VOLPE center The National Transportation Systems Center

U.S. Department of Transportation
Research and Innovative Technology Administration

A Summary of Proceedings for

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1. SUMMARY OF PRESENTATIONS

1.1. Panel 1: A Safety Roadmap To 2020 PCIVs: Background And Objectives

1.1.1. Workshop Opening By Nelson (Ned) Keeler

Acting Director of the Volpe Center.

Mr. Keeler welcomed the workshop participants and noted that this research project was included in the 2007 "*Points of Pride*"[1] because it will facilitate the design and development of lighter, more fuel-efficient, and safer next generation vehicles. He acknowledged the presence of the NHTSA PCIV safety research project sponsors, thanked the presenters and panel moderators and invited all participants to provide their expert inputs to assist the Volpe team in developing an improved and more detailed PCIV safety R&D roadmap.

1.1.2. "Welcome, Introduction And Charge To Participants."

Stephen Summers, Chief, Safety and Restraints Research Division, NHTSA Vehicle Safety Research Office.

Mr. Summers noted that Congress provided sustained funding starting in 2006 for NHTSA to initiate and continue a research effort "*to examine the possible safety benefits of lightweight Plastic and Composite Vehicles.*" To date, planning-oriented research products were prepared by both industry and by the Volpe Center PCIV safety R&D 2020 roadmap. The ongoing and future NHTSA-sponsored research effort aims to refine, build and implement the roadmap, by identifying promising near-term research opportunities. The workshop will help transition from planning to a sustainable, coordinated research, by providing inputs on specific roadmap priorities and steps to ensure future PCIV safety, and by identifying cooperative R&D opportunities.

1.1.3. "PCIVs: Redefining Sustainable Transportation For The 21st Century."

James Kolb, Senior Director of Automotive Programs, American Chemistry Council- Plastics Division (ACC-PD) & Suzanne Cole, President, Cole & Associates, Inc.

The ACC-PD presentation stressed the multiple benefits of increasing the use of automotive plastics from the current average of 10% by weight: improved fuel-efficiency and reduced emissions by light-weighting, crash safety, design flexibility, durability and environmental sustainability through end of life (EOL) recyclability:

"Plastics consume only a small fraction- just three percent_ of U.S. oil and natural gas"
"Substantially advancing the role of plastics in the automotive industry holds the promise of energy independence, economic growth and environmental sustainability."

Highlighted promising automotive applications of plastics include use of:

- High strength- to- weight materials, such as self-reinforced plastics (SRP) for load floors, pedestrian protection and aerodynamic applications;
- Novel polymers and plastic composites in advanced power-trains, fuel tanks and batteries for next generation hybrids and fuel cell vehicles;

[1] Posted at http://www.volpe.dot.gov/infosrc/docs/pop07.pdf

- Plastics to make SUVs less top-heavy to reduce rollover crashes, foam-filled B-pillars to help absorb impact and molded plastic door panels that incorporate integral safety features to improve side-impact crashworthiness;
- Plastics to enable future cars to have more crush space for improved safety and crash compatibility, yet be light for better fuel efficiency;
- Plastic bumpers and fenders to improve pedestrian safety in crashes;
- Corrosion-resistant composites in truck boxes and fuel tanks, to improve both durability and fuel efficiency.

He noted the federal role (Department of Energy and National Science Foundation) in funding R&D to develop predictive engineering tools for composites and called on the experts to make revolutionary changes in considering the role of plastics to enhance safety and redesign future cars, rather than as metal substitutes. The American Chemistry Council Plastics Division (ACC-PD) is currently updating its 2002 Automotive Technology Integration Roadmap report so as to complement and strengthen the NHTSA safety R&D map, to spotlight challenges and opportunities and refine R&D priorities.

1.1.4. "Status And Goals Of NHTSA Sponsored Research On 2020 PCIV Safety"

Dr. Aviva Brecher and Dr. John Brewer, Volpe Center

For the past three years (FY06-08) the Congress has funded the National Highway Transportation Safety Administration (NHTSA) to undertake research on:

"*Plastic and Composite Vehicles.--The Committee recognizes the development of plastics and polymer-based composites in the automotive industry and the important role these technologies play in improving and enabling automobile performance. The Committee recommends ($500,000) to continue development of a program to examine possible safety benefits of Lightweight Plastic and Composite Intensive Vehicles [PCIV]. The program will help facilitate a foundation between DOT, the Department of Energy and industry stakeholders for the development of safety-centered approaches for future light-weight automotive design."*

The Volpe Center was tasked by NHTSA to evaluate and summarize the knowledge base on automotive light-weighting materials safety issues, to identify national and international research partnerships relevant to PCIV safety, and to develop a PCIV Safety Research Roadmap to 2020 that highlights R&D priorities to resolve technology challenges. Initial research has focused on the review and evaluation of national and international R&D efforts (e.g., by USCAR/DOE consortia), and on assessing the state of knowledge on crash energy absorption (CEA) properties, test and performance standards and predictive mechanical performance models for composite and hybrid materials. Consensus R&D priorities for PCIV crash safety performance were identified for near, mid and long-term, based on a survey of safety and materials experts. The PCIV safety R&D roadmap[2] built on and complemented the earlier technology integration roadmap[3] developed by the American Plastics Council (APC), now the American

[2] "*A Safety Roadmap for Future Plastics and Composite Intensive Vehicles*" 2007, is posted at http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/NRD/Multimedia/Crashworthiness/4680PCIV_SafetyRoadmap-Nov2007.pdf

[3] The American Plastics Council's 2002 technology integration roadmap and 2006 workshop summary and ESV-2007 paper "*Enhancing Automotive Safety with Plastics,*" by M. Fisher, J. Kolb and S. Cole at www-nrd.nhtsa.dot.gov/pdf/nrd-01/esv/esv20/07-0451-W.pdf

Chemistry Council- Plastics Division (ACC-PD). High-leverage collaboration opportunities on R&D with selected DOE/USCAR industry consortia on automotive light-weighting materials, and with standards developing organizations, and the university based centers of excellence on plastics and composites were also identified.

Continuing Volpe Center research aims to develop in greater detail the PCIV Safety Roadmap R&D priorities identified in the report, and to define metrics and milestones for progress in PCIV safety. This workshop is designed to engage SMEs and provide inputs on specific PCIV safety issues, in order to:

- Build consensus on the PCIV Safety Roadmap R&D priorities;
- Refine fruitful near-term R&D priorities for improving crashworthiness prediction, measurement and verification for future PCIVs.
- Identify, characterize and quantify the "potential safety benefits" of proposed lightweight composites in emerging PCIV design concepts;
- Determine safety challenges and safety technology opportunities for emerging and future PCIV concepts.

Experts' inputs will be distilled and summarized to optimize payoff from the NHTSA R&D by entering into collaborative, high leverage research partnerships in the next phase.

1.2. Panel 2: Light-Weighting Materials And Technologies To Enhance Vehicle Safety

1.2.1. "Overview Of FreedomCar And Its Composites Crash-Energy Management Work."

Dr. Joseph A. Carpenter, Jr., Light-weighting Materials Technology Area Development Manager, Office of Vehicle Technologies, DOE.

The DOE Office of Energy Efficiency and Renewable Energy (EERE) Vehicle Technologies Program has maintained since 1993 a strong light-weighting materials (LM) research effort (approximately $22.3M in fiscal year 2008) as part of the Materials Technologies thrust under the FreedomCAR and Fuel Initiative. The USAMP/DOE Cooperative Agreement includes light-weighting materials R&D teams of OEMs, suppliers, and universities such as the Automotive Composites Consortium (ACC), a Multi-Materials Vehicle (MMV) activity, and other groups working on metals and high performance steel. The goals of the FreedomCAR light-weighting materials R&D program are to reduce structural mass (relative to 2004 baseline) by 50% for 30% to 40% improved fuel efficiency, to maintain 85% recyclability, and to do so affordably and with equal or better safety.

The relative weight savings and costs of light-weighting materials substitution options relative to steel indicate that carbon-fiber-reinforced polymer composites (CFRPCs) could reduce vehicle weight by 50 to 60% at a higher cost (2 to 10X) while glass-fiber-reinforced polymer composites (GFRPCs) could reduce weight by 25 to 35% with modest cost increase (1.0 to 1.5X). While a significant focus of the research has been on lowering the cost of CFRPC's production and processing, other RD&T focus areas included glazing (glass), crashworthiness, and recycling.

Two slides are reproduced below to highlight the multiple advantages of using automotive composites (Fig. 1), the most important of which is the superior CFRPC crash-energy absorption (Fig. 2).

Some barriers to light-weighting include: higher materials cost, lack of established industrial base for and familiarity with such materials, the large sunk cost in steel auto-manufacturing equipment, and consumer preference to date for large, heavy vehicles with crash safety advantages.

Ongoing lightweighting materials R&D efforts through 2010 will focus on some practical aspects of fiber-reinforced composites: cost, processing, joining, nondestructive testing (NDT), recycling, and crashworthiness. These will be demonstrated in several focal projects.

Energy management research addresses crash energy management (CEM) in general and the crash absorption of bonded structures in particular. A specialized testing machine has been developed for applications in automotive crash performance prediction.

Materials research includes R&D on improved predictive modeling of polymer matrix composites (PMCs), end-of-life recycling, and on novel natural fiber composites (NFC).

Automotive Composites Consortium research will provide input to Focal Project IV, which will develop and evaluate a prototype composite underbody, a carbon fiber sheet molding compound (SMC) hood, a composite front end structure, and a composite seat assembly. Case studies presented (cf. composite pick-up boxes in the Ford SportTrac, Toyota Tacoma and Honda Ridgeline) demonstrated advantages for both OEMs and customers. Furthermore, a holistic approach to designing new vehicles (e.g., Toyota 1/X concept car) shows the synergistic benefits (33% weight reduction and 50% fuel efficiency improvement) would result from use of CFRPCs for body and chassis in conjunction with advanced batteries and a hybrid power train. A significant challenge, however, is to preserve and improve crash safety.

Trends in automotive composites applications suggest that economic and political pressures will affect market penetration of next generation vehicles:

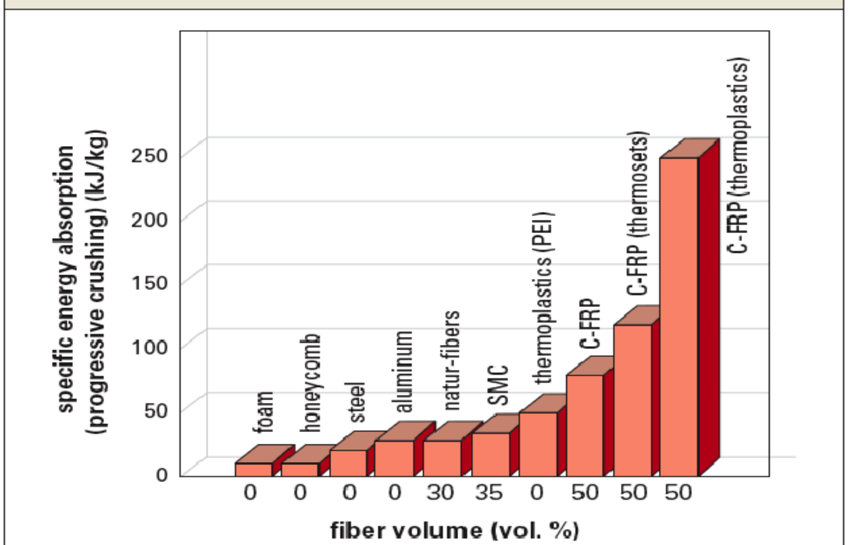
- Steel will continue to dominate in high-volume mass market vehicles;
- Glass-fiber reinforced PMCs will compete with light metals (aluminum and magnesium) at production volume over 50,000-100,000 vehicles per year;
- Natural fibers could challenge glass fibers;
- CFRPCs will continue to be used in the higher end, lower volume vehicles (less than 50,000 vehicles per year), mainly to enhance performance rather than fuel efficiency;
- The successful development of lower cost CFRPCs with lower performance specifications than for aerospace applications could open up high volume automotive applications.

