CHARACTERIZING AND ENHANCING THE SAFETY OF FUTURE PLASTIC AND COMPOSITE INTENSIVE VEHICLES (PCIVs)

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ABSTRACT

There is concern that a trend toward smaller, lighter, fuel-efficient vehicles could adversely affect overall fleet safety. Since 2006, the U.S. Congress has directed the National Highway Traffic Safety Administration to "*examine the possible safety benefits of lightweight plastic and composite intensive vehicles (PCIVs)"* with Federal and industry stakeholders. This paper identifies near-term research priorities and partnership opportunities to facilitate the deployment of safe and energy efficient PCIVs by 2020.

A critical literature review and focused survey of subject matter experts identified knowledge gaps on automotive composites crashworthiness and consensus safety research priorities. Initial results were published in a 2007 PCIV Safety Roadmap report with milestones to 2020. The roadmap was developed to address development of plastics and composites crashworthiness test standards, improved computational simulation tools, and automotive design strategies.

Additional inputs on key safety issues for automotive composites were obtained from an August 2008 experts' workshop, which examined in depth critical near-term research priorities and strategies to meet crash occupant protection challenges for future PCIVs.

There is broad consensus that future PCIV structural composites with high energy absorption may enhance crash safety by preserving occupant compartment strength and protecting crush space. Near-term cooperative research is needed to:

- improve understanding of composite failure modes in vehicle crashes,
- develop a database of relevant parameters for composite materials, and
- enhance predictive models to avoid costly overdesign.

PCIV safety research is synergistic with ongoing NHTSA research (hydrogen and alternative fuel vehicle safety, integrated safety, crash occupant protection), the US Government (DOE/USCAR consortia), and the global automotive industry and research community.

This paper concentrates on safety-related research issues, assuming that other potential barriers to PCIV deployment (e.g., economic viability, manufacturability, sustainability) will be resolved. An updated safety roadmap and supporting cooperative research efforts are planned to facilitate the development and deployment of PCIVs with equal or superior crash safety by 2020.

INTRODUCTION

In fiscal year 2006, the United States Congress directed the National Highway Traffic Safety Administration (NHTSA) to *"begin development of a program to examine the possible safety benefits of lightweight Plastics and Composite Intensive Vehicles (PCIVs)*" and to develop a foundation for cooperation with the Department of Energy (DOE), industry and other automotive safety stakeholders. NHTSA tasked the Volpe National Transportation Systems Center (Volpe Center) to conduct focused research, in cooperation with industry partners from the American Plastics Council (APC), now the American Chemistry Council - Plastics Division (ACC-PD).

NHTSA's goal is to evaluate the potential safety benefits of plastics and composites applications in the emerging lighter weight, more fuel efficient and environmentally friendly vehicles. The PCIV safety research project is synergistic with ongoing NHTSA research efforts (hydrogen and alternative fuel vehicle safety, integrated safety, crash occupant protection). PCIV safety research also supports global and national efforts to improve vehicles' energy efficiency and preserve the environment with equal or better safety performance and affordability.

THE PCIV SAFETY RESEARCH ROADMAP

In 2007, the Volpe Center published "*A Safety Roadmap for Future Plastics and Composites Intensive Vehicles (PCIV)*" [1]. The report described the approach, activities, and results of an evaluation of potential safety benefits of PCIVs. The safety-focused effort complemented earlier and more general technology integration roadmaps developed by ACC-PD [2].

A simplified summary of the 2020 PCIV Safety R&D Roadmap priorities is shown in Figures 1 and 2. Figure 1 summarizes the strategic research priorities and timeline for 2020 PCIVs while Figure 2 addresses options to enhance PCIV safety performance.

Strategic Priorities for 2020 Plastics and Composite Intensive Vehicles Safety Assurance

Major Challenges: Perform focused, coordinated and integrated safety research, development, test, and evaluation Program to improve crash-safety performance of plastic/composite components and subsystems for a 2020 PCIV.

Research, Development, Test, and Evaluation Priority

	Near-term (2007-2010)	Mid-term (2010-2015)	Long-term (2015-2020)
Materials Selection	Perform research and technology to address "knowledge gaps" on crash-safety performance of PC materials	Modeling and simulation to verify and validate plastic/composite crash safety in structural, semi-structural applications	Demonstrate integrated safety performance for prototype PCIV to enable commercial deployment
Materials Selection	• Standardize testing protocols for composite materials	• Validate plastic/composite materials choices in safety applications	• Industry crash-test and self-certify PCIV safety
Testing Crash Performance	• Characterize mechanical behavior of plastic/composite materials in safety applications	• Prototype and test components (door panels, roof, front and back "crush boxes")	• Identify and overcome PCIV crash-compatibility problems for all occupants
Testing Crash Performance	• Establish comprehensive Database for light-weighting materials options	• Verify and validate for baseline PCIV design to evaluate integrative safety system performance	• Demonstrate enhanced PCIV safety performance for older occupants (using advanced dummies)
PCIV Integration	• Refine predictive engineering tools for Modeling and Simulation of PCIV components and system crash performance	• Devise and evaluate special crash- protection needs for older occupants	• NHTSA verifies PCIVs compliance with crash- safety regulatory requirements
Milestones		• Test Standards Issued • CHM-17 Crash Energy Database Standardized and Current • Modeling and Simulation Crash Safety Tools Available	• PCIV Structural and Propulsion Validated for Realistic Crash Loads • Full PCIV System is Crashworthy • Improved Older Occupants Survivability is Demonstrated

Figure 1: Strategic priorities for 2020 plastics and composite intensive vehicle (PCIV) safety assurance [1]

Enhancing Plastics and Composites Intensive Vehicles Safety Performance With Plastics

Challenges / Milestones

- Design concepts
- Materials screening
- Testing standards
- Simulations and validation
- Systems integration
- Crash safety testing
- Performance metrics
- PCIV deployment

