Status of NHTSA's Hydrogen and Fuel Cell Vehicle Safety Research Program

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Abstract

The FreedomCAR and Fuel Initiative is a cooperative automotive research partnership between the U.S. Department of Energy, the U.S. Council for Automotive Research (USCAR), and fuel suppliers. It was initiated in 2002 as part of the President's goal to reduce U.S. dependence on foreign oil, improve vehicle efficiency, reduce emissions, and make hydrogen fuel cell vehicles (HFCVs) a practical and cost-effective choice for large numbers of Americans by 2020.

Following the announcement of the FreedomCAR program, NHTSA began collecting information on the status of hydrogen vehicle technology and drafting a research plan to address the impact of fuel cell and hydrogen fuel systems on vehicle safety. In 2004 NHTSA published the plan in the Federal Register for public comment and issued a voluntary request to manufacturers asking them to provide written information on their strategies to ensure that hydrogen fueled vehicles attain a level of safety comparable to that of conventionally fueled vehicles [1]. Additionally, NHTSA published an updated version of this plan for the 19th Enhanced Safety of Vehicles Conference [2].

Funding to initiate NHTSA's hydrogen safety research program was not made available until 2006. This paper provides a status report on several projects assessing hydrogen fuel system safety that were initiated that year, and the follow-on work that will be conducted in 2007.

Introduction

NHTSA's mission is to save lives, prevent injuries, and reduce vehicle related crashes, which it does through a variety of means including testing and statistical research, regulation and enforcement, and educational programs. Often a safety problem will be identified through statistical analysis of real world crash data or reported failures, and then a test program is executed to determine the cause and to assess remedial strategies.

Previous reports have identified fuel system integrity as the unique safety challenge in hydrogen and fuel cell vehicles [1,2]. Current Federal Motor Vehicle Safety Standards (FMVSS) for fuel system integrity set performance criteria to limit crash induced leakage in vehicles powered by liquid fuels and compressed natural gas, and impose post-crash electrical isolation and electrolyte spillage limits for electric vehicles [3]. However, no analogous regulations currently exist in the U.S. to ensure fuel system integrity for hydrogen or fuel cell systems because crash integrity information does not exist to support data-driven performance requirements. Research is required to assess the unique characteristics of hydrogen and fuel cell propulsion system safety performance in crashes.

Hydrogen is colorless, odorless and difficult to contain when compared to conventional fuels like gasoline, diesel, and compressed natural gas. Its flammability, buoyancy, and dispersion properties are different; and it can cause embrittlement of some metals, which could lead to failure of fuel lines and other components. Hydrogen storage methods range from very high-pressure gas storage to cryogenic liquid, and chemical and solid metal hydrides. Each of these storage methods presents specific hazards should the containment fail due to a crash or defect in fail-safe design. Because fuel cells are electrical devices they operate at high voltage and currents so that electrical shock, isolation, and ignition of surrounding materials are issues to be considered in a safety assessment.

In addition to the challenges presented above concerning fuel handling and fuel system architecture of hydrogen and fuel cell vehicles, there are more practical concerns that set them apart from conventionally fueled vehicles in terms of safety assessment.

First, there is a lack of real world safety performance data because the vehicle population is very small. Hydrogen fuel cell vehicles number only in the hundreds worldwide, are used under strictly controlled conditions in demonstration fleets, and are typically accompanied by trained personnel from the manufacturers that build them. The vehicles are prototypes and preproduction prototypes for which very few of a given model exists. Because they are experimental vehicles, they are also usually over-engineered to meet more stringent safety factors than those to which a typical production vehicle would be built. If any particular safety issue comes up in the demonstration of the vehicle, the manufacturer is on hand to pull it out of service and repair or retire it immediately based on assessment of the problem. Because these vehicles are managed so closely, there is no history associated with them of real world driving experience, maintenance, aging, or crash exposure.

A second issue which affects the practical aspect of assessing hydrogen fueled vehicle safety is the cost and availability of components and vehicles to test. Vehicles are not currently available on the open market for purchase and testing. Other than testing conducted in-house by manufacturers, the results of which are proprietary, there is no opportunity at this time for an independent safety assessment of vehicle crashworthiness.

A third concern is the relevance of any safety assessment that is conducted on prototype vehicles or their components. As mentioned earlier, prototypes are expensive, low production vehicles that may be over-designed for safety and utilize components, materials, and packaging architectures that are not representative of designs that will eventually be mass-produced for the market.