Advantages of Composites in the Automotive Industry

- Weight: Reduction of 20%-40+% (versus steel)
- Styling flexibility: Deep draw panels not possible stamped in metal
- Tool Investment: 40%-60% save in part tooling vs steel
- Part Consolidation: Reduced assembly costs and time
- Customer Satisfaction: Resistance to corrosion, scratches, dents, and improvement in damping and NVH
- Safety: Highest specific energy absorption of all major structural materials

Figure 1, Advantages of Automotive Composites

Figure 15: Advanced composites' remarkable crash energy absorption
Carbon-fiber reinforced polymer (C-FRP) crush cones and similar structures can absorb ~120 kJ/kg if made with a thermoset resin like epoxy, or ~250 with a thermoplastic, vs. ~20 for steel.[309] Crush properties can also be optimized by mixing carbon with other fibers.



Source: Herrman, Mohrdeck, & Bjekovic 2002, p. 17.

Figure 2, Relative Crash Energy Absorption (CEA) of composite materials

1.2.2. "Crashworthiness Testing Of Advanced Materials."

Dr. Charles David Warren, Field Technical Manager of Transportation Composite materials Research at the DOE Oak Ridge National Laboratory (ORNL).

Dr. Warren discussed the ORNL Test Machine for Automotive Crashworthiness (TMAC) facility. This specially designed machine can deliver tensile or compressive loads up to several hundred kiloNewton (kN) at a constant velocity up to 8 m/s. A high speed, small load test machine is available for tensile tests of coupon specimens up to 22 kN in static and dynamic tests at constant speeds to 18 m/s.

The intermediate rate TMAC was developed for static and dynamic testing that complements drop tower and sled test facility data in order to shed light on the transition from static to high strain rate impacts. The performance of glass fiber reinforced composites (GFRC) is highly strain rate dependent, so good data over a full range of crush loads are necessary to characterize structural behavior during crashes. The TMAC is used by ORNL, industry, ACC and other researchers to develop both materials behavior data and predictive analytical models for crash events (see www.ntrc.gov).

The mean crush force for a composite specimen is a strong function of its geometry. It varies nonlinearly with impact speed. Strain rate-dependent GFRC tube crush data were shown. Snapshots of crush tests of a woven carbon fiber composite tube at 4 m/s and a braided glass fiber composite tube at show fine debris indicative of significant microscale failures and energy absorption. A magnesium tube at 0.5 m/s exhibited far larger debris, though it did not buckle as is common for many metallic tubes in this loading configuration.

ORNL collaborates with automotive and materials industry partners on state-of-art modeling and simulation. Recent efforts examined the behavior of joints between metal and composites. Joint integrity was quantified, including creep, fatigue, and environmental exposure damage. This research enabled prediction of catastrophic failure for multi-materials parts and hybrid structures. The ORNL TMAC facility and the analytical capabilities developed for it are open and free to industrial users willing to publish and share test results. Industry users who wish to protect proprietary information are charged a fee that allows ORNL to recover its costs.

1.2.3. "Factor Of Two: Halving The Fuel Consumption Of New U.S. Automobiles."

Lynette Cheah and Prof. John Heywood, MIT Sloan Automotive Laboratory.

The presentation summarized results of a recent MIT study co-authored with C. Evans and A. Bandivadekar[4]. Technology options to halve fuel consumption (in liters per 100 km) by 2035 relative to the 2006 baseline include both accelerating the market penetration of more efficient alternative power-trains (diesel, turbocharged, hybrids), and vehicle weight reduction. The was authors asserted that fuel consumption reductions could be realized through fleet-wide weight reductions of up to 35% by combining light-weighting, downsizing, and redesign. **Figure 3** (DOE 2007 data) displays a trend in vehicles from 1984 to 2004 of increasing mass fraction of lightweight metals, plastics, and composites. Plastics/composites currently comprise less than 10% of vehicle mass, with only a slight increase since 1984. Vehicle material substitution could further reduce weight by 20% in 2035.

[4] See report posted at http://web.mit.edu/sloan-auto-lab/research/beforeh2

The incremental cost estimates of light-weighted vehicles indicate that polymer composite- intensive bodies are more costly for OEMs: the unit cost for glass-fiber reinforced body is estimated at $400 but a carbon fiber reinforced body could be $720 to $1,100 or more, depending on production volume and economies of scale. This is comparable to aluminum unibody vehicles and much higher than high strength steel. Although there are safety concerns associated with downsizing the fleet, the MIT study concluded that lighter vehicles can be designed for safety by using structural reinforcements, side airbags, crumple zones and other safeguards. They note that, without additional measures such as these to enhance safety, lighter vehicles pose less risk to other vehicles on the road but may engender more risk for their own occupants.

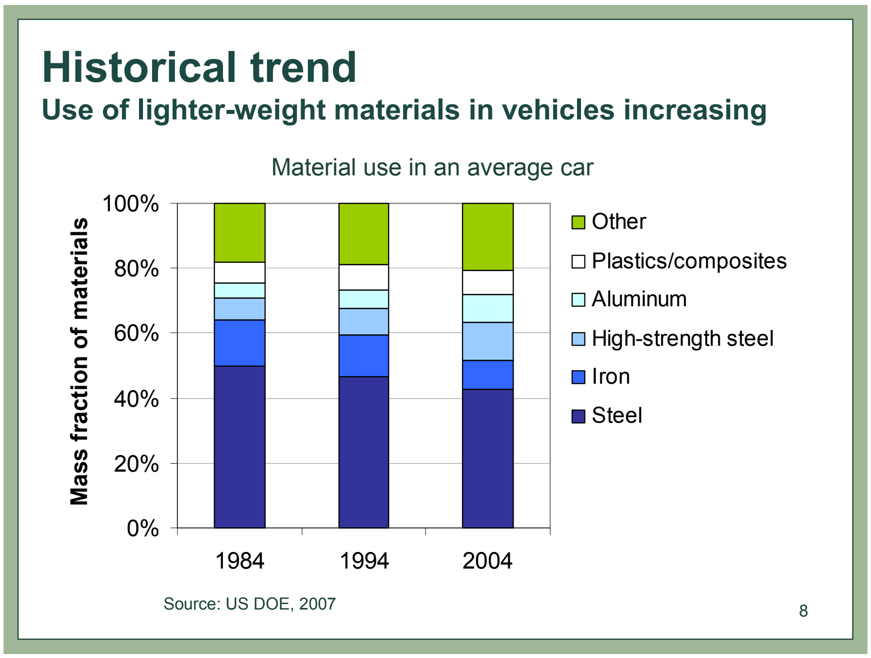


Figure 3, Trend shows increasing use of automotive light-weighting materials over time
(DOE 2007 data cited by MIT)

1.2.4. "The Real-Life Crash Safety Performance Of Small, Light Cars, And Safety Attribution Challenges."

David Zuby, Senior Vice President for Vehicle Research, Insurance Institute for Highway Safety (IIHS) Vehicle Research Center.

The presentation started with a video clip comparing low-speed (10 km/h) crash performance for two vehicles each equipped with plastic composite bumper. One vehicle performed well, limiting damage to repair costs less than $700, while the other sustained damage costing more than twice that to repair. A graph of repair cost following such crashes vs. rear bumper weight by material type indicated that the performance of plastic and composite bumpers is similar to that of aluminum and steel bumpers.

There are crashworthiness challenges for small and light vehicles, since physics and statistical crash analyses confirm that both mass and size are protective: Mass is protective in multiple vehicle crashes, since the lighter car velocity changes more. The author asserts mass is protective in single vehicle crashes since among vehicles with otherwise same characteristics, the lighter vehicle will have higher acceleration. Size protects due to larger crush zones and/or passenger space, allowing for slower deceleration of the occupants and lower intrusion risk.

A graph of driver deaths per million registrants for model cars between 1982-85, 1992-95 and 2002-05 over a wide range of vehicle weights (2000-5000 lbs.) shows that safety has improved over time due to better vehicle designs and restraints, but that death rates decrease monotonically as vehicle weight increases. Based on 2006 FARS data for new cars (1 to 3-year-old), the fatality rate (driver deaths per million vehicle registrations) are lowest for the largest vehicle in each class (cars, SUVs, and pick-ups). The fatality rates for the largest cars are lower by a factor of two than those of the smallest car.

Although some claim that smaller and lighter cars are more maneuverable and can more easily avoid collisions, the IIHS data analysis of collision-coverage insurance claims per million registered vehicles (adjusted for driver and geographical attributes) indicates that mini cars and small cars are involved in crashes at a slightly higher rate than larger vehicles. Since vehicle size (shadow or footprint) is strongly correlated with curb weight, it is difficult to know a priori the extent to which light-weighting a vehicle, while preserving size, is possible from analyses of current designs. It was noted that increasing crush zones without changing overall vehicle size could adversely impact occupants' comfort and cargo space. Better and stronger occupant restraints could restrict movements and diminish driving comfort. Therefore, the type of advanced restraints (e.g., 4-point safety belts, vests, and helmets) and vehicle designs used for light-weight carbon fiber composite racing vehicles would not be transferrable to mass market small cars. Trade-offs between vehicle size, weight, comfort, convenience, fuel efficiency and safety aspects will affect future vehicle materials and designs.

Promising safety enhancements to be deployed in all future vehicles (including PCIVs) to prevent crashes (with quantitative justification presented) include: integrated safety systems (e.g., pre-crash sensors with inflatable or expanding crush zones), and crash avoidance systems such as forward collision and lane departure warning, blind spot detection, brake assist, and electronic stability control systems (ESC).

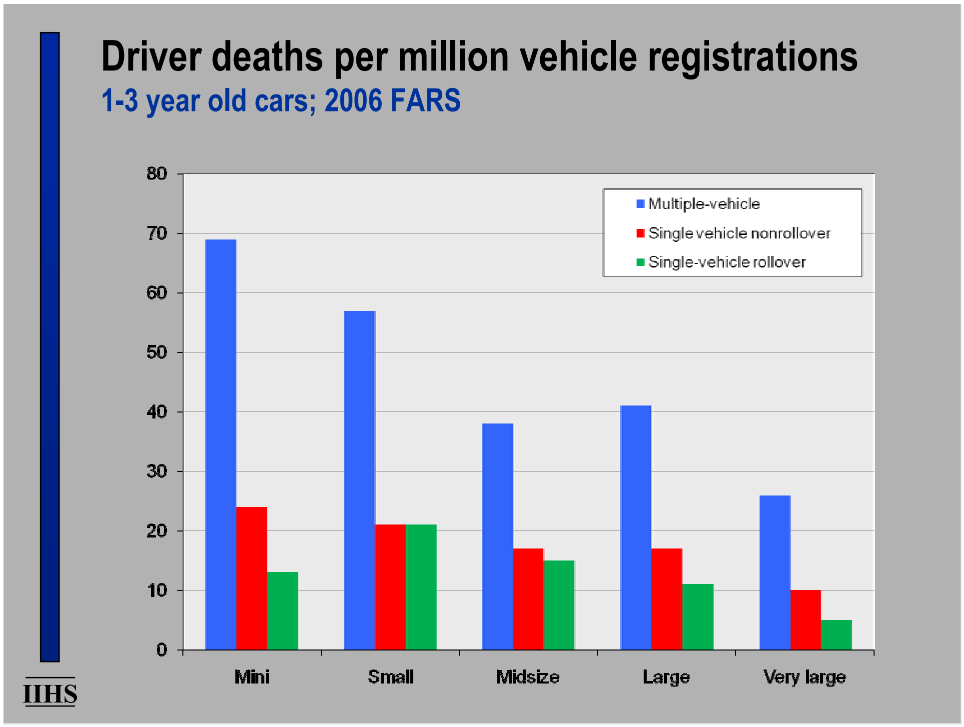


Figure 4, The 2006 FARS data show that new car driver fatality rates in multiple-vehicle crashes are nearly three times larger for mini cars than for the largest vehicles.