Performers	Near-term (3-5 years)	Mid-term (5-10 years)	Long-term (10-15 years)
Industry – Government – University Public Private Partnerships (P3)	Research, Development, and Technology on Automotive Composites	Test & Evaluation Of PCIV Prototype Crash Safety	System Integration of PCIV Safety Technologies 10-15 yrs.
	Develop Testing Standards and Safety Evaluation Tools for PCIV Designs 1 yr.	Crash Safety Verification & Validation Simulations 5-6 yrs.	PCIV Commercial Deployment 15+ yrs.
	Select Lightweight Structural Materials for PCIV 2-3 yrs.	Crash Safety Testing & Validation For PCIV Subsystems and Vehicle 6-8 yrs.	
	Develop PCIV Materials Processing / Parts Fabrication 3-5 yrs.		
NHTSA Role	NHTSA Monitors Progress in Crash Safety Research and Development	NHTSA Evaluates Results of Crashworthiness Verification & Validation	NHTSA Verifies PCIV Crash Safety Compliance (NCAP and FMVSS)

Figure 2: Enhancing plastics and composite intensive vehicle (PCIV) safety performance with plastics [1]

The Volpe Center conducted structured interviews with leading subject matter experts (SMEs), representing a broad cross-section of automotive safety stakeholders. Interviews were complemented by written inputs and supporting materials provided by the SMEs. The process identified priority knowledge gaps and safety research and development (R&D) needs to predict the crashworthiness of automotive composites. The SMEs encouraged NHTSA participation in cooperative research efforts on automotive light-weighting, and in standards development activities for structural polymeric composites.

The Volpe Center also reviewed and summarized the knowledge base on automotive light-weighting materials crash safety, and identified related national and international research programs offering high-leverage partnership opportunities. Federal and industry initiatives identified include the DOE FreedomCAR and Fuel Partnership consortia and the Advanced Lightweight Materials Program [3], which develops strong, lightweight vehicle material options to improve energy efficiency.

There is broad consensus that future PCIV structural composites with high energy absorption may enhance crash safety by preserving occupant compartment strength and volume to optimize crush space. Composite materials standards development efforts are particularly important for designing PCIVs that meet NHTSA crashworthiness requirements and the associated occupant protection challenges.

These roadmaps defined safety-related R&D activities for near-term (three to five years), mid-term (five to ten years) and longer term (ten to 15 years), as well as milestones and metrics for progress towards the successful design, development, and deployment of lightweight, fuel-efficient and environmentally sustainable PCIVs. Near-term cooperative research is needed to:

- improve understanding of composite failure modes in vehicle crashes,
- develop a database of relevant parameters for composite materials, and
- enhance crash damage predictive models to avoid costly overdesign.

The focus of this project was on the identification of PCIV crash safety research needs germane to the NHTSA vehicle safety mission, and complementary to DOE/USCAR industry consortia research on vehicle light-weighting materials [3]. Thus, it was assumed that other potential barriers to PCIV deployment (e.g., economic viability, manufacturability, sustainability) would be resolved by 2020 through other efforts.

Research Needs to Predict the Crashworthiness of Composite Automotive Structures

The safety roadmap development effort identified high-priority research needs for advancing the design and analysis of composite automotive structures for crashworthiness. These would enable greater utilization of automotive plastics and composite materials in future PCIVs. They include:

- Continued refinement of full three-dimensional analysis modeling tools;
- Understanding of how failure and energy absorption are controlled by processes at several length scales;
- Inclusion of all damage modes (and associated failure models criteria) in computational models;
- Consideration of interaction effects in crashes;
- Standardized tests for fatigue, creep, and aging effects;
- Consideration of structural configurations in impact crash performance;
- Understanding issues related to manufacturing and lifetime handling;
- Inclusion of probabilistic aspects of failure; and
- Identification and proper modeling of the actual crash reality (i.e., geometry and force).

Research Needs for Occupant Safety

High confidence in PCIV safety performance characterization will also require research to:

- Improve statistical crash data analysis to understand how severity of injuries and survivability vary with age and identify mitigation options.
- Develop stronger passenger compartment designs with frontal crush boxes.
- Improve the occupant restraints and seating systems to restrict side head movements and limit head and neck injuries.
- Adaptive restraint systems "tuned" to occupant size, weight, and age or fragility.
- Reduce impact loads with customized occupant space (seating, bolsters, belt system) for improved protection and comfort.
- Optimize the design and performance of the combined passive and active restraints system ("sum total of interior passive foams, active air bags and belts").
- Verify that PCIVs would be sufficiently safe in the case of a post-crash fire.

Other industry-identified priority PCIV safety applications include:

- Four-point seat belts and seat belt limiters to protect aging drivers;
- Plastics that have strain-to-fail characteristics similar to steel that are not strain rate or temperature sensitive;
- Vehicle structure that produces a similar vehicle crash pulse as current production vehicle structures using metal (aluminum or steel);
- Enhanced visibility (glass composites to reduce nighttime glare); and
- Pre-crash sensors for gentler deployment of safety devices (smart air bags, load limiters, inflatable seat belts).

Near-Term Safety Research Priorities

The near-term (three to five year) PCIV R&D priorities identified in the roadmap process include:

- Stronger foam filling on side doors and posts, combined with soft foam padding on interior surfaces to mitigate side impact intrusions;
- Rigid "structural foams" to fill in and reinforce metal roof structure and pillars in order to mitigate rollover injuries;
- Use of lightweight plastic structures in roofs to lower the center of gravity of top heavy vehicles;
- Improvement of cushioning and belt restraints (e.g., use woven cylindrical seat belts, four-point attachments);
- Use of "smart" materials for "smart" safety devices; and
- Standardization to high-performance safety subsystems (such as head restraints, seat system designs, etc.).

