables rates, yield surfaces were first developed analytically and then obtained explicitly. All the state variables used in the model are defined and concisely represented in terms of second- and fourth order-tensors.

The plastic strain surface was defined on the basis of the Tsai-Wu failure criterion. The polynomial approach turned out to be inconsistent for small stress values in the fiber and the transverse tension direction, and, consequently, a quadratic formulation was utilized and analyzed for consistency. The parameters used for this purpose were the same as those used in the Tsai-Wu polynomial.

The damage surface is defined based on the energy release associated with crack growth. The levels of fracture toughness in the modes I, II, and III are compared to the thermodynamic damage forces. The damage evolution is related to typical failure mechanisms in composite materials such as fiber rupture, inter-fiber, and intra-fiber fracture.

Experimental data obtained from inter-fiber shear load-unload cycling tests are used to define the plastic and damage anisotropic associative hardening evolution. The plastic and damage thresholds were obtained by using nonlinear extrapolation. The thermodynamic isotropic hardening plasticity force was defined as a 3-order Prony series as a function of the isotropic plasticity internal variable. The coefficients of the Prony series were obtained by fitting the appropriate data extracted from the in-plane shear load-unload experiments.

Similarly, the isotropic hardening damage force was defined as a third-order exponential series, expressed as a function of the isotropic damage internal variable. The coefficients of this exponential series were obtained by fitting the appropriate data extracted from the in-plane shear load-unload experiments.

The plastic strain surface and the damage surface coefficients were obtained from the undamaged material properties, strength properties, and ultimate or critical material properties. Since the thermodynamic isotropic hardening force was obtained for the case of in-plane shear evolution, a correction was performed in the other evolutions in order to assure that failure will occur when the strength values were reached.

This model was implemented in the commercial finite element analysis software ANSYS as a new, user defined material. The results produced by the model were validated by simulating a loading-unloading tension test of a [±45°]2S composite laminate [13]. Figure 2 illustrates a comparison of experimental and calculated data.

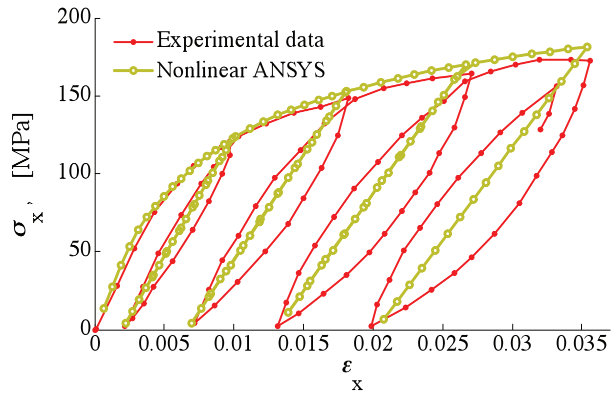

Figure 2. Experimental data with FE Results.

The new durability prediction model was also successfully used to simulate a four-point bending test of a [±45°]2S composite laminate, as shown in Figure 3 .

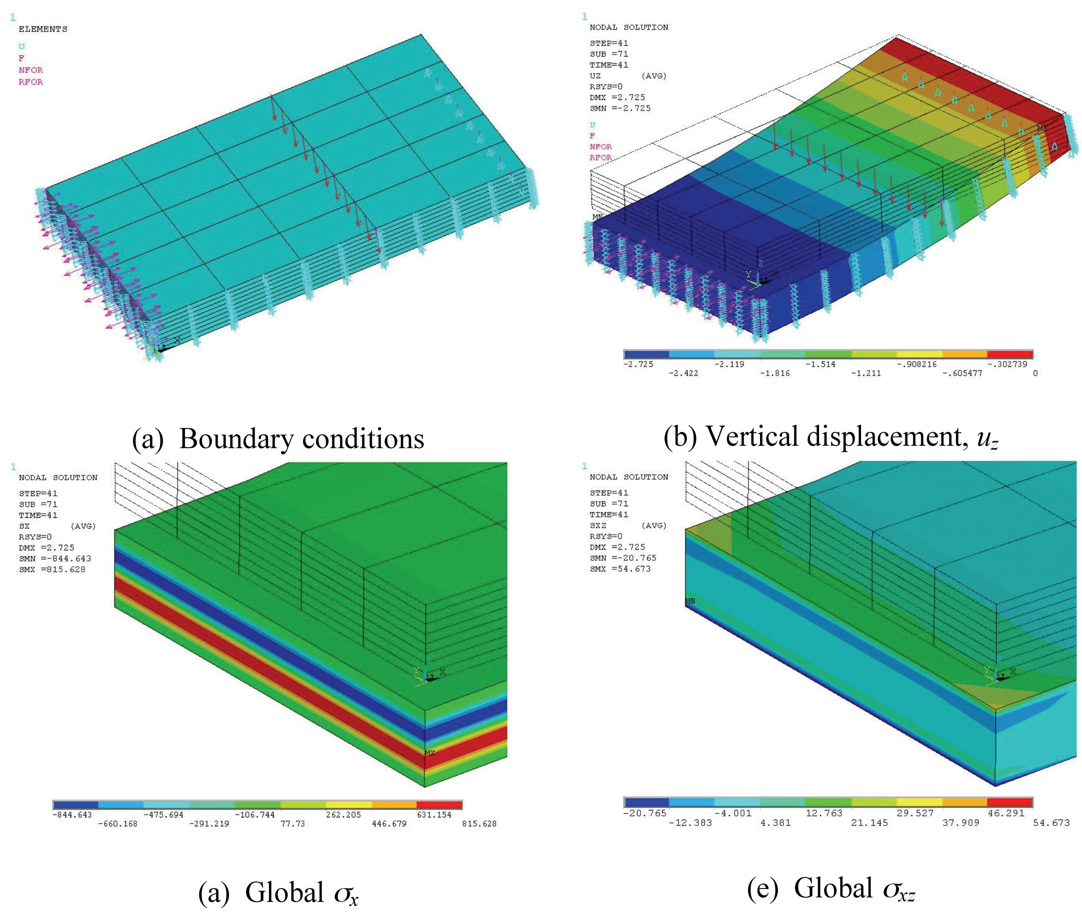

Figure 3. [0/90]s 4-Point Bending Model Using Nonlinear Ansys

Conclusions

The current state-of-the-art in the area of lightweight materials and designs for light-duty vehicles, as well as the discussions with industry representatives, indicate that weight savings of about 25% could be achieved through the adoption of ultra high strength steel. The current project pursues the goal of achieving additional weight savings in light-duty vehicles, by using carbon fiber composite materials in combination with an integrated material-structural design approach for selected components or assemblies of a 2007 Chevy Silverado.

A three-dimensional analytical / computational model has been developed for quantifying the damage evolution and the corresponding residual properties in fiber-reinforced composite laminates, with applications to automotive body panels. The model has been implemented as a new type of material in a Finite Element Analysis software package and it has been validated by using published experimental results.

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