1.2.5. "Sustainability: A Future Worth Living For Coming Generations."

Mary Fraser, Marketing Manager at BASF Corporation, keynote lunch speaker.

The BASF philosophy is that it can foster innovations by creating value, and that sustainable development is a core value for business success for this large, global chemical manufacturer of plastics and composite automotive safety and structural products (e.g. bumpers, airbags, and foams), see www.basf.com/usa and http://www.automotive.basf.com/p02/Automotive/en_GB/portal

The BASF strategic goal to support sustainable development and environmental protection; it developed a methodology to measure the "sustainability" of their products, namely "eco-efficiency analysis (EEA)." This structured and quantitative approach integrates ecological impact assessment with economics over the product lifecycle, and promotes the efficient use of materials and energy in production, and considers environmental impacts and waste, including logistics and infrastructure. For instance, BASF plastics strive to be recyclable and biodegradable. The presenter illustrated how the 'eco-efficiency" of alternative options for materials was compared against environmental and cost factors for a 4-cylinder intake manifold, and resulted in both material savings and reduced environmental impact. She warned about "eco-confusion," pointing out that bio-based versus conventional (petroleum) derived plastics and composites may not be "green" and that "eco-efficiency" analysis (environmental impact versus cost) is needed. For instance, less than 4% of global oil production is used to produce plastics, and only 0.16% for transportation sector plastics. Of the global thermoplastic resin market in 2007, transportation used only 4% vs. packaging at 33%.

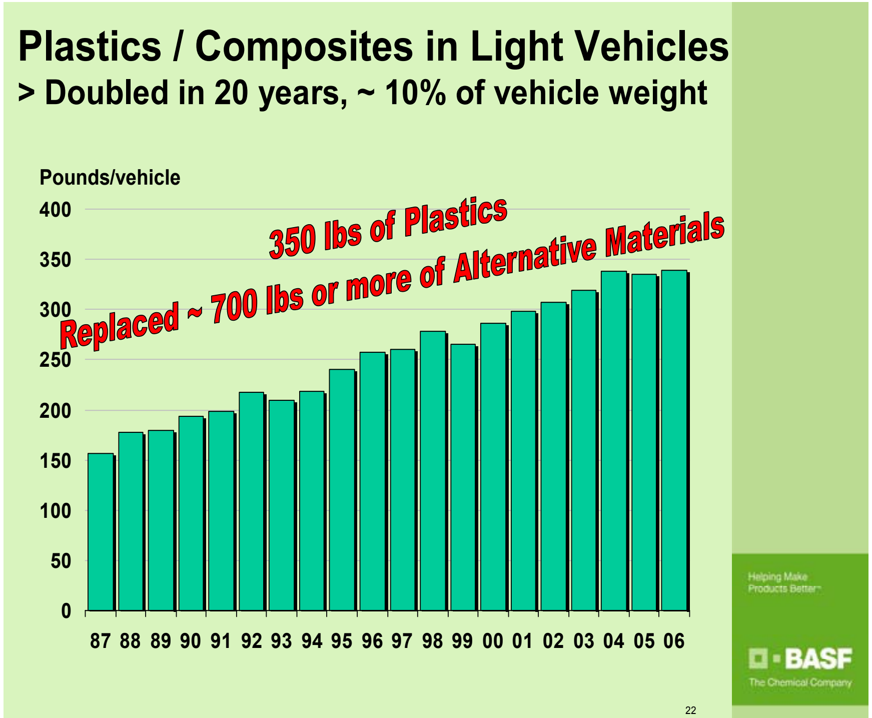


Figure 5, Illustrates the growth of automotive plastics and composites, which doubled over 20 years to the present 10% weight average.

1.3. Panel 3: Composite Materials Testing Standards, And Crashworthiness Models

1.3.1. "Characterization Of Automotive Composite Materials- Designing Real Cars With Carbon Fiber Composite Bodies[5]."

Prof. Paolo Feraboli, University of Washington, and Chair of CMH-17 Crashworthiness Working Group.

The presentation highlighted the uses of advanced composites in the design of real cars today. There are both volume and structural issues that influence automotive applications of advanced composites. The materials, cost, and technology for high-cost, low-volume (fewer than 1000 per year) luxury vehicles with carbon fiber bodies differ from those for high-volume, low-cost mass-market vehicles. A systems approach to vehicle design for crash safety and occupant survivability requires maintaining the occupant space integrity, providing adequate restraints, using crash-absorbing devices, and providing means of egress after the crash.

The design techniques for structural composite crashworthy cars are not yet suitable for mass-market vehicles. Carbon fiber reinforced plastic (CFRP) monocoque bodies for luxury vehicles are designed to provide a rigid, survivable space in a crash. However, they require expensive materials (e.g., 24K tow carbon fiber fabrics with toughened epoxies) and are labor intensive to manufacture. Examples of high-end car models with CFRP monocoque body and metallic crash box are the Ferrari Enzo (Ferrari F50, Maserati Mc12); Bugatti Veyron, Porsche Carrera GT; Mercedes/McLaren F1; and Pagani Zonda.

[5] Note that proprietary images of the Lamborghini Murcielago were removed from the posted presentation.

An example discussed in detail was the McLaren SLR roadster or "supercar". Only 700 vehicles are produced per year, with 3000 total to date. The body panels, doors, upper roof safety cell are made by various molding methods: resin film infusion (RFI), resin transfer molding (RTM), sheet molding compound (SMC). The two crush cone composite boxes are very light (7.5 lbs.) with triaxial carbon fiber braids and a transverse member to distribute the impact load across the cone. The doors are made of carbon fiber preimpregnated (prepreg) tape with steel intrusion beams for added protection. This body has a lightweight, high strength carbon fiber shell. The curb weight is 1900 kg [4200 lbs]. It costs approximately $500,000.

Another composite luxury vehicle discussed was the Lamborghini Murcielago, which has a CFRP monocoque body, but metallic front and rear frames. Because the composite production technologies in use are slow and labor intensive, there are efforts to find solutions with lower material and processing costs

The requirements of the US Federal Motor Vehicle Safety Standards (FMVSS) are constantly evolving. The new FMVSS 214 side-impact protection pole-impact test imposes certification constraints that are particularly difficult to meet with a CFRP monocoque construction.
In seeking to improve automotive design for crashworthiness, the University of Washington (UW) partnered with Boeing and adopted the aerospace industry's building block approach that proved so successful for the Boeing 787. The 787's FAA safety certification was based on analysis supported by test data. The design of the vehicle for crash energy absorption required advanced progressive failure analyses of increasingly complex structures, supported by tests ranging from small specimens to full-scale vehicles.

The Composite Materials Handbook 17 (CMH-17) organization is an FAA-supported effort that evolved from a military handbook for composites (MIL-HDBK-17). CMH-17's Crashworthiness Working Group (CWG) is a cooperative effort supported by the Joint Advanced Materials Structures (JAMS) Center of Excellence at the University of Washington. The CWG is co-chaired by UW, GM, and Boeing members. It is developing a coupon-level test standard for crushing composite materials. A review of state-of-the-art finite element analysis (FEA) crashworthiness modeling tools is underway in order to develop useful guidelines.

There are unique problems in predicting failure of composite materials, particularly because they are anisotropic and non-homogeneous with important effects occurring on several length scales. Although lamination theory predicts elastic responses well, there are no universally accepted failure criteria. As a result of numerous interacting damage modes, post-elastic behavior is remarkably difficult to model. As structural complexity increases from small test specimens to the component and system level, the apparent disparities in material properties dictate empirical testing to confirm component behaviors. In summary, there are still major research and development needs to develop specialized design guidelines, analytical tools, and test standards for composite materials in crash applications.

1.3.2. "Plastics And Composites: The Benefit Of Industry Accepted Testing And Modeling Goes Beyond Implementation."

Dr. Jackie Rehkopf, Exponent, Inc. and past- Chair, SAE High Strain Rate Plastics Consortium (SAE HSRPC).

The Society of Automotive Engineers (SAE) High Strain Rate Plastics Consortium (HSRPC) was formed in 2001 as a research group under the SAE Cooperative Research Program. Its goal was to develop an industry standard for High Strain Rate Tensile Testing of plastics. Such a standardized test would permit data to be generated consistently and therefore compared across laboratories and suppliers. The Consortium had 12 industry members, representing leading materials suppliers and automotive manufacturers, with the University of Dayton Research Institute (UDRI) as principal investigator. The objective was to develop a standardized high strain rate tensile test for automotive plastics and composites, such as reinforced and non-reinforced thermoplastic polyolefins (TPOs), and to document their behavior to failure. The high strain rate testing protocol was developed to control or consider all aspects: specimen geometry, loading, and other system characteristics (time lag, filtering, frequency, constant velocity).

Round robin tests were conducted separately for load measurement and strain measurement at rates of 1 to 500 strain per second. The round robin series was conducted for five common automotive polymer materials with 12 laboratories focusing on load measurement and four laboratories concentrating on strain measurement. Results from such standardized tests provide mechanical property data that can be input to FEA models, and guides development of new materials with desired high strain rate ductility and strength characteristics.

During the Cooperative Research work, an SAE subcommittee was also formed under the Plastics Committee for the purpose of cascading the cooperative research work into an SAE standard. Based on the high strain rate tensile tests protocols and resulting data, the Subcommittee developed SAE J2749 Recommended Practice, "High Strain Rate Tensile Testing of Polymers", which is near release. Discussions with ASTM D20 Plastics Committee are underway for adapting it to become a global standard.

There is a need for plastics/composites testing standards that reflect industry-accepted methods and academic considerations, and that assist in best-practice materials selection procedures for robust product design. As industry implementation of plastics/composites increases, there are broader concerns related to potential litigation and public perception of material performance and structural integrity in real world crashes. One illustrative example cited was the requirement for new, additional tests back in the mid-90s for plastic fuel tanks beyond those required for traditional steel tanks. In general, sufficient standardized testing will need to be conducted not only to develop models to confidently predict crash performance, but also to proactively address potential public perceptions and potential litigious aspects of using plastics/composites for structural and/or energy-absorbing components. Examples were given for laminated glass windows, carbon fiber deck lids, and composite lift-gates.

1.3.3. "Multiscale Modeling For Crash Prediction Of Composite Structures

Prof. Jacob Fish, Professor of Engineering and Director of the Multiscale Science and Engineering Center at Rensselaer Polytechnic Institute (RPI).

The presentation elaborated on the unique challenges of scaling automotive composite properties from coupons to components and to entire vehicle systems. Advantages and disadvantages of alternative extrapolation approaches were highlighted: phenomenological, which depends on experimental data for all architectures; "direct homogenization", which is reliable but computationally complex; and an intermediate "reduced order homogenization" as a practical engineering modeling approach. Reduced order homogenization is fast and accurate, as documented in several cited RPI references. The latter multi-scale modeling approach was verified on unit cell tests for composite materials, as well as with large scale crash predictions of composite cars manufactured by the Big 3 (in cooperation with DOE/ORNL and USCAR/ACC). There has also been verification with ships, aircraft, engines, fan blades, and nanostructures.

Prof. Fish showed that experimentally observed displacement versus load curve is close to model predictions, and the deviation for tube crush simulations depends on the mesh size (fine to coarse) for structure modeling. Animated impact simulations were shown with real tests indicating that the analysis could accurately predict the time and failure mode of a GE composite fan blade.

Prof. Fish asserted *“Composites are structures unto themselves. …reduced order homogenization (models) may be required and are often effective.”*

1.3.4. "Predicting Whole Vehicle Crash Safety Performance From Lab Tests Of Composite Coupons And Panels: Identifying Key Technical Barriers"

Prof. Paul Lagace, Professor of Aeronautics, Astronautics and Engineered Systems, MIT Department of Aeronautics and Astronautics, Technology Laboratory for Advanced Materials and Structures (TELAMS).