A cross-functional PCIV industry team identified additional near-term research topics to address specific NHTSA safety requirements in the relevant Federal Motor Vehicle Safety Standards (FMVSS) through the use of:

- Interior plastics and foams to address applicable NHTSA safety requirements (e.g., FMVSS 201 - Occupant protection in interior impact; 207 - Seating systems; 208 - Occupant crash protection; and 214 - Side Impact protection);
- Vehicle body enhancement foams that address NHTSA crash safety performance regulations (e.g., FMVSS 208, 214, and 216- Roof crush resistance);
- Seatbacks responsive to standards (e.g., FMVSS 202A - Head restraints); and
- Bumper structural strength for both occupant and pedestrian protection in low speed crashes (49 CFR Part 581 – Bumper Standard).

Mid-Term Safety Research Priorities

The mid-term (five to ten year) R&D priorities identified in the roadmap process include:

- Validated composite components;
- OEM design guidelines for automotive composites;
- Validated crashworthiness performance of Carbon Fiber Reinforced Composites using improved:
  - Testing standards for high-rate impacts;
  - Energy absorption predictive tools;
  - Three-dimensional computer modeling of material behavior versus time;
  - Durability testing standards;
  - Verification in full-scale field testing; and
  - Integrated designs for active seat belt, air bags, and seat systems to enhance protection in side impacts.
- Development of new PCIV designs (three to seven years); and
- Marketing of successful PCIV prototype (seven to ten years).

The industry team specified priorities such as:

- Interior and exterior plastic applications;
- New Federal Motor Vehicle Safety Standards (FMVSS) for vehicle occupant protection development that appropriately accommodate PCIVs; and
- Vehicle body engineered systems to support new FMVSS requirements.

Long-term Safety Research Priorities

The long-term (ten to 15 year) R&D priorities identified in the roadmap process include:

- Utilization of improved fiber reinforced plastics for rigid door panels, to tailor energy absorption to depth of deformation in side crashes;
- Improved vehicle occupant protection;
- Reduce the mass of the entire fleet, or reduce the mass of the heaviest vehicles;
- Improved passive and active safety devices that can compensate for any disadvantage of lighter weight and smaller size cars in collisions with larger and heavier vehicles; and
- Use of advanced materials (e.g., nano-composites, hybrid polymers, bio-polymers, and natural fiber materials) in automotive safety applications, but only to the extent they can meet crash and performance requirements.

THE 2008 PCIV SAFETY WORKSHOP

In August 2008, NHTSA sponsored and the Volpe Center organized and hosted a workshop for subject matter experts (SME) entitled *"The Safety Characterization of Future Plastic and Composites Intensive Vehicles"* [4]. Its primary purpose was to obtain and integrate inputs and clarifications to the roadmap process that would facilitate the definition, characterization, and quantification of safety benefits expected from using advanced plastics and composite materials for the next generation of mass-market lightweight, fuel-efficient vehicles. A related goal was to gather lessons learned from the use of structural composites in high-end, high-performance sports and racing cars that could be applied to mass-market PCIVs.

Approximately 50 leading experts on automotive safety and advanced materials representing government, industry, academia, and standards developing organizations attended the workshop. Presentations and focused discussions contributed to refining the near-term vehicle safety research roadmap, to facilitate safety-centered PCIV design and deployment by 2020. The workshop findings will broaden, deepen and clarify the PCIV Safety Roadmap research and development priorities, and better define relevant PCIV safety metrics and milestones. [4]

The thematic presentations were followed by focused panel discussions that engaged the experts on specific PCIV safety issues in order to:

- Build consensus on the PCIV Safety Roadmap research and development priorities
- 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.

Industry experts noted that plastics consume just 3% of US oil and natural gas and account for only 10% of the material in automobiles, but offer the possibility of improved fuel-efficiency (through mass reduction), design flexibility, durability, environmental sustainability through end of life (EOL) recyclability, and enhanced crash safety. Additional safety-enhancing applications were cited such as plastic bumpers and fenders to improve pedestrian safety in crashes.

Refined Definition of PCIVs

The focused discussion after the first technical session addressed the definition of PCIV. There was the sense that, for the time being, systems such as the engine block were not plausible applications for intensive utilization of plastics. Other vehicle systems were more amenable to redesign in plastics and composites. Attendees representing Original Equipment Manufacturers (OEMs) and material suppliers 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 less stringent than the DOE/USCAR light-weighting "Factor of Two" goal desired for improved fuel efficiency.

Automotive Safety Applications of Plastics and Composites

Attendees were asked to expand on the list of applications in which the use plastics and composites could enhance vehicle and fleet safety. The safety benefits for the structural and semi-structural applications in the Body In White (BIW) were treated separately from those applications designed to sustain impacts and the interior applications of padding intended to redistribute, deflect and cushion impact forces on the occupants (thicker, softer plastic foams, air bags, and restraints).

Data indicate that smaller and lighter vehicles are more "crash-involved" (despite presumed enhanced maneuverability) and therefore less safe in collisions with heavier and larger vehicles [5]. Some experts believe that weight disadvantage in crashes could be offset by maintaining size and crush space to protect the occupants. The use of strong but lightweight composites could improve both safety and fuel efficiency. At any given crash velocity, lighter cars have less crash energy. Reduced vehicle weight across the fleet could also reduce the weight disparity and improve crash safety. [6]

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 compartment crush protection, but these nose cones may not be sufficiently robust in off-axis collisions and shear loading to be applicable to passenger vehicles. 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). Such lightweight PCIVs would presumably have a shorter stopping distance as well.

Workshop participants believed that careful application of plastics and composites could enable enhanced crush zone dimensions with minimal impact on interior and exterior dimensions. Robust crush zone behavior is needed for this concept to be viable in production vehicles. Designers particularly cautioned against using high energy absorption components to shrink the crush zone; the effect would be to spike the deceleration forces on the occupant compartment, yielding greater occupant decelerations and increased risk of injury.

Attendees noted the promise of composite parts to promote structural engagement during vehicle-to-vehicle crashes, but these concepts would need to be supported by:

- Parts consolidation
- Mass adjustments
- Flexibility in designing component geometry
- Design to improve energy absorption
- Improved understanding of the effects of process and geometry on performance.