Despite these challenges, a strong interest in effecting a safe transition to hydrogen and fuel cell vehicles is supported by government and industry worldwide. This support has been critical to the implementation of NHTSA's research program. Collaboration and cooperation is essential to promoting a comprehensive safety initiative that will provide benefits to consumers, the economy, and the environment.

Objective

The objective of this research program is to assess fuel system integrity of hydrogen and fuel cell vehicles through real world data collection, research testing, and analysis. This assessment will ultimately support promulgation of FMVSS and Global Technical Regulations (GTRs) that afford an equivalent level of safety to vehicle occupants, emergency response personnel, and the public, to that provided by enforcement of the existing fuel system integrity requirements for conventionally fueled vehicles.

Status of 2006 Research Projects

Four safety assessment projects were initiated in 2006 for hydrogen and fuel cell vehicles. These projects were selected in conjunction with market research consisting of collaborative talks with stakeholders in government and industry on the scope of near-term research topics, the state of recommended practices ensuring fuel system safety performance, and the availability of test articles from which useful test protocols could be developed and executed to assess a subset of fuel system safety issues at the component and subsystem levels. It is anticipated that the results of these projects form a foundation for a future assessment of fuel system integrity and fire safety at the full vehicle level.

Projects are discussed in the order of their initiation:

Project 1: Evaluation and Comparative Assessment of the Fuel System Integrity Performance Requirements of Existing Industry Standards and Government Regulations

NHTSA is actively working with other countries and international communities to develop GTRs for vehicle safety under a Program of Work of the 1998 Global Agreement administered by the United Nations World Forum for the Harmonization of Vehicle Regulations. Consequently, NHTSA has been collaborating with international partners to develop a GTR for hydrogen fuel cell vehicles. The effort, which was formally kicked off in FY 2006, seeks to ensure the development of a comprehensive, performance-based and data driven GTR that would ensure the integrity and safety of hydrogen fuel cell powered passenger vehicles. A GTR is desirable because it would enable manufacturers to build vehicles for a global market, easing the economic burden of producing vehicles designed to meet divergent national and regional regulatory safety requirements.

There are several Standards Developing Organizations (SDOs) and regulatory bodies that have issued final or draft requirements for hydrogen fuel cell vehicle safety. During the development of a GTR or FMVSS, these standards and regulations can be used as the basis for technical discussion. In order to better understand these requirements, NHTSA is conducting a comparative assessment of those standards, directives and regulations specific to onboard vehicle fuel system safety and crashworthiness at the component, system, and full vehicle levels. Table 1 shows a list of the standards under consideration at this time. Culmination of this project will result in a final report detailing similarities, redundancies, and differences in performance and design restrictive requirements of each standard. This study is being conducted by Battelle Memorial Institute under NHTSA contract. The final report will be made available in 2007.

Table 1: Standards for Fuel System Integrity of HFCVs

Standard	Title/Description
SAE J2578	Recommended Practice for General Fuel Cell Vehicle Safety
SAE J2579	Recommended Practice for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles (draft)
ISO 23273-1	Fuel Cell Road Vehicles – Safety Specifications – Part 1: Vehicle Functional Safety
ISO 23273-2	Fuel Cell Road Vehicles – Safety Specifications – Part 2: Protection Against Hydrogen Hazards for Vehicles Fueled with Compressed Hydrogen
ISO/DIS 23273-3	Fuel Cell Road Vehicles – Safety Specifications – Part 3: Protection of Persons Against Electrical Shock
WP.29 Draft Standard for Compressed Gaseous Hydrogen	Proposal for a New Draft Regulation for Vehicles Using Compressed Hydrogen
WP.29 Draft Standard for Liquid Hydrogen	Proposal for a New Draft Regulation for Vehicles Using Liquid Hydrogen
Japanese HFCV Regulations	Attachment 17, 100, 101
CSA HGV2	Standard Hydrogen Vehicle Fuel Containers (Draft)
CSA HPRD1	Standards for Basic Requirements for Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers (Draft)

Project 2: Failure Modes and Effects Analysis (FMEA) for Compressed Hydrogen Fuel Cell Vehicles

A failure modes and effects analysis is a tool through which potential failures, and remedial fail-safe strategies may be assessed and ranked in terms of consequence to assist engineers in reiterative design to mitigate hazards. Prior to conducting any physical testing of HFCVs, NHTSA decided that a structured, high-level FMEA would be helpful in determining potential areas of concern for assessment of HCFV crashworthiness and fuel system safety.

This assessment formalizes the process through which NHTSA determines how best to implement its test plan to generate data that evaluates fuel system safety performance under the current front, side, and rear impact conditions specified in the FMVSS.