This presenter reviewed the key challenges to reliably predicting the crash performance of composite-rich vehicles based on laboratory testing of small coupons and current model capabilities. The performance objectives for a structure inherently define its *failure* and assessment of any damage should be viewed in that context. Structural performance of a composite part depends on its configuration which in turn determines the stress distribution in response to impact loading, the possible damage mechanisms, and any residual strength after initial damage.

The "building block approach" involves testing and progressive design analysis at a number of defined structural scales to characterize coupons, sub-elements (e.g., stiffener), elements (e.g., stiffened panel), sub-components and components to verify that a composite structure performs mechanically as designed.

The practice of designing composite vehicles is predominantly empirical or semi-empirical. It relies on testing to confirm the “knock-down factors” applied to higher levels of structural complexity. This practice is safe and low risk, “effective but not efficient”. It is overly conservative for safety assurance, and there is no ability to confidently predict the actual failure and thus the energy absorption of the composite structure as this involves prediction of "failing" as opposed to prediction of "not failing".

It is implicitly assumed in the building block approach that failure mechanisms are similar at all scales, which may not be true. A key research need is to achieve a basic understanding of failure modes (e.g., debonding, delamination, buckling, transverse cracking, etc.) at the base level. Since there are multiple damage modes, there is a need to identify the damage mechanisms at each length scale and how they interact. Advancing the state of art in design of composite material components will primarily require advances in the understanding of damage initiation, propagation, and energy absorption and in associated appropriate failure criteria.

The presenter argued that basic research must be focused on understanding composite material damage mechanisms along the "tree of length scale" and how properties vary probabilistically. Variability of properties from multiple sources and across all scales leads to modeling uncertainties that cannot be "computed" without improved analysis and understanding. Because of "unknown unknowns" (i.e., "We don't even know what the critical parameters are, let alone their value.") and inherent limitations of semi-empirical models, the predictions of final failure and crash safety have low fidelity and reliability when compared to tests of real crash structures.

1.4. Panel 4: Industry Best Practices And Perspectives On 2020 PCIV Safety

1.4.1. "Thinking Out Of The Metallic Box."

Dr. Khaled W. Shahwan, Experimental & Computational Mechanics Department, Chrysler Technology Center-Scientific Laboratories, Chrysler LLC and Chair, Crash Energy Management (CEM) Working Group, Automotive Composites Consortium (ACC), US Council for Automotive Research (USCAR).

Dr. Shahwan reviewed the history and precompetitive cooperative R&D activities of the ACC- founded in 1988- and of the USCAR partnership, founded in 1992. Other ACC groups focus on Materials, Processing and Joining of automotive composites, in order to cooperatively develop, demonstrate and evaluate prototypes organized in Focal Projects (FPs): FP I - a composite front end; FP II - a composite pick-up box; FP III - a composite intensive Body-in-White (BIW); and FP IV - composite underbody and seats.

"Thinking out of the metallic box" is important for designing future PCIVs because industry experience with testing, characterization, modeling and prediction using metallic intensive components is not fully transferable to fiber-reinforced polymeric (FRP) components. FRP composites exhibit complex multi-phase materials with unique mechanical behavior. Such structural materials require significantly more advanced modeling tools. While metallic components crush and absorb energy via limited energy-absorption mechanisms (e.g., plasticity), composites crush and absorb energy in many vastly varying complex ways, ranging from local- to large-scale mechanisms.

The objectives of the EM Working Group are to:

- Characterize the properties of composites, including dominant micro, meso- and macro-mechanical damage initiation, propagation, and energy absorption;
- Develop, verify and validate robust modeling tools to predict the crash behavior of structural composites;
- Develop guidelines for design, testing, modeling and analysis of structural composites.

One of ACC's research focuses is on how composite structural tubes absorb crash energy. Many structural composite materials were studied including random carbon/glass chopped fibers, 0/90 textiles, and 0/30/45/60 braided textiles. "High" Specific Energy Absorption (SEA measured in joules/kg) material systems tend to exhibit progressive fragmentation or splaying during crushing. "Low" SEA systems, however, tend to respond in less progressive fashion and may involve global structural response. Schematic examples were shown that contrasted energy absorption mechanisms in metallic and composite structural tubes. Example results showing displacement vs. force illustrate some of the effects of tube wall thickness and loading speed (quasi-static and dynamic) on SEA. The influence of including matrix plasticity in computational models on the predictive capabilities was demonstrated via preliminary examples.

Several sandwich structures with different materials and architectures (e.g., webbing and stitching construction) were also investigated, and some examples of the crush modes of sandwich panels were shown. One of the concepts employed in modeling composites is the Representative Unit Cell (RUC) which typically include matrix and fiber tows. However, one the most challenging aspects of using RUCs is the size of an RUC with respect to the local and global dimensions, as well as the minimum numbers of RUC needed to accurately model damage initiation and damage-zone propagation. This can have significant influence on the scaling of the systems' mechanical strength as well as its fracture energy release.

A partial list of the EM working group projects (both experimental and computational) performed by universities, national laboratories, research center, suppliers, and ACC industry partners shows that much progress has been made toward understanding and predicting composites' characteristics and response through multi-pronged long-term coordinated efforts."

1.4.2. "Examples Of Composites And Plastics In Automotive Vehicles."

Dr. David A. Wagner, Technical Leader, Vehicle Design Research & Advanced Engineering, Ford Motor Company.

The presentation started with an overview of the Ford Motor Company as a global enterprise with five unique brands and a 2007 production volume of 6.5 million vehicles. Safety and health are a key focus area for Ford Research and Advanced Engineering, with research efforts addressing accident prevention, occupant protection, crash partner protection and simulation methods. Vehicle weight, driving performance, trailer tow capability and vehicle design combine to direct the powertrain design and all these factors combine to produce the fuel economy of the vehicle. Comparing two five passenger vehicles, the Ford Focus (25/35 mpg city/highway) vs. the Ford Escape Hybrid (34/30) showed that good fuel economy can be attained with different shaped vehicles having markedly different cargo capacities (13.8 cubic feet for the Focus and 66 (two passengers)/27 (five passengers) cubic feet for the Escape) but at different prices. The average weight distributions by sub-system (chassis, powertrain, body structure, etc.) for a given curb weight pickup truck and passenger car were illustrated to show where the greatest gains in mass reduction might be accomplished.

Implementing composites in new vehicle designs requires overcoming many challenges. In addition to crash modeling, energy absorption, and structural integrity, there are concerns regarding material performance, design and analysis capabilities, aging and environmental effects, durability, recyclability, fire and flammability, component manufacturability, joining and vehicle assembly, etc.

Current plastic and composite processing methods allow for either high structural performance in low volume and high cost (e.g., Aston Martin Vanquish) or limited structural performance for low cost at high volume. Improvements are needed in forming sheet molding compound (SMC) and in liquid composite molding (LCM) using carbon or carbon and glass fiber reinforcements to enable better structural performance at high volume and low cost . Comparing materials by complexity and size for different production processes against their economical production volume shows that some methods (e.g., SMC, thermoplastic compression molding (TCM), pultrusion) are economical for parts of small to medium size and complexity in annual production volumes of 50,000 to 150,000. Hand lay-ups are only economical for small volume components.

Three examples of successful integration of composites and plastics in production Ford Motor Company vehicles were discussed:

- The Aston Martin Vanquish has an adhesively bonded carbon and glass fiber composite structure. The production is less than 1000 cars per year. Each vehicle sells for approximately $220,000. An exploded view of the Vanquish shows many composite parts, including the crash rails and front end crash structure, rear floor, tunnel, A-pillars and body sides.
- The Ford GT is another high value, low volume vehicle featuring lightweight advanced materials. Advanced manufacturing processes are used to produce and integrate the various materials and components. The GT is a multi-material vehicle with an aluminum space frame, super-plastic formed aluminum fenders and deck lid outer, a carbon fiber composite inner deck lid structure covering the engine, and a glass fiber composite hood panel.
- The Ford Focus is a high volume vehicle (175,000 units in 2007) that incorporates low cost plastic components such as injection molded plastic trim for pillars, roof rails and headers (interior head impact zones). Low cost plastics used for injection molded components include polypropylene (PP), thermoplastic polyolefin (TPO) and ABS[1] thermoplastics.

Ford identified four major challenges to high performance and high volume structural polymers in automotive applications:

- improved composite materials
    - must be recyclable
    - carbon fiber must be more affordable,
- robust analytical tools for predicting crash energy absorption including fractures, for determining final shape from manufacturing and under severe loadings and for predicting joint behavior,
- enhanced component production methods (processing, cycle times), and
- improved vehicle assembly techniques, including faster cycle times, robust coating and painting processes, and effective adhesive joint nondestructive evaluation (NDE).

Ford has been using plastics and composites in vehicles when it makes both good engineering and business sense. However, additional future large-scale applications will be enabled by research and development on high performance structural components produced at low cost with fast cycle times as well as the development of analytical tools able to predict failure and simulate crash performance from component to full-scale vehicle.

[1] ABS is a copolymer of Acrylonitrile, Butadiene, and Styrene, with medium strength and performance at medium cost; ABS is often used as the cost and performance dividing line between standard plastics (poly- vinyl chloride-PVC, polyethylene-PE, polystyrene-PS, etc.) and engineering plastics (acrylic, nylon, acetal, etc.).

1.4.3. "Lightweight Materials For Enhanced Safety Of PCIVs."

Kevin Pageau, Account Manager, Tegrant Corporation.

Polymer foams play a key role in enhancing vehicle crash safety and ensuring compliance with Federal Motor Vehicle Safety Standards (FMVSS) for side impact (FMVSS 214), head impact (FMVSS 201-201U), seating and headrests (FMVSS 207/202a) and bumper systems (FMVSS 581). The primary foam materials with good energy absorption include expanded poly-propylene (EPP), a recyclable thermoplastic; rigid polyurethane (PU), a higher density thermoset material; and expanded polystyrene (EPS), a resin with high energy absorption and low cost.

The safety advantages of polymeric foams include their good stiffness to weight ratio, moldability, formability into complex shapes, and manufacturability (fast and low cost tooling, low pressure processing). An important property of these foams is that their density can be varied to improve energy absorption and meet other application requirements. As illustrated for EPP, the strain rate behavior of foams is self-similar; that is, they exhibit non-linear but predictable stress-strain curves (The higher the impact speed, the greater the energy absorbed.)

Figure 6, Illustrates the most common automotive foam applications.

The foam density can be tailored to specific occupant protection needs:

- in side impacts, lower density foam is used for thorax bolsters while medium-to-high density foam is used for pelvic bolsters;
- for head impact protection, the density and shape of the foam can be varied to meet specific vehicle geometric requirements;
- for seating components, various densities are used in headrest cores and seat cushions;
- for front and rear bumper systems, more rigid foams are optimized for pedestrian protection;
- PU foams are also injected as cavity and void fillers to enhance structural performance by improving energy absorption and reducing the propensity for buckling;
- in sandwich panels, various foam densities might be used between rigid (high modulus) layers.

In conclusion, molded foams are versatile and promise to strengthen current and next generation vehicle crash performance, either as structural members during impact as either skin or cores for sandwich structures (doors, floor, seating modules), and as preforms to be wrapped in carbon fiber. Foams could clearly complement and cost-effectively enhance future PCIV structural safety based on experience to date if they are properly integrated to provide interior occupant protection as padding or if used as exterior structural materials and form-fillers.

1.4.4. "Material And Manufacturing Process Selection Criteria For Automotive Product Development."

Michael Hunt, Senior Advanced Engineer, Meridian Automotive Systems, Inc.

This presentation by a major Tier 1 automotive supplier[6] discussed the rationale ("how and why") of materials and manufacturing selection. The presenter focused on the integration of plastic and composite materials in current vehicles. Several factors have contributed to the growth of automotive plastics and composites including: enhanced performance, FMVSS requirements, weight reduction (to mitigate oil price increases and stricter CAFÉ standards), cost savings, and improved quality.