Current Practice for Automotive Materials Selection

It is crucial to understand how new materials and technologies infiltrate a generation of vehicles. Industry representatives discussed the process of materials selection. The key criterion is value, including initial cost, life cycle cost, and profitability in the context of performance. In particular, a material change can occur only if the value or unique capability (e.g., safety benefits) is clear to both producers and customers.

Materials selection is increasingly facilitated by better data on crush characteristics and by evolving modeling tools. Mandatory performance requirements (e.g., new CAFE regulations) hold the promise of encouraging the use of composite materials for both light-weighting and crash strength. The value of durability, longevity and damage tolerance of composites might also spur further material substitution. On the other hand, a potential unintended consequence of improved durability and immunity to corrosion is that it might delay fleet renewal and thus fleet penetration of future safety advances.

The value of a composite system or sub-system must be considered at the vehicle level. The point was made several times at the workshop that feedback loops such as mass compounding (i.e., lighter structure requires smaller engine, etc.) can enable concepts that might appear questionable as isolated material replacements. The ability to optimize a structure early in the design process (in lieu of material replacement in a subcomponent redesign) can radically affect material selection.

Design tradeoffs will come into play in these applications just as in any other. For example, enhanced safety might be enabled at the expense of reparability. Automobile manufacturers must carefully consider how this might affect consumer acceptance. It might be acceptable if the expense of replacement components and their installation could be kept low relative to traditional repair.

Alternatively, OEMs might consider how economical repair of composite components could become a more viable option for PCIVs. Repair education for OEM dealership and independent repair shops would be essential to ensure quality and integrity of the repair. Repair facilities would likely need to be OEM-certified in plastics and composites repair. A partnership might 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.

Analytical Techniques for Estimating Crash Safety Performance

The process of developing computational models and comparing them to physical reality is important. The degree of imperfection of a model and the regime over which the model is accurate can eventually lead to understanding of the underlying phenomena. Thus, advances in materials characterization and computational modeling often go hand-in-hand.

The safety analysis of a vehicle depends on the fidelity of several analytical layers. Material models must appropriately capture the behavior of materials (especially deformation and failure) over a wide range of loading environments. Once these models are verified for general material classes, parameters for specific materials must be determined – usually through extensive material testing. These properties may be sensitive to manufacturing processes. Finally, the component geometry and loading details must be understood and modeled. Each of these layers will be important in the design and testing of plastic and composite components expected to see crash loading.

There is concern that not all failure modes and conditions are accurately addressed by current models. The consequence is often that good engineering practice results in costly overdesign. Models can particularly have trouble with the myriad local failure conditions and interactions that are important on the microscale. For example, composites plies with unidirectional fibers can be subject to transverse cracking which can adversely affect strength. A failure criterion developed for and verified with fabric composite structures could therefore significantly overestimate component properties if applied to a structure with unidirectional plies.

Participants were concerned with appropriate materials characterization. Baseline static and dynamic data are needed for all categories of composites in order to evaluate their crash compatibility. Another need is to define appropriate test coupons for different types of composites (e.g., fiber-filled, long vs. short fiber, weave, etc.). Precompetitive cooperation in developing material models and test specimens was deemed preferable. "Round robin" testing and modeling was suggested (e.g., modeling of specific medium-size component, specific loading) to determine the degree of disagreement between different test procedures and models.

It was also noted that material properties determined from coupon tests can be quite different from the in situ values realized in composite components. Processing affects material properties and models often do not reflect these effects adequately.

There was concern regarding the confidence in current computational analyses. Attendees indicated that 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 can reach 80-90% accuracy. At the vehicle level, it appears that engineering modeling tools are currently inadequate to predict real crash performance for specific materials and designs, while real-world crashes are difficult to control and simulate.

Therefore, one suggestion was to revive the DOE/USCAR Automotive Composites Consortium (ACC) Focal Project 3 (FP3) whole vehicle crash analysis effort. FP3 had been 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 models for multi-materials vehicles must improve considerably. The key questions are:

- 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?

Crash energy management that combines protective designs with advanced structural materials was considered by the SMEs at the workshop to be the key safety research need [4]. Multiple approaches to energy management warrant considerations of multiple materials and material configurations (resin, foam, profiles, etc). The use of plastics and hybrid, sandwich structures that combine metals and composites may be more cost effective than polymeric composites per se.

CONCLUSIONS REGARDING THE PCIV SAFETY RESEARCH STRATEGY

Safety research for future PCIVs must be strategically focused on providing adequate tools and data to the automotive industry. This will allow the industry 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 could be explored as a method to enhance and facilitate the deployment of integrated safety concepts. In particular, the ability to tailor shape and stiffness could be used to "tune" the vehicle's structure and may create sufficiently enhanced maneuverability to optimize some crash avoidance strategies. There could 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.

Several research topics suggested by the SMEs also appear as priority activities identified by the November 2005 ACC-PD workshop [2]. Those selected for the Safety Roadmap development have near-term aspects (e.g., development of improved predictive tools and certified databases on the mechanical properties of advanced automotive composites) that can be continued in the mid-term (e.g., verification and validation of the improved crashworthiness modeling tools). Similarly, the most promising mid-term activities should also have promise and payoffs for long-term PCIV safety technology integration and deployment. For instance, PCIV prototyping and crash testing are needed to demonstrate enhanced protection for all occupants, including the elderly.

NEXT STEPS

Follow-on research partnerships are planned to broaden, deepen, and implement the key near-term PCIV Safety Research Roadmap priorities.