Usually, original equipment manufacturers (OEMs) issue performance specifications for a part or subsystem which describe the vehicle manufacturing process, product cost, mass, etc. The specifications include a call for a design and development verification plan with requirements for static and dynamic load limits and durability. The OEM suppliers can choose materials and processes that meet the specifications. Suppliers' inputs can influence the final vehicle designs if offered early in the conceptual program phase, pre-prototype phase or as part of an advanced development project open to novel technology applications.

Materials choice is based on several considerations, not simply mechanical performance such as impact strength, or environmental durability (weathering, UV stability, and thermal stability) but also economic considerations (e.g., tooling investment required for the expected annual production). An illustrative case study compared steel, aluminum, and sheet molding compound (SMC) alternatives for a hood assembly. The study showed cost advantages for composite vs. steel and aluminum at volumes below

[6] See Meridian postings at http://www.meridianautosystems.com/index.php , e.g. the removable SMC hardtop assembly for the DCX Jeep Wrangler, bumpers and energy management systems, closure panels and "hybrid" solutions (composites, thermoplastics, metals) to meet performance, mass, and cost targets.

150,000 per year, but comparable cost crossover above that volume. The weight of the hood assembly is lowest for Aluminum and highest for steel, with SMC between the two.

Plastic and composite automotive applications of interest to OEMs include bumper and roof systems, SMC body panels and front-end bolsters, battery trays, pickup truck boxes, underbody aerodynamic shields, etc.

Barriers to greater use of plastic and composite materials by OEMs are well known: higher baseline cost than steel; the need for improved Computer-Aided Engineering modeling tools; and persistent lack of product engineers' familiarity with the materials.

The plastic and composite materials of greatest current interest to OEMs are:

- SMC, given its stable raw material prices and cost competitiveness below annual production volume of 100,000;
- Carbon fiber, if and when class A body panels can be made affordably;
- Direct-compounded long fiber thermoplastics (DLFT) that can be made on-site at manufacturing plant to reduce material costs and processed into compression-molded parts with superior impact performance.

Future market prospects for plastics and composite materials are promising, since they offer both cost and weight savings, and because emerging hybrid and electric vehicles are going to be "game changers".

1.4.5. "Strain And Displacement Management In Automotive Composites."

Dr. Peter H. Foss, Staff Researcher, Materials and Processes Lab, General Motors (GM) Research and Development Center.

The presentation addressed displacement management for composites in crash- critical structural applications. Displacements must be managed without catastrophic failure. Because decelerations are limited by biomechanical requirements, overall displacements are relatively independent of the structure. Currently, composites are seldom given a primary role in crash energy absorption.

This presentation cited two examples of composites usage in automotive applications:

- The first example discussed the performance of composite liftgates relative to compliance testing for FMVSS 301, Rear Offset Deformable Barrier Test. The test mass of the moving deformable barrier in this test was 1386 kg (about 3050 lbs). The barrier approached at 80 km/hr (about 50 mph). While its load-displacement behavior in normal use must be elastic, the liftgate must deform plastically under impact loads. Composite materials considered for the part were: long glass fiber polypropylene (LGPP) and Twintex-reinforced LGPP. They were both tested for load-displacement performance compared to the steel baseline.
- The second example was an Automotive Composites Consortium project to replace a steel floor pan structure, consisting of 27 components and 12 reinforcement parts, with composites. A Sheet Molded Compound (SMC) design required only a dozen components with ten reinforcements. The effort determined that a chopped fiber SMC that was selectively reinforced with continuous fiber woven fabrics met the requirements and saved 15 to 18 kg of final mass of the assembly. This strategy promoted localized damage to manage the overall displacement without a catastrophic failure. It was noted that, while the approach was

practically demonstrated, the failure models are insufficiently robust at present to eliminate the need for verification testing.

1.4.6. Closing Remarks

Stephen Summers, NHTSA PCIV safety program manager closed the workshop by thanking participants for their inputs regarding research and development priorities, challenges, and opportunities to achieve desired PCIV safety benefits by 2020. He indicated that the next step will be to summarize and distill workshop findings so as to refine the research and development roadmap and to productively focus research on the key PCIV safety priorities with highest leverage and payoff.

2. SUMMARY OF FOCUSED DISCUSSIONS

2.1. Panel 1 Focused Discussion

The focused discussion following the first panel presentations was led by **Dr. Tom Hollowell,** WTH Consulting, and focused on the following questions:

2.1.1. What Is The Definition Of A PCIV (Percent Plastics Contents)?

The definition of a PCIV as meant by the Congress is not clear. The volumetric or weight fraction of plastics (P) and composites (C) in a multi-materials vehicle is relative to the present baseline automotive average contents of approximately 10% plastics and more than 75% steel by weight, with other materials (aluminum, magnesium, titanium, glass, fiberglass, cloth, etc.) present. Some discussion on whether the engine block (now aluminum) and the powertrain should be considered separately from the chassis and frame. Attendees representing Original Equipment Manufacturers (OEMs) and materials supplier indicated that a minimum of 30% to 40% (by weight) plastics and composite content in one or more subsystems beyond interior trim could qualify a vehicle as a PCIV. (Note that this is below the DOE/USCAR light-weighting "Factor of Two" goal desired for improved fuel efficiency.)

2.1.2 What Are The Potential Safety Benefits Of Plastics And Composites In Next-Generation Vehicles?

Points mentioned orally by the participants (and others noted on 3x5 cards to preserve confidentiality) include:

- The safety benefits attributable to plastics and composites may have to be separately evaluated for structural and semi-structural uses in the Body In White (BIW), i.e. the structure and closures without trim, chassis, motor, upholstery from uses designed to sustain impacts; and the interior uses of softer plastic foams air bags and restraints, door and roof padding intended to redistribute, deflect and cushion impact forces on the occupants.
- Data indicate that smaller and lighter vehicles are more “crash-involved” (despite presumed enhanced maneuverability) and less safe in collisions with heavier and larger vehicles. This crash compatibility challenge could be offset by maintaining size and crush space to protect occupants, while using strong but lightweight composites to improve both safety and fuel efficiency.
- Reduced vehicle weight across the fleet could reduce the weight disparity and improve crash compatibility and safety.
- Lighter cars have less crash energy.
- A safety benefit of carbon-fiber composites (CFC) in vehicle structures is superior specific energy absorption (SEA);
- Formula 1 racing cars have strong CFC nose cones for driver crush protection, but they may not be sufficiently robust in off-axis collisions and shear loading.
- From a clean-sheet approach, lighter structural materials might permit optimization and flexibility in design of “package space”, and promote better maneuverability for crash avoidance (through “tunability” of vehicle handling), as well as a shorter stopping distance.

2.1.3 What Are The “Top 3” R&T Priorities To Enable PCIV Development And Deployment By 2020?

This question was asked twice of the workshop attendees – at the end of Focused Discussion 1 and Focused Discussion 4. It generated a great deal of discussion both times. The results are combined in Chapter 3: Findings.

2.2. Panel 2 Focused Discussion

The open discussion was led by **Dr. Joseph Carpenter** and addressed three questions:

2.2.1. How Are Light-Weighting Vehicle Materials Selected, Tested, And Integrated With Design Platforms?

- The "current practice in the auto industry is evolution, not revolution." A material change can occur only if the value (performance, cost) or application (to safety) is clear.
- Key materials selection criteria are cost and value. Related economic criteria are life cycle cost and profitability.
- A "core" set of candidate composite materials needs to be selected for specific energy absorption tests before proceeding to whole vehicle crash analysis.
- Materials selection is increasingly enabled by better data on crush characteristics (e.g., CMH-17) and by evolving modeling tools
- Mandatory performance requirements (e.g., compliance with increased CAFÉ rule) might encourage choice of composite materials for both light-weighting and crash strength.
- The value of durability, longevity and damage tolerance of composites might spur materials substitution. On the other hand, there might be an unintended consequence of improved durability and immunity to corrosion; it might delay fleet renewal and thus deployment of future safety advances.

2.2.2. How Well Can We Estimate Crash Safety Contributions From Structural Materials, Components, And Whole Vehicle Designs?

There was some disagreement as to whether current predictions are "reasonable," or material models and failure criteria currently in use are really applicable. One attendee remarked that: "*We have simulation tools, not predictive tools*." The implication is that general behavior can often be simulated, especially if it can be directly correlated with a test, but predictions of details of failure locations or failure loads are seldom sufficient. Responses indicated that:

- At the material level there is less than 50% confidence in predicted performance of composites, whereas a confidence level of more than 90% is desirable. While steel analysis is typically much greater than 90% accurate and aluminum is about 90% accurate, the commonplace factor of two errors with composites often necessitate specialized "development programs."
- At the component level, composite crash predictions are now 80-90% accurate (using updated Abaqus/Explicit model).
- At the vehicle level, it appears that engineering modeling tools are inadequate to predict real crash performance for specific materials and designs, while real-world crashes are difficult to control and simulate. Therefore, a suggestion was to revive the DOE/USCAR ACC Focal project 3 (FP3) whole vehicle crash analysis effort, which was scaled down to component level.
- Since extreme confidence in crash performance is required to set the signal processing requirements for airbag deployment, the Finite Element Analysis (FEA) models for multi-materials vehicles must improve considerably.

2.2.3. How Can Structural Composites For Light-Weighting Overcome The Crash Compatibility Challenge?

Several responses noted the potential for composite parts to promote structural engagement during vehicle-to-vehicle crashes, but only if supported by:

- More flexibility in shape, and parts consolidation to promote structural engagement in a crash
- Mass adjustments
- Redesign to encourage structural engagement, and improved energy absorption
- Understanding of the effects of process and geometry on performance.

Other responses noted that carefully enhancing crush zone dimensions with minimal impact on interior and exterior dimensions would be helpful. Compatibility requires making crush zones work as intended in real crashes. Plastics/Composites (PC) might help if used to increase crush zone length while shedding weight. However, using high Specific Energy Absorption (SEA) characteristics in crush zone design to absorb more energy in the same distance will simply lead to higher occupant cell decelerations and potentially higher risk of injury.

Several respondents were concerned with appropriate materials characterization, which is needed as baseline static and dynamic data for all categories of composites, in order to evaluate their crash compatibility. Another need is to define appropriate test coupons for different categories/types of composites, e.g., fiber-filled long vs. short fiber, weave, etc.
It was also noted that material properties from coupons are different than in components Processing determines material properties, and models do not reflect these effects.

Some respondents emphasized that there are system level effects that could dominate, such as:

- Mass compounding (i.e., lighter structure requires smaller engine, etc)
- Consideration of relative composites durability (longevity, tolerance of damage) and how its benefit should be valued: e.g., would extreme durability impede penetration of safety advances?
- Consideration of trade-offs: Safety can be accomplished in some cases at the expense of ability to repair. How do you create a consumer model that would make this acceptable? Can the expense of replacement be controlled so as to match the cost of repair? How does this impact quantity and distribution of replacement costs?
- Repair could become a viable option for PCIVs. Repair education for OEM dealership and independent repair shops is essential to ensure quality and integrity of the repair. Repair facilities should be certified in plastics/composites repair. A partnership could be formed between the plastics industry, automotive experts and the Independent Council for Automotive Repair. Reliable repair cost estimates could be established once repair techniques are developed and quality certified. OEM design optimization and materials characterization are important considerations for cost effectiveness and quality assurance for component repair.

To understand how we can make use of the differences in vehicle material properties in a crash, we need to:

- Conduct/evaluate crash analysis of a full composite vehicle;
- Better understand how does a reduction in effective crash speed of 30 mph to 27 mph reduce fatalities/injuries, and quantify the benefits to educate consumers.

2.3. Panel 3 Focused Discussion

A theme developed in this session even before the focused discussion. It was widely asserted that "soft" issues (definitions, semantics, design philosophies) need as much attention as the "hard" issues (designing and interpreting tests, characterizing material behavior). For example, aviation regulations require analytical proof with experimental verification that a component would not fail in service under various defined conditions. The ability to estimate and confirm minimum residual strength is insufficient for crash analyses, however, there are significant drawbacks (e.g., excessive deceleration of the occupant compartment) to having too much residual strength and stiffness (rather than controlled failure) in a crash event. The stochastic character of the component properties and the crash loading profoundly complicate the matter. Approximate approaches such as homogenization make excellent engineering sense in many analyses, but may be extremely detrimental in this context.

The discussion led by Prof. John Heywood addressed the following questions*:*

2.3.1. What Are The Top 3 Knowledge Gaps In Composite Materials Characterization For Modeling Vehicle Crashworthiness?

- Understanding what happens in composite failure: defining, describing, and measuring it
- Understanding load introduction during crush (in models, in specimens, in structures) to optimize energy absorption
- Study strain rate effects on P/C materials and structures
- Deriving materials information out of dynamic tests of specimen or structure
- Damage assessment and longevity implications for "fender benders," though some assert significant real world data exists
- Do properties (e.g., strength) of constituents (fiber, matrix) differ with processing?
- Understand stochastic issues in coupon mechanical properties; obviously the properties depend heavily on format (matrix selection, fabric vs. braid vs. chopped vs. unidirectional)
- Definition of "failure," especially given its progressive nature and interaction of numerous modes. What is relative importance of stochastic influences?
- Effective communication between automotive and aerospace segments experience with composites, given that processing/structures/functions are quite different
- Robustness of processing – more of an issue than with metal.

2.3.2. How Well Can Computational Methods (e.g., Finite Element Analysis) Predict Crash Performance?

Attendees concurred that the process of developing models is crucial

- The process of developing models is an important exercise that leads to understanding
- Local physics (e.g., fiber/matrix interface) are tough to model
- Note many examples in presentations
- Is the current level of effort sufficient?

They were also keenly aware that currently available models are not sufficient to predict plastic and composite vehicle crashworthiness:

- There have been constant significant improvements, but coders can only code the models they're given

- The "Garbage In/Garbage Out" (GIGO) predicament: both model and material property data must be correct for analysis to be correct.
- Homogenization can be a good assumption, but it is inconsistent and occasionally misleading
- "*We are making good progress on individual damage modes, but the interaction of multiple damage modes (highly likely) is still a problem*"
- A significant example was debated: One attendee noted an outstanding correlation between an analysis and test results. Another pointed out that the results, while impressive, predicted the crushing failure of a component manufactured of woven graphite fabric cloth, which inherently inhibits transverse cracking. Any implication that this analytical technique can be simply extrapolated to non-woven components might therefore be significantly misleading.
- "Unknown unknowns" is a major challenge - as present, we simply don't know all materials, design, and structures issues for plastics and composites
- "*Having data is necessary, but not sufficient, to having a model*"
- Precompetitive cooperation in developing models is preferable
- "Round robin" testing and modeling was suggested (e.g., modeling of specific medium-size component, specific loading) to determine the degree of (dis)agreement between different test procedures and models.

2.3.3. How Can Crash Safety Contributions From Structural Composites Be Best Quantified?

- It is important to consider the method of energy management from a safety standpoint. Multiple approaches to energy management warrant considerations for multiple materials and material configurations (resin, foam, profiles, etc). The use of plastics per se may be more cost effective than composites per se. Considerations for early design optimization vs. material replacement can influence the decision to use one material over other.
- Specific contributions to crashworthiness can be based on experience with components in development prototypes.
- There is a need to do a round robin test on vehicle subsystem: less than the front end, but more than just a bumper, for 2 or 3 candidate material systems (and processes)
- We need to clarify first the key questions:
  - How to predict failure in non-homogeneous materials?
  - How precise does this failure prediction for a material choice need to be?
  - How does the failure impact surrounding material?
  - Is failure propagation consistent in failure mode?

2.4. Panel 4 Focused Discussion

The discussion led by **Dr. Khaled Shahwan**, Chair of Energy Management Working Group of the Automotive Composites Consortium, aimed to identify the "Top 3" priorities for the following key issues:

2.4.1. Industry Criteria For Structural (Composite) Materials Selection

Participants noted the following criteria currently considered by industry:

- Robustness
- Cost and economics (availability)
- Processing and manufacturing considerations including cycle time
- Ability to model and predict accurately

- Recyclability
- Compatibility with whole vehicle design
- Ability to characterize all properties for various designs

2.4.2. Metrics And Milestones For PCIV Safety Assessment

- Metrics:
  - Design, develop, model and test a PCIV that meets or exceeds FMVSS standards.

- Milestones:
  - Building and testing of large scale structural components to gather data for development and correlation of predictive models
  - Development of reliable, validated response models that robustly and accurately predict crush performance for components and full vehicle system
  - Additional significant focal projects (e.g., select a material, develop front end, conduct round robin computational simulations, and validate analysis with tests)

2.4.3. Technology Barriers And Opportunities For PCIV Safety

The discussion identified barriers to higher volume production of high performance structural polymers in future automotive applications. They were essentially the same as those identified by David Wagner (Ford) in his presentation, namely the need to improve:

- composite materials structural performance
- the analytical tools for predicting crash energy absorption, especially for arbitrary shapes and joints
- carbon fiber affordability
- end-of-life recyclability
- component production methods (processing, cycle times), and
- vehicle assembly methods (including coating and painting, adhesive joint nondestructive evaluation (NDE), etc.)

2.4.4. Priorities For PCIV Safety Roadmap Near-Term Research And Development

The question was again asked about near term R&D priorities relevant to future PCIV. Once again, these were not all related to safety, but include economics and manufacturability issues. These were also combined with the responses from those given in the first panel discussion and are summarized in Chapter 3.

3. FINDINGS FOR PCIV SAFETY RESEARCH PRIORITIES

3.1. Research and Technology Priorities Identified by Workshop Attendees

In the focused discussions following the first and fourth panels, the workshop attendees identified PCIV safety research and technology priorities. While there was no consensus among the experts regarding a definitive "Top Three," there were some obvious trends. Some attendees noted the necessity of accelerating research and development efforts to ensure that these technologies make it into the design cycle for model year 2020 PCIVs, as they may require major changes in vehicle structural design and manufacturing infrastructure.

The participants' suggestions most appropriate for NHTSA and collaborative PCIV safety research could be grouped into four general categories:

- Composite Materials Testing, Characterization and Database – Develop, improve, and standardize tests on size scales from coupon (material property) to full component (performance verification)
  - Generate test data for simulation models to verify the reliability of failure prediction
  - Study composites performance in real crash modes since energy absorbing (EA) structures in real crashes often do not perform as designed
  - Review current industry standard test methods for crash safety as they apply to plastics and composites vs. steel and other metal structures
  - Develop standard tests to characterize plastics and composite mechanical behavior
  - Sponsor "round-robin" testing and analysis on vehicle systems (e.g., a simplified front-end)
  - Evaluation standards for individual materials and structures and for the crashworthiness of the integrated vehicle
  - For various composites, conduct crash test modeling for a range of automotive structures, not just front ends (e.g., side panels, and rear)
  - Demonstrate safety at vehicle level
  - Develop a materials crush database

- Crash Failure Modeling and Analysis - Develop failure models to support analysis of crushing, fatigue, and other failure modes.
  - Improve failure prediction
  - Improve Finite Element Analysis (FEA) predictive engineering models that adequately predict crash energy absorption and vehicle performance
  - Improve scaled material characterization of composites
  - Advance and refine damage prediction tools and capabilities

- Alternative Crash Safety Techniques - Investigate synergies with NHTSA integrated safety concepts.
  - Study how crash avoidance technologies can enhance lightweight vehicle safety
  - Identify new crashworthiness strategies (like deployable crash zones)
  - "Tune" vehicle structures to optimize maneuverability

- Damage, Repair, and Longevity – Viable PCIVs will need to retain their safety characteristics throughout the vehicle's lifetime, even if significant structural repair is required.
  - Increase understanding of aging and longevity (in-service properties)
  - Understand fatigue, aging and environmental degradation on crash performance over vehicle life (20 years)
  - Plastic and composite repair manuals developed with industry could increase repair quality and reliability.
  - Education in proper plastics and composites repair techniques with appropriate materials characterization for OEM Dealer and independent repair facilities, possible education partnership with the Independent Coucil for Automotive Repair (ICAR).
  - Repairability methods and cost (cost and feasibility of repair vs. replacement)
  - Tolerance for minor damage without loss of structural strength (what lessons from a aerospace composites apply?), i.e. durability and residual strength
  - Monitor health and integrity for composite structures - need reliable predictive models

Three other categories of suggested PCIV research priorities are indirectly related to the NHTSA mission research portfolio, but are essential for the successful deployment of future PCIVs and could be addressed by the DOE/USCAR automotive light-weighting materials program:

- Non-Crash Safety Concerns – Investigate other safety-related issues for plastics and composites
  - Flammability and combustion byproduct toxicity tied to exposure criteria

- Design, Manufacturing, and Production – Safe PCIVs will not penetrate the marketplace if their components cannot not be produced quickly and reliably
  - Develop appropriate modeling of component production methods to assure parts meet specifications.
  - Improve fastening and joining technologies
  - Identify "classes " of plastics and composites considered likely for PCIVs
  - Develop precompetitively a general design guide by pursuing consensus on selecting the best composite material and process for PCIV designs

- Economic Issues - Acknowledge that economic issues can also be non-starters that would delay or prevent PCIV deployment by 2020.
  - Other R&D priorities for industry include: the state of US knowledge and infrastructure for innovation to implement PCIVs relative to Europe and Asian manufacturers;
  - Economic, manufacturability, and maintainability issues for PCIVs:
    - lower cost constituent materials (fibers, matrices)
    - initial and lifecycle cost, including potential benefits in parts consolidation, coating and painting, adhesive joining, and nondestructive evaluation (NDE),
    - manufacturing rate and quality control,
    - end-of-life considerations such as recyclability.

3.2. NHTSA PCIV Safety Research Strategy

Safety research for future PCIVs must be strategically focused on providing adequate tools and data to the automotive industry to allow them to confidently design and produce economically viable commercial light and fuel- efficient vehicles with crash safety performance equivalent to or better than today's vehicles. The most basic element of this research will require enhancing the understanding of relevant crash environment material failure mechanisms and their interactions. As these are better understood, standardized test specimens can be developed and material property databases generated. The material models and experimental data must then be integrated into robust analytical capabilities. When these systems approach the accuracy currently enjoyed by those for metals, expensive test and re-design cycles can be eliminated.

The weight and space savings available through part consolidation should be explored as a method to enhance and facilitate the deployment of NHTSA's integrated safety concepts. In particular, the ability to tailor shape and stiffness could be used to "tune" the vehicles structure and may create sufficiently enhanced maneuverability to optimize some crash avoidance strategies. There should also be efforts to understand the effects of material aging, structural repairs, and of non-crash or post-crash safety issues such as toxicity and flammability. This work could be performed cooperatively, in public-public and public-private partnerships, and be coordinated and integrated with associated topics in manufacturing capabilities, material costs, and sustainability, since the long-term economic viability of PCIV production is as important as enhanced performance.

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APPENDIX 2, BIOGRAPHICAL PROFILES FOR SPEAKERS, PANELISTS AND MODERATORS

"THE SAFETY CHARACTERIZATION OF FUTURE PLASTICS AND COMPOSITE INTENSIVE VEHICLES (PCIVs)"

Dr. Aviva Brecher is a National Technical Expert in Transportation Safety, Health, and Environment, in the Planning and Policy Analysis Division, Office of Surface Transportation Programs, at the DOT/RITA Volpe Center. Her recent work focused on the safety, health and environmental analysis of emerging transportation technologies, such as: a safety research roadmap for plastics and composite intensive vehicles (PCIV); a hydrogen and alternative fueled transportation R&D roadmap; transit advanced electric drive and urban maglev systems; remote sensing, and security applications of GPS position, navigation and timing (PNT), including unmanned aerial vehicles (UAVs); transit EMF safety guidance for planners; and transportation 2050 visioning. Her transportation work portfolio also includes: multi-modal strategic planning and analysis; Research and Technology program planning, transportation futures and innovation forecasts, and regulatory and policy analysis and risk assessment and management, electromagnetic radiation exposure safety standards, She has over 30 years of technical work experience in academia, business and government, and holds Physics BS and MS degrees from MIT, and a Ph.D. in Applied Physics from UCSD. She published numerous technical reports and articles, served on professional societies committees (APS, IEEE, AAAS, TRB), is Fellow of the American Physics Society (APS) and American Association for the Advancement of Science (AAAS), and a former Sigma Xi Distinguished Lecturer, Congressional Science Fellow. Japan Society for the Promotion of Science Fellow, and Zonta International Amelia Earhart Fellow. Asteroid 4242-Brecher was named in honor of her and her husband's contributions to Planetary Astronomy and Astrophysics.