Ongoing NHTSA-sponsored PCIV safety research will focus on the near-term consensus PCIV R&D priorities identified above. PCIV R&D partnership opportunities, that are being currently explored so as to leverage limited resources, include:

- Collaboration with the DOE National Laboratories and DOE/USCAR light-weighting materials crashworthiness and occupant safety consortia;
- Joint funding (with the ACC-Plastics Division and DOE) of Standards Developing Organizations (like the Society of Automotive Engineers), to accelerate the development of testing standards of polymeric composites at high strain rates typical of vehicle crashes;
- Participation in collaborative efforts to update the Composite Materials Handbook (CMH-17) materials testing, database development and modeling tools, specifically its Crashworthiness Working Group (CWG);

- Co-sponsorship of leading academic research Centers of Excellence pursuing research on automotive and aerospace composites.

Further strategies to cost effectively meet the crash safety challenges for lighter vehicles will be considered. The Volpe Center team plans to investigate how overall crash safety in crashes is impacted by structural application of advanced materials for given weight, size and geometry. The team will consider how occupant safety in lighter vehicles can be enhanced by combining crash avoidance systems with advanced occupant restraints.

The approach of this multi-year project and accomplishments to date are intended to facilitate development and deployment of next generation safe and fuel efficient PCIVs by 2020.
This conference offers an opportunity to invite international cooperation on automotive composite materials crashworthiness characterization, quantification, modeling and demonstration [7, 8]. Progress in safety research, technologies and strategies for emerging global platform automotive prototypes of smaller and lighter composite-rich vehicles can inform this project. Inputs from and knowledge sharing with international peers and stakeholders promise to accelerate the resolution of potential PCIV crash safety challenges. International cooperation to quantify the safety of structural composite materials in the early design phases is needed to achieve common goals for crash safety performance and enable early deployment of energy-efficient, sustainable, affordable commercial PCIVs by 2020.

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STATUS OF NHTSA'S HYDROGEN AND FUEL CELL VEHICLE SAFETY RESEARCH PROGRAM

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ABSTRACT

Safety information is vital to support the FreedomCAR and Fuel Partnership, a cooperative automotive research effort between the U.S. Department of Energy, the U.S. Council for Automotive Research (USCAR), and fuel suppliers. This partnership began in 2003 as part of the President's goal to reduce U.S. dependence on foreign oil, improve vehicle efficiency, reduce vehicle emissions, and make fuel cell vehicles a practical and cost-effective choice for large numbers of Americans by 2020. NHTSA's safety initiative complements these efforts by conducting research to support determination of fuel system integrity performance criteria that address the unique hazards posed by the onboard storage of hydrogen and the operation of high voltage fuel cells used to provide electrical current for hydrogen fuel cell vehicle (HFCV) powertrains.

This paper provides a description and timeline of the research tasks initiated in fiscal year 2009 to support the development or acceptance of proposed safety performance criteria for HFCVs. This is the third such status report published in these conference proceedings [1,2].

INTRODUCTION

Current Federal motor vehicle safety standards (FMVSS) set performance criteria for fuel system crash integrity for vehicles using liquid fuels, compressed natural gas, and battery drive systems. Analogous FMVSS do not currently exist for hydrogen fueled vehicles, but are desired by industry in order to facilitate their introduction into the marketplace. To this end, NHTSA has initiated a research program to generate data to assess the safety performance of HFCV fuel systems under similar crash conditions to those prescribed in the existing FMVSS, and to identify and assess any additional life-cycle safety hazards imposed by these unique propulsion systems. Examples of such hazards are rapid release of chemical or mechanical energy due to rupture of high pressure hydrogen storage and delivery systems, fire safety issues, and electrical shock hazards from the high voltage sources, including the fuel cell stack and ultracapacitors.

In addition to generating research data to support the development of the FMVSS, NHTSA has also undertaken co-sponsorship, with Germany and Japan, of an effort to develop a global technical regulation (GTR) for HFCVs under the auspices of the Economic Commission for Europe, Inland Transport Committee, World Forum for Harmonization of Vehicle Regulations (UN/ECE WP 29 Group pf Experts on Passive Safety (GRSP), Working Group on Hydrogen).

The objective of this working group is to develop a GTR in the 2010 – 2012 timeframe that (1) attains equivalent levels of safety as those for conventional gasoline powered vehicles, and (2) is performance-based and does not restrict future technologies [3].

BACKGROUND

For the purpose of ensuring fuel system integrity of passenger vehicles in front, side and rear impact crashes, NHTSA has promulgated regulations that impose limits on post-crash fuel leakage under representative crash test conditions. Analogous regulatory requirements exist for electrical isolation of high voltage batteries in electric and hybrid electric vehicles, post-crash. These conditions are defined in FMVSS 301, Fuel System Integrity, FMVSS 303, Fuel System Integrity of Compressed Natural Gas (CNG) Vehicles, and FMVSS 305, Electric-powered vehicles: electrolyte spillage and electrical shock protection [4]. FMVSS 301 limits liquid fuel leakage to 28 grams per minute post crash, and FMVSS 303 limits the leakage of natural gas to an energy equivalent measured by a post-crash pressure drop in the high pressure portion of the fuel system. FMVSS 305 requires an electrical isolation limit in ohms/volt post-crash between the high voltage battery and the vehicle chassis. Additional component level performance requirements for compressed natural gas cylinders are imposed in FMVSS 304, Compressed Natural Gas Fuel Container Integrity [5].

In the interest of providing a safe test environment, current vehicle compliance crash tests are conducted using a non-flammable substitute in the fuel tank so that post crash fuel leakage may be measured without posing a fuel-fed fire hazard to laboratory personnel or property. In the case where vehicles normally use liquid fuels, Stoddard fluid is the substitute, and in the case where vehicles use compressed natural gas, the substitute is nitrogen gas. The fuel storage systems are filled to 100% capacity prior to testing.

If the vehicle is electric or an electric/internal combustion engine (ICE) hybrid, the propulsion battery is charged to its nominal or operational voltage and the vehicle ignition is in the "on" position (traction propulsion system energized) prior to the crash test so that post-crash electrical isolation between the battery system and the vehicle electricity-conducting structure can be verified.