Dr. John C. Brewer joined the Volpe Center in 1991. During his career at the Center, he has worked on the Federal Aviation Administration's Aging Aircraft Program, conducted risk analysis of hazardous materials in aircraft cargo compartments for the Office of Hazardous Materials (now part of the Pipeline and Hazardous Materials Administration), developed a strategic plan for the Wire System Safety Interagency Working Group of the White House Office of Science and Technology Policy, and performed crashworthiness studies of motor vehicles using finite element computational methods for the National Highway Traffic Safety Administration. His current NHTSA research focuses on vehicle compatibility.

Prior to his service at the Volpe Center, Dr. Brewer worked for the Department of the Army at the Natick Research, Development, and Engineering Center in Natick, MA, where his research included composite applications to airdrop technology and advanced mobile shelters. While at Natick, he also developed a technology base master plan for airdrop systems. In addition, he has worked as Chief Design Engineer for a private firm that develops continuous spooled composite tubing for the oil services industry.

Dr. Brewer received his S.B. (1983), S.M. (1985), and Ph.D. (1988) degrees in Aeronautics and Astronautics from the Massachusetts Institute of Technology. His graduate research related to failure mechanisms in advanced composite materials. He recently completed his Masters in Business Administration (2004) degree primarily through distance learning at Suffolk University in Boston under the sponsorship of the Volpe Fellows program. He has been a member of the American Institute of

Aeronautics and Astronautics, Sigma Gamma Tau, Sigma Xi, Beta Gamma Sigma, the Engineering Society of Detroit, and the Society for the Advancement of Material and Process Engineering.

Dr. Brewer has written and presented numerous papers in composite technology, aircraft longevity, and crashworthiness in refereed journals and international conferences. He received the Superior Achievement Award (Research and Special Programs Administrator's Bronze Medal) in 2001. He was selected as an Excellence in Government Fellow in 2002. Dr. Brewer has three patents in the fields of parachute technology and aviation damage tolerance, for which he has received recognition from the United States Secretary of Transportation. He has served as acting division chief of the Vehicle Crashworthiness Division. In the fall of 2005, he served a 30-day voluntary assignment with the Federal Emergency Management Agency in the wake of Hurricanes Katrina and Rita. He has obtained certification from the Project Management Institute as a Project Management Professional.

Dr. Joseph A Carpenter, Jr. is the Lightweighting Materials Technology Development Area Manager, in the Department of Energy Office of Vehicle Technologies, a key part of the FreedomCAR and Fuel national research partnership with the automotive and energy industry. Prior to joining DOE, he held R&D and research management positions at Chrysler Corporation, the Oak Ridge National Lab (ORNL) and the National Institute of Standards and Technology (NIST). He holds Bachelor and Doctoral degrees in materials from Virginia Tech.

Lynette Cheah is a PhD Candidate in the Engineering Systems Division at the Massachusetts Institute of Technology (MIT), and a researcher at the Sloan Automotive Laboratory. Her research focus is on the life-cycle energy and environmental impacts, and material flow assessments in transportation systems. Her current project evaluates the feasibility and impact of passenger vehicle weight and size reductions in the U.S. Prior to returning to graduate school, she worked in the national agency for science and technology research in Singapore, overseeing the environmental science and engineering portfolio. Lynette holds a B.S. civil and environmental engineering from Northwestern University, and a M.S. in management science from Stanford University.

Suzanne M. Cole is President of Cole & Associates, Inc., a management-consulting firm, specializing in regulatory and legislative affairs. CAA represents clients in the automotive, chemicals, plastics, energy, and medical industries. Suzanne has extensive automotive product marketing, regulatory and legislative affairs experience. She has testified frequently before Congress on automotive safety and environmental issues. She was instrumental in the expanded outreach of NHTSA's CIREN network of level one-trauma centers throughout the United States. Suzanne works with clients to advance new automotive safety technology. Suzanne has worked closely with the University of Michigan Program for Injury Research and Education (UMPIRE) to promote interaction between automotive engineers and trauma physicians to create advanced safety technology. She served on several SAE technical committees, was a keynote speaker for the SAE WEC on automotive legislative and regulatory issues; and was nominated in 2004 and 2005 for the SAE WEC Breed Award for Women's Leadership. Suzanne received multiple awards from the International Society of Plastics Engineers, including the 2005 Outstanding Officer Award, 2006 Honored Service Member Award, and Outstanding Chairman's Award for "Leadership, Inspiration and Extraordinary Service in the Promotion of Scientific and Engineering Knowledge of Plastics in the Automotive Industry". Suzanne is past Chairperson of the Society of Plastics Engineers Automotive Division and Environmental Division. Suzanne organized and chaired the Automotive Innovation Awards Program, known as the Academy Awards of the Automotive

Plastics Industry; in 2004 and 2005. She also organized and Chaired Global Automotive Safety Conferences in 2000, 2001and 2002; which brought together automotive OEM, supplier executives and engineers with the regulatory community to discuss auto safety design, injury prevention, new materials applications, telematics and electronic data recorders. As Chairman of the 2002 "Racing To Safety" conference sponsored by Ford Motor Company and DaimlerChrysler, convened a panel of racing experts to discuss racing safety and injury prevention. Suzanne also served on numerous legislative committees at the federal and state levels: She was appointed by Governor Engler to the Michigan Broadband Development Authority; and served on the Resource Conservation and Recovery Act Revisions Committee in Congress and the Presidents Export Council. She has testified before congress on automotive safety and environmental issues. In addition, she authored and contributed to several articles on automotive safety, vehicle emissions and diesel technology for Automotive Industries Magazine and other automotive publications. Suzanne authored a white paper for the University of Michigan Transportation Research Institute on global automotive environmental issues.

Formerly, Suzanne was Vice President of Regulatory Affairs and General Manager of Federal Programs at National Environmental Testing (NET) in Boston, where she oversaw all Federal Programs interacting with the Joint Staff of the Joint Chiefs of Staff, the EPA, FDA and many others. She held leadership positions within the Council of Independent Laboratories and was appointed by the Governor of New Mexico to head the laboratory accreditation council. . Suzanne also held positions as Vice President, Analytic and Biological Laboratories, Farmington Hills, Michigan; effectively expanding their market outreach and production testing facilities to Argentina, Canada, Chile, Germany and Mexico. She also held positions as a legislative aide in Congress. Suzanne holds a B.S. in Chemistry from the University of Michigan, an MBA from the University of Michigan and a Masters in Chemical Engineering from Wayne State University.

Mary Fraser is a Marketing Manager in BASF Corporation's Engineering Plastics Division. She is responsible for developing the group's sustainability strategy. In this role, she assesses the market's needs for sustainable materials and aligns BASF Engineering Plastics strategy and product portfolio to better meet the needs from an environmental and economic perspective

Prior to this role, Mary held various other roles within BASF including Product Business Manager for Compounded Nylon and Polyester; Automotive Interior Marketing Manager, Engineering Plastics; Automotive Sales Manager, Performance Polymers and Urethanes.

Mary earned her MBA from The University of Michigan, Ann Arbor, MI and her Bachelor of Chemical Engineering from The University of Detroit Mercy, Detroit, MI.

Dr. Paolo Feraboli is Assistant Professor in Aerospace Structures and Materials, Department of Aeronautics and Astronautics of the University of Washington since 2005. Since then he has been collaborating with The Boeing Co., Federal Aviation Administration (FAA), and Automobili Lamborghini S.p.A. on various research projects related to the development of analytical and experimental techniques for composite materials. He has authored over 45 publications, and chairs the Composite Materials Handbook-17 Working Group on Crashworthiness (former MIL-HDBK-17), chairs the Technical Division for Durability and Damage Tolerance of the American Society for Composites, and is a member of the AIAA Materials Technical Committee. Since early 2006 he has been an active participant in the technology development of the composite-intensive Boeing 787 Dreamliner. He earned his Ph.D. from the University of California at Santa Barbara, and holds previous degrees in Mechanical Engineering from the University of Bologna, Italy.

Dr. Jacob Fish is the Rosalind and John J. Redfern Chair, Professor in Engineering and Director, Multiscale Science and Engineering Center, Rensselaer Polytechnic Institute. For over 25 years, Dr. Fish has been in the forefront of multiscale computational science and engineering, an emerging discipline that bridges the gap between modeling, simulation and design of products based on multiscale principles. He has an accomplished track record of technology transfer to industry. His multiscale methodologies have been employed by industry for manufacturing processes of GE90 fan blades; design of turbo-engines for GE and Rolls-Royce; simulation of aerospace structural components for Lockheed-Martin and Sikorski; optimization of energy absorption mechanism for lightweight composite cars manufactured by Ford, GM and Chrysler and numerous nanotechnology applications including nanodevices and nanocomposites sponsored by Northrop-Grumman, Sandia National Laboratory, Army Research Laboratory and Department of Energy.

Dr. Fish received the 2005 USACM Computational Structural Mechanics Award "in recognition for his contributions to multiscale computational methods". For his "significant contributions to computational science and engineering" he received 2003 Rensselaer School of Engineering Research Award. Dr. Fish has written over 150 journal articles, book chapters and books, two of which have won the best paper awards in the 1995 ASME International Computers in Engineering Conference and in the 1993 Structures, Structural Dynamics, and Materials Conference. His new book, A First Course in Finite Elements, was released last summer to wide acclaim. The book has been integrated into curriculums at universities across the globe, and is currently being translated into Japanese and Portuguese. Dr. Fish is a Fellow of American Academy of Mechanics, United States Association for Computational Mechanics (USACM) and the International Association for Computational Mechanics (IACM). More details can be found at http://www.rpi.edu/~fishj

Dr. Peter H. Foss is a Staff Researcher in the Materials and Processes Lab at the General Motors Research and Development Center. He received a Bachelors degree from the University of Maine in 1981 and a Ph.D. from the University of Connecticut in 1985, both in Chemical Engineering. Since that time, Peter has worked at the General Motors Research and Development Center, where he does research on virtual prototyping of plastics and composites. His research interests include the simulation of injection molding, thermoforming and other composites manufacturing processes, with a special interest on coupling process simulation with design, optimization and performance simulation.

Dr. John B. Heywood is Sun Jae Professor of Mechanical Engineering and Director of the Sloan Automotive Laboratory at the Massachusetts Institute of Technology. He did his undergraduate degree in Mechanical Engineering at Cambridge University and his graduate work at MIT. He then worked for the British Central Electricity Generating Board on magneto-hydrodynamic power generation. Since 1968 he has been a faculty member at MIT, where is he now Director of the Sloan Automotive Laboratory and Sun Jae Professor of Mechanical Engineering. His research is focused on the design and operating characteristics of internal combustion engines, their fuels requirements, and broader studies of future transportation technologies and their fuel consumption and greenhouse gas emissions. He has also worked on design and manufacturing issues in MIT's Leaders for Manufacturing Program where he was Engineering Co-Director. He is currently involved in studies of the energy and environmental impacts of future technology and fuels. He has published some 190 papers in the technical literature, holds a number of patents, and has won several awards for his professional contributions. He holds a Sc.D. degree from Cambridge University for his published research contributions. He is a author of a major text and professional reference "Internal Combustion Engine Fundamentals," and co-author with Professor Sher of "The Two-Stroke Cycle Engine: Its Development, Operation, and Design." From 1992-1997 he led MIT's Mechanical Engineering Department's efforts to develop and introduce a new undergraduate curriculum. In 1982 he was elected a Fellow of the Society of Automotive Engineers. He was honored by the 1996 U.S. Department of Transportation National Award for the Advancement of Motor Vehicle Research and Development. He is a consultant to the U.S. Government and a number of industrial organizations. He was elected to membership in the National Academy of Engineering in 1998. In 1999, Chalmers University of Technology awarded him the degree of Doctor of Technology honoris causa. He was elected a Fellow of the American Academy of Arts and Sciences in 2001. He is now co-directing MIT's Mechanical Engineering Department's Center for 21st Century Energy which is developing a broader set of energy research initiatives. In January 2003, Professor Heywood was appointed Co-Director of the Ford-MIT Alliance. In 2004, City University, London, awarded him the degree of Doctor of Science, honoris causa.

William Thomas (Tom) Hollowell, Ph.D, has recently retired after 32 years of service from the National Highway Traffic Safety Administration (NHTSA), where he served as the Director of the Office of Applied Vehicle Safety Research. He was responsible for formulating and executing research programs to achieve Agency objectives in projects relating to vehicle structures and occupant restraint systems, human injury, crash avoidance, and heavy truck safety. He is an internationally recognized expert in vehicle crash safety, having published over 50 technical papers on vehicle crashworthiness, crash modeling, crash testing, accident statistics, and impact biomechanics. Dr. Hollowell was elected a Society of Automotive Engineering (SAE) Fellow in January 2005. Upon retirement, Dr. Hollowell has continued to be active in motor vehicle safety. He serves as an associate editor for the Journal for Traffic Injury Prevention and is active in the SAE. In December 2007, he established his consulting business. Among his clients are the American Chemistry Council, the European Commission, the Japanese National Traffic Safety and Environment Laboratory, Nagoya University in Japan, and the SAE.

Michael Hunt, Senior Advanced Engineer at Meridian Automotive Systems, Inc. is a 21-year veteran engineer in the automotive industry, having served at Meridian Automotive for the past 14 years. Seven of these years were spent in Meridian's energy management group engineering bumper beams, fascias and EPP energy absorbers. Mike has a diverse product design and manufacturing background, having worked with Meridian's thermoplastic, thermoset, and metals divisions. In addition to working in Product Design assignments, he as also worked in Meridian's Commercial Development Group. Mike's current assignment at Meridian is to work with the automotive OEM's engineering communities and identify where Meridian's product portfolio offers cost, weight, or performance improvements and develop specific product design proposals to meet those needs. Mike is a member of the Automotive Composite Alliance (ACA), a division of the American Composites Manufacturing Association (ACMA). He's a board member for the Lake George Property Owners Association and a registered Boy Scout of America leader, serving as a District Committee Member and as an Assistant Scoutmaster.

Nelson (Ned) H. Keeler, Acting Director at Volpe Center is also Director of the Office of Aviation Programs. He joined the Volpe Center in January 2006 after concluding a very successful assignment as the Director of NASA's Independent Verification and Validation Facility in Fairmont, WV (2001-06), where he was responsible for the overall management of the IV&V Facility providing mission critical software.

Ned holds a Bachelor's degree in Engineering from the United States Coast Guard (USCG) Academy and was commissioned as an officer in 1963. He received his aviator's wings in 1965 and amassed over 6,000 pilot hours during his career, principally flying search and rescue, and law enforcement missions. In 1970, Mr. Keeler received his master's degree in Electrical Engineering from the U.S. Air Force Institute of Technology. He also served as an avionics engineer, radio navigation researcher, information resource management systems engineer and program manager. He was a commander of a USCG Air Station and the USCG Research and Development Center. His work at the center resulted in the award of a Legion of Merit medal and recognition both nationally and internationally. After his Coast Guard career, Ned joined NASA, serving in the Space Station Freedom program, and later in the Office of Space Flight's Advanced Launch Technology and Advanced Flight Systems programs.

Mr. Keeler then left NASA for private industry, first working for Stanford Telecommunications as its Navigation Department Manager, and then to GTECH Corporation as Projects Director, before returning to NASA.

Jim Kolb is the Sr. Director of Automotive Programs for the Plastics Division of the American Chemistry Council which includes the Automotive Center located in Troy, MI. He is responsible for representation of the plastics industry to automotive OEM’s, automotive tier suppliers and allied associations such as USCAR, AIAG and OESA. Jim is also responsible for implementing several new anticipated initiatives as outlined in the Plastics Division’s *“Plastics in Automotive Markets Vision and Technology Roadmap,”* including research, government advocacy and automotive plastics infrastructure improvement.

His automotive and plastics expertise includes over 30 years of experience in the industry with a number of suppliers, including Dow Automotive, Essex Specialty Products and Bayer USA. He has held positions in sales, commercial development and marketing; participating in a number of industry firsts for plastics in the auto industry such as bumper systems, body panels, instrument panels and passenger safety systems. Prior to coming to the Plastics Division, he was with Omni Tech International Ltd., a global consulting firm for the chemical and plastics industries, where he led automotive business & market development, including commercialization of bio-based industrial materials.

Paul A. Lagace is a Professor of Aeronautics and Astronautics and of Engineering Systems at the Massachusetts Institute of Technology. He currently serves as co-Director of the Technology Laboratory for Advanced Materials and Structures (TELAMS) and served for several years as the co-Director of the Leaders for Manufacturing (LFM) and Systems Design and Management (SDM) Programs -- both joint ventures of the School of Engineering and the Sloan School of Management. He is a highly regarded international authority on the response and failure of composite structures and recognized as a national leader for the development of composite structures technology. He has frequently served as an advisor and consultant to industry and government agencies. He graduated from M.I.T. in 1978 with an S.B. in Aeronautics and Astronautics and pursued his graduate education at M.I.T. in Aeronautics and Astronautics earning his S.M. in 1979 and his Ph.D. in 1982. Since joining the faculty in 1982, Professor Lagace has conducted research in the areas of mechanics, fracture, longevity, damage resistance, and damage tolerance of composite materials and their structures. The work has an experimental orientation, but development of analytical tools has also been pursued with a particular objective of developing efficient analytical methodologies that are useful in performing parametric studies early in the design process. More recent work has specifically addressed the issues of lengthscales in the damage and failure of composite materials and their structures and the use of such in structural design. He has published widely on these topics and on general topics related to composite materials and their structures. He has recently pursued interest in the more generic systems issues related to technology and its use.

Professor Lagace has taught courses in the areas of mechanics of materials and structures with special emphasis on composite materials and their structures and has developed courses dealing with manufacturing with composite materials and advanced topics in composite materials and structures. With James Mar, he developed the video course series "Composite Materials". His recent interests have led him to develop courses in “Systems Thinking” and a freshman course on the “Essentials of Engineering”. He has received departmental teaching and advising awards, an Institute award for excellence in undergraduate teaching, and a Class of 1960 Faculty Fellowship. He is a MacVicar Faculty Fellow in recognition of his contributions to undergraduate education. He is a member of several societies, a Fellow of the AIAA, the ASC, and the ASTM, and has served as President of the International Committee on Composite Materials, being recognized as a World Fellow of Composites. In addition, he has served on a number of governmental committees and as a consultant to industry. He has received awards from various organizations and has delivered invited talks around the world

Kevin Pageau is currently an Account Executive with Tegrant Corporation. For the past 9 years he has worked with various Tier 1 suppliers and OEM’s developing and commercializing thermoplastic foams for energy absorbing applications in headliners, door panels, instrument panels, and seating systems. Kevin has over 25 years of automotive plastics application development experience, holding leadership positions in sales and engineering at GE Plastics, BP Amoco, and various automotive suppliers. He is a Senior Member and Honored Service Member, Society of Plastics Engineers (SPE), and member of SAE. He holds a BS, Mechanical Engineering, Michigan Technological University

Dr. Jackie Rehkopf is a Senior Engineer at Exponent, in the Vehicle Engineering Practice, investigating issues related to failure analysis and part performance. Prior to joining Exponent, Dr. Rehkopf worked for 12 years in materials R&D for an automotive OEM. Dr. Rehkopf has developed expertise in high strain rate behavior of materials, having developed testing capabilities for high strain-rate tensile/compression testing at rates representative of automotive crash situations, and having evaluated a broad spectrum of materials for vehicle applications including AHSS, aluminum, magnesium, engineering plastics, and glass-fiber reinforced plastics. Dr. Rehkopf also has expertise in the areas of fatigue and creep, with emphasis on reinforced and non-reinforced polymers. Dr. Rehkopf has vast experience with component performance, particularly plastic fuel tanks and other fuel system components, bumpers, energy-absorbing foams, and plastic interior vehicle components. In concert with this, Dr. Rehkopf has authored material and engineering specifications, conducted root cause analyses on manufacturing and field failures, and supported finite element analyses with experimental data and selection of material behavior models. She holds degrees in Civil Engineering (B.A. Sc. and. Ph. D).in from the University of Waterloo.

Dr. Khaled W. Shahwan is Current Chair of the Energy Management Working Group (EMWG) of the Automotive Composites Consortium (ACC) and works in the Experimental & Computational Mechanics Department of the Chrysler Technology Center-Scientific Laboratories, Chrysler LLC. He has been an active member within various ACC groups for 12 years. Prior to 1999, he was at Ford Research. He has over 19 years of R&D experience in computational mechanics and composites, and published over 30 publications. He is an Associate Fellow of the AIAA; Associate Editor of the *Journal of Engineering Mechanics;* Vice/Past Chair of the Stability Committee (EMI-ASCE); Member of ASME, ASCE, AAM, ASC, & USACM. He holds a Ph.D.in Aerospace Engineering from the University of Michigan-Ann Arbor, an MS Aerospace Engineering, and MS and BS degrees in Civil Engineering.

Stephen Summers is Acting Division Chief for the Structures and Restraints Research Division in the National Highway Traffic Administration (NHTSA) Office of Applied Vehicle Safety Research. He joined NHTSA in 1990 as a mechanical engineer working on vehicle safety research. Since then he has been responsible for a wide range of safety research assignments, including vehicle compatibility, rollover, advanced glazing systems, door latch, and heavy truck rear under-ride. He holds B.S. and M.S. degrees in Mechanical Engineering from the University of Maryland.

David A. Wagner is Technical Leader, Vehicle Design Research & Advanced Engineering at Ford Motor Company, where he helps shepherd cutting edge technologies developed by Ford researchers to the company’s brands and conducts his own research in the areas of lightweight vehicles and materials. “Lightweight materials are an important aspect in gaining fuel economy, but the vehicles must also be safe during a crash situation and durable for fifteen years,” he says. “Our goal is to increase fuel economy while maximizing the safety and durability of our vehicles.” He has been at Ford for eighteen years in research and advanced engineering, working on lightweight vehicles, safety and materials. Prior industrial experience includes six years at Exxon Production Research in Houston working on offshore oil platforms and pipelines. He holds a Ph.D. from Stanford University, and Mechanical Engineering degrees (M.S.C.E and B.S.C.E.) from the University of Notre Dame.

Charles David (Dave) Warren is currently the Program Manger for Transportation Composites at Oak Ridge National Laboratory. He is the Field Technical Manager for Composites in the Automotive Lightweighting Materials effort, a part of the FreedomCAR Initiative of the Department of Energy Office of Vehicle Technologies. With 20 years of experience in the field of composite materials, Dr. Warren is a graduate of Vanderbilt University where he completed all of his undergraduate and graduate work in materials science and engineering. Formerly, as lead materials engineer for developing the Peacekeeper, Small ICBM and Rail Garrison programs Dr. Warren served as a Captain in the United State Air Force prior to joining ORNL in 1991. Dr. Warren has authored 45 technical publications mostly in composite materials development and application.

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APPENDIX 3, ACKNOWLEDGEMENTS

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