In developing the test plan for HFCV safety assessment, NHTSA considered these existing standards as a starting point, and began to develop a strategic plan for addressing component and system level safety, by filling in the matrix in Figure 1.

<table>
<tr><th></th><th>Fuel System Integrity in Crashes</th><th>Container Integrity</th><th>Electrical Isolation Of Fuel Cell Stack</th></tr>
<tr><td>(Analogous FMVSS requirements)</td><td>(FMVSS 301/303)
Post-crash leakage limits</td><td>(FMVSS 304)
Pressure cycling, burst, and bonfire exposure</td><td>(FMVSS 305)
Electrical isolation of high voltage system</td></tr>
<tr><td>Test condition modifications for HFCV's</td><td>Test with an inert fuel as with previous FMVSS crash testing?

Test at low pressure to assess increased vulnerability of composite containers to impact loading?</td><td>Real world data indicates localized flame, life cycle integrity are safety issues.</td><td>Conduct post-crash fuel cell stack isolation testing with an inert/no-fuel inventory?</td></tr>
<tr><td rowspan="2">Research tasks to assess safety performance under proposed test conditions

(Industry standards, Japanese Regulations) [6,7,8,9,10,11]</td><td>Assess fueling options for crash test:
He fill
H_2 fill
Low Pressure H_2 fill</td><td>Cumulative life cycle testing vs. discrete testing
(SAE 2579/ISO 15869 test procedures)</td><td rowspan="2">Assess Helium/no fuel option using megohmmeter
(apply an external voltage and conduct resistance test)

Assess low volume H_2 testing option to allow function of fuel cell during crash test</td></tr>
<tr><td>Assess hazardous conditions in and around vehicle posed by pass/fail H_2 leak rates/volumes</td><td>Engulfing bonfire vs. localized flame impingement test</td></tr>
</table>

Figure 1: Research Task Matrix to Assess Fuel System Integrity of HFCVs

Performance based criteria which have been proposed by other standards developing organizations and regulatory authorities were also considered in developing the research matrix. (Society of Automotive Engineers (SAE), International Organization for Standardization (ISO), Japanese regulations, European Integrated Hydrogen Project (EIHP) drafts.) For the sake of clarity, the research tasks identified in the cells in the matrix are given the following titles and will be discussed in order. Each of these tasks was initiated in October 2008. Therefore, as of this writing, they have not progressed to the point of generating results. The periods of performance for these tasks range from eight to twenty-four months.

Task 1: Proposed Fueling Options for Crash Testing

Task 2: Cumulative Fuel System Life Cycle and Durability Testing

Task 3: Hydrogen Leakage Limits/Fire Safety

Task 4: Electrical Isolation Test Procedure Development

Task 5: Localized Fire Protection Assessment for Compressed Hydrogen Cylinders

PROGRAM OVERVIEW

Task 1: Proposed Fueling Options for Crash Testing

Background The Japanese regulation, Attachment 17, Technical Standard for Fuel Leakage in Collisions, Etc., requires testing with helium as the non-flammable surrogate for hydrogen, and prescribes an average leakage limit of 131 NL/min (normal liters/minute) over the following 60 minute period. However, for the purpose of conducting fuel system integrity crash tests of hydrogen fueled vehicles, SAE 2578, Recommended Practice for General Fuel Cell Safety, allows three different fueling options for determining post-crash hydrogen leak rate and setting pass/fail criteria equivalent in energy content to FMVSS 301/303 leakage criteria. Tests may be conducted utilizing hydrogen or helium as a nonflammable substitute at full service pressure, or utilizing low pressure hydrogen. Conducting vehicle crash tests at full service pressure is consistent with the fill requirements of FMVSS 303, which utilizes nitrogen as the non-flammable substitute for CNG. However, NHTSA has witnessed some vehicle manufacturer crash tests employing the low pressure hydrogen option. Using low pressure hydrogen allows for monitoring of fuel cell electrical output and isolation post-crash. Also, the storage cylinders, specifically Type IV composite cylinders, which are used to store hydrogen at pressures up to 10,000 psi, are more vulnerable to impact at low pressure. At high pressure the cylinders are more resistant to deformation during impact, due to increased stiffness from the opposing internal load on the composite cylinder walls, thus the low pressure test option may be considered "worse case."

Objective The purpose of this research effort is to determine the most appropriate fueling conditions for conducting fuel system integrity crash tests of hydrogen fueled vehicles, and to assess pass/fail leakage requirements that are analogous to those prescribed for vehicles utilizing conventional liquid fuels and CNG. In making this determination, existing regulations and industry standards should be considered.

General Requirements NHTSA's test plan for this task consists of three subtasks:

The first subtask consists of conducting controlled leak tests to determine whether the scaling up of a low pressure leak to represent a high pressure leak, (due to increased flow rate at higher pressure), is a viable approach, as proposed in SAE J2578. A comparative assessment between hydrogen and helium leaks will also be conducted to provide pressure-based and mass-based comparisons.

The second task is to conduct a comparative assessment of Type IV container strength at high and low pressures that simulate front, side and rear crash exposures, and to determine the loading conditions under which composite cylinders are most likely to fail. NHTSA will conduct dynamic impact or drop tests simulating vehicle crashes, on cylinders filled to 10% and 100% of service pressure in both the horizontal and vertical orientations.

The final subtask will be to assess the crash performance of hydrogen cylinders which are packaged in vehicles. In the absence of any commercially available HFCVs for testing, NHTSA will conduct full-scale crash tests on CNG vehicles which have been retrofitted with hydrogen storage systems to establish baseline fuel system vulnerability data, and develop test procedures.

The cylinders used for testing will be representative, both in pressure rating and internal volume, of those installed in HFCVs. Using representative cylinder sizes is important because the proposed allowable leak rate in grams per minute is a constant. Because the allowable pressure drop for a given leak rate is inversely proportional to cylinder size, large cylinders may be more difficult to monitor, given the smaller allowable pressure drop. Combining that with corrections for instrumentation tolerances and temperature fluctuations, the total measurement error could exceed the allowable ten percent of the measured pressure drop.

Task 2: Cumulative Fuel System Life Cycle and Durability Testing

Background The Society of Automotive Engineers (SAE) recently drafted Technical Information Report (TIR) 2579, Recommended Practice for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles, which specifies durability and expected service performance verification testing of hydrogen vehicle fuel systems. These are tests that evaluate the cumulative, compounded stress of multiple exposures of the fuel system to pneumatic fueling/defueling (pressure cycling), and parking during variable ambient temperature conditions, including durability of the fuel system after drop and chemical exposure. Existing standards for high pressure fuel systems, such as CNG, require a series of discrete tests that may not provide an adequate assessment of real world exposures. For CNG vehicles however, real world fuel system performance data is available. This TIR document is intended for use during the 2008-2009 pre-commercial period of technology development and vehicle evaluation to obtain fueling and fire exposure performance data that is lacking. Industry is currently conducting research to evaluate these test methods in order to ensure that they are appropriate and practical.

Objective Because there is little real world or experimental data available concerning the safety performance of high pressure composite fuel systems, research is needed to generate cumulative lifetime exposure data. It is expected that on-road demonstration vehicles may not yet incorporate systems consistent with these requirements; however, data is needed to simulate field experience from these draft procedures.

General Requirements NHTSA is conducting its own evaluation of these test procedures, including an assessment of fuel system performance to modifications of these test procedures, based on the results of the initial testing and on additional alternatives, such as those under consideration in Japan [12], to assess cumulative lifecycle exposures under differing conditions of use.

Task 3: Hydrogen Leakage Limits/Fire Safety

Background SAE 2578 and the Japanese regulations for post-crash fuel system integrity specify leakage limits for hydrogen for the 60 minute period following front, side and rear crash tests. These limits are based on energy equivalence to the leakage limits specified in FMVSS 301 for liquid fuels, and FMVSS 303 for compressed natural gas. However, the properties of hydrogen are different from other fuels and may pose lesser or greater risk of fire post-crash. Gasoline will pool and dissipate slowly. CNG, like hydrogen, is lighter than air and will rise and dissipate. Hydrogen will dissipate more rapidly than CNG if it is not confined, but may be able to enter into vehicle compartments more easily than liquid fuels or CNG, and has a much wider range of flammability in air than other fuels.

Objective NHTSA is conducting research, including theoretical calculation and experimental verification, of the fire safety of proposed hydrogen leakage limits. This assessment will support rulemaking objectives to adopt post-crash pass/fail leakage criteria that provide an adequate level of safety to passengers, rescue personnel, and other people in the vicinity of a crash.

General Requirements Research tasks will determine the time and leakage rates required to attain hydrogen concentration levels in confined areas such as the trunk, occupant compartment, and under hood that reach or exceed the lower flammability limit. Hazardous conditions will be assessed by conducting ignition tests in confined areas approximating vehicle compartment volumes at different hydrogen concentrations. Follow-on testing will simulate post crash leakage into the occupant compartment, trunk area, and engine compartment, of conventional vehicles, including vehicles which have been crash tested in front, side and rear impact tests, to determine hydrogen leakage rates that would impose hazardous conditions post-crash.

Task 4: Electrical Isolation Test Procedure Development

Background As mentioned earlier, in the interest of providing a safe test environment, current vehicle compliance crash tests are conducted using non-flammable substitutes for fuel so that post-crash fuel leakage may be measured without posing a fuel-fed fire hazard to personnel or property. Electric vehicles are tested with a fully charged battery.

In the case of fuel cell vehicles, where the high voltage source is a fuel cell stack rather than a battery, the operating voltage is dependent upon the flow of hydrogen through the stack and the electrochemical reaction with oxygen which generates electrical current. Therefore, in order to maintain the operating voltage of the stack to measure post-crash isolation, hydrogen must be present. However, since hydrogen is flammable, using it in a crash test environment may pose additional risk to personnel and property.
In order to mitigate this additional risk, some industry practices and existing regulations for hydrogen fueled vehicles indicate a preference for crash testing with helium onboard rather than hydrogen. The Japanese Regulation, Attachment 17, Technical Standard for Collisions, Etc., requires that helium be used as a substitute for hydrogen when conducting crash tests to measure post-crash leakage.

Drafts of SAE 2578, "Recommended Practice for General Fuel Cell Vehicle Safety," allow three different fueling options for crash testing and calculation of allowable leak rates. These options are based on fueling to capacity with helium or hydrogen, or fueling with reduced pressure hydrogen. The draft document states that "fuel system integrity and electrical integrity may be tested simultaneously or separately. If performed separately, electrical integrity testing can be performed with a partial or no fuel inventory." This statement implies that electrical integrity testing may be accomplished with an inactive fuel cell, but does not explicitly state how to conduct the test. SAE J1766, "Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing," also suggests using an isolation resistance tester (also called a megohmmeter) to perform electrical isolation testing, but does not provide a procedure for doing so [9].

The Japanese regulation, Attachment 101, Technical Standard for Protection of Occupants against High Voltage in Fuel Cell Vehicles, Attached Sheet 3, Insulation Resistance Measurement Method, allows using a megohmmeter to apply a high voltage from the outside to measure isolation resistance when the drive battery is disconnected and the fuel cell in a stopped state. This requirement does not apply post-crash, but it is similar to the SAE requirement in that the vehicle's high voltage system is effectively "unfueled" in the stopped state. Section 2-1-3-1 states that, "after confirming that no high voltage is applied," (i.e., from the vehicle), "the insulation resistance shall be measured by applying a DC voltage higher that the operating voltage of the powertrain.

In summary, it appears that it may be possible to measure electrical isolation using a megohmmeter to apply an external voltage to an inactive fuel cell, but precautions must be taken to ensure that there is no residual voltage present on the vehicle at the time of the test. Given the complexity of fuel cell vehicle electrical systems, testing is required to ensure this test can be conducted without damaging either the test equipment or the vehicle electrical system, or result in any false readings or electrical faults.

Objective The objective of this research task is to develop the test procedure for conducting post-crash electrical isolation verification for fuel cell vehicles, in the absence of hydrogen, for the reasons discussed in the previous section. In developing the test method, an electrical system representative of a real HFCV electrical system should be used to conduct the tests.

General Requirements NHTSA is conducting research to determine whether post crash electrical isolation testing using a megohmmeter is feasible, and whether additional precautions concerning residual energy, fuel cell coolant, or any other unforeseen electrical system issues need to be addressed when considering this option.

Task 5: Localized Fire Protection Assessment for Compressed Hydrogen Cylinders

<u>Background</u> Localized fire exposure at a location remote from a cylinder's pressure relief device(s) can cause high pressure composite containers to rupture if the rising temperature increases internal pressure above the cylinder's burst pressure, or when the material strength of the cylinder is lost as the composite is burned away.
This hazardous condition has been identified in the real world of CNG vehicles, causing the rupture of 3600 psi rated storage cylinders [13,14]. Currently, hydrogen cylinders are rated to even higher service pressures of 5000 to 10,000 psi. In engulfing bonfire tests, pressure relief devices (PRDs) usually activate and vent before the cylinder strength is compromised. Therefore, a localized flame test procedure that can be used to assess whether a vehicle's fuel system performs safely has been sought by stakeholders, and one such test was recently developed under a Transport Canada contract. This procedure assesses the effectiveness of shielding and remote sensing technologies that mitigate the hazards of this fire condition.

<u>Objective</u> The objective of this research task is to employ the localized fire test developed under contract to Transport Canada to assess the performance of mitigation technologies, which either protect the entire system from flame exposure, or ensure activation of PRDs under this test condition.

<u>General Requirements</u> Evaluate various fire protection technologies that will reduce the risk of cylinder failure during a vehicle fire (i.e., remote sensing, heat transfer, etc.).

1. Obtain samples of various protective coating materials and evaluate fire resistance using localized fire test procedure.

2. Apply selected coating materials to unpressurized composite-reinforced tanks and determine their insulating properties when exposed to localized fire test conditions.

3. Evaluate the ability of various remote sensing technologies to detect heat on the extremities of tanks and activate pressure relief devices.

4. Conduct evaluation of pressurized hydrogen fuel tanks using localized flame test procedure with factory supplied heat shielding and, if necessary, with various protective coating materials

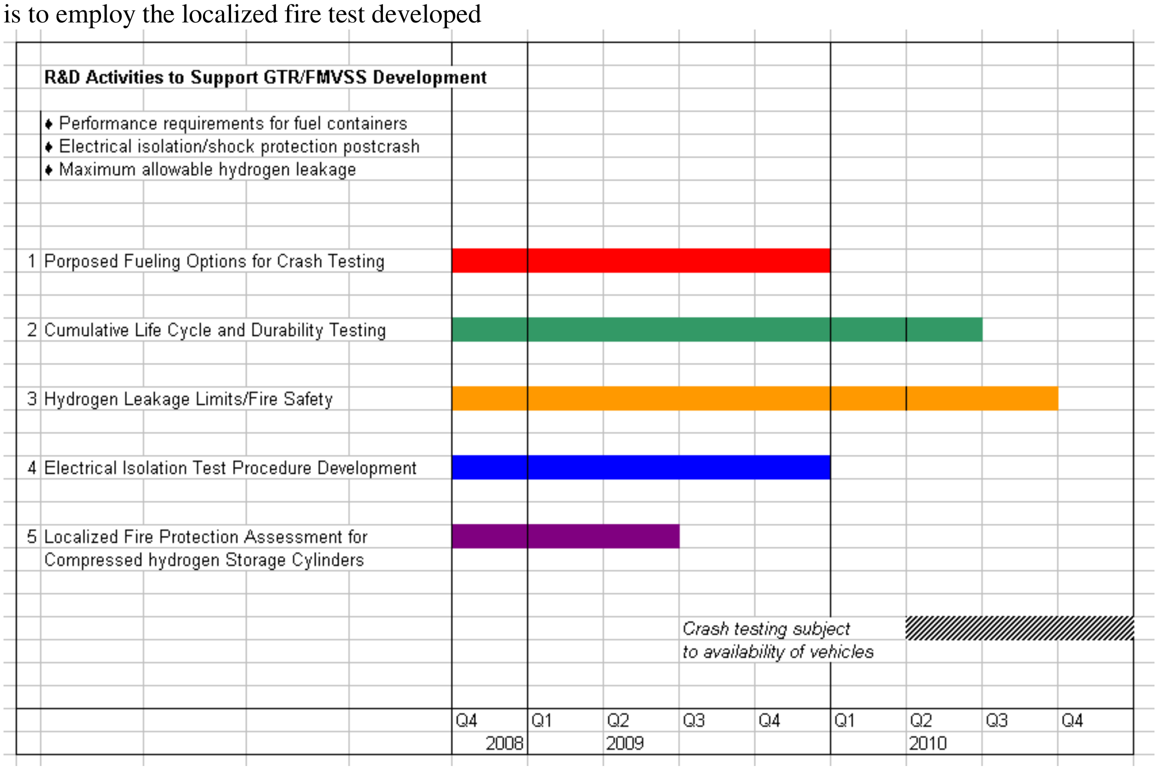

Figure 2: Timeline for Completion of Research Tasks 1 – 5

Research Timeline and Future Planning:
The research tasks described briefly in this paper are scheduled for completion in 2009 and 2010 as illustrated in Figure 2.
A task management system is being employed to prioritize, refine, and integrate flexibility into the task work plans as the program progresses. NHTSA is also monitoring international progress in vehicle design, codes and standards development, safety assessment, and demonstration fleet performance. Advances in any of these areas may effect the direction and focus of NHTSA's research efforts, and certainly will serve to guide future strategic planning.

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