The first task under this project, which is being conducted by Battelle under consultation with NHTSA and vehicle manufacturers, is development of a generic, high-level schematic of a compressed HFCV fuel system. This schematic is not representative of any one vehicle design. It identifies and links the components that are expected to be common in all vehicle architectures. This includes multiple hydrogen storage tanks, (assuming around 4 kilograms of onboard hydrogen storage), fill port, the fuel delivery system, coolant system components, fuel cell stack, humidifier, valves, pressure relief devices, regulators, pumps, and hydrogen sensors.

From this schematic, a table is being developed that lists each of the critical components in the vehicle schematic, which at this point number around thirty, and applies the seven descriptors shown in Table 2 below, to each:

Table 2: FMEA Table Outline and Example Entries (Work in progress)

N	Subsystem/ Component	Component Description	Component Function	Potential Failure Modes	Failure Mode Consequence	Counter measure	Relative Risk
1	Compressed Hydrogen Storage Tanks	Type III, IV Rated to 10,000 psi Temp 20 - 180 F	Store and deliver hydrogen fuel to fuel system				
2	Thermally activated Pressure Relief Device (PRD)	Thermally activated valve that employs thermal expansion or melting to activate	Release pressure in case of extreme temperature exposure				
n							

Upon completion of populating Table 2 through the sixth descriptor, "Countermeasures," a panel of experts will convene to prioritize and rank each failure mode in terms of the risk and hazard imposed by that failure.

The final report from this assessment will be available in 2007.

Project 3: Electrical Isolation Test Procedure for Hydrogen Fuel Cell Vehicles

Fuel cells generate electricity through a catalytic chemical reaction between hydrogen and oxygen. Current FMVSS 305 *Electric-Powered vehicles; electrolyte spillage and electric shock protection*, sets post–crash requirements for electrical isolation of the high voltage system for electric vehicles, but is written specifically for vehicles utilizing high voltage batteries. In the case of a crash, FMVSS 305 requires that electrical isolation be maintained between the charged traction battery system and the vehicle chassis. Unlike a battery, which is an electrical storage device, the operating voltage of a fuel cell stack is dependent upon the hydrogen flow through the system. The goal of this project is to develop an analogous test procedure for evaluating electrical safety of high voltage fuel cell systems under the same front, side and rear crash conditions prescribed in FMVSS 305.

Of concern is the fire safety of conducting crash tests with a combustible fuel onboard the vehicle. Currently, NHTSA conducts FMVSS compliance crash tests using non-flammable surrogate "fuels" to detect post-crash fuel system leakage. In the case of liquid-fueled vehicles, such as those utilizing gasoline or diesel, a replacement called Stoddard solvent is used. Stoddard solvent has a specific gravity close to that of liquid fuels, but is much more difficult to ignite. For testing compressed natural gas (CNG) vehicles, nitrogen is used as the surrogate to detect fuel leakage through a pressure drop in the system. NHTSA has not yet promulgated a standard for crash testing hydrogen fueled vehicles, but it would be likely, given the recommendations of current industry practices (i.e., those being reviewed under project 1) that helium would be used as a surrogate fuel to assess fuel leakage in crashes.

Since a hydrogen supply is necessary to provide the electron flow through the high voltage propulsion system of a fuel cell vehicle, determining electrical safety in a crash test using helium as the surrogate energy carrier would not keep those portions of the propulsion system that are dependent upon the fuel cell for power generation active. Therefore, NHTSA is exploring different methods for testing post-crash electrical isolation in a laboratory setting that minimize the risk to the technicians conducting the tests.

Under this contract, Battelle, in consultation with NHTSA and vehicle manufacturers, is developing a generic schematic of an HFCV electrical system and tabulating isolation hazards and requirements in conjunction with a review of applicable industry standards for shock prevention. The standards under review are listed in Table 3.

Table 3: Standards for Electric Shock Protection

Standard	Title
ISO 23273-3:2006	Fuel cell road vehicles – Safety specifications – Protection of persons against electric shock
ISO 6469-3:2001	Electric road vehicles – Safety specifications – Protection of persons against electric hazards
SAE J1766 June 1998	Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
SAE J1766 April 2005	Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle High Voltage Power Generation and Energy Storage Systems Crash Integrity
FMVSS 305	Electric-powered vehicles; electrolyte spillage and electrical shock protection
SAE J2579	Recommended Practice foe Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
IEC 60479-1 & 2	Effects of current on human beings and livestock

Several test methods are under consideration for measuring post-crash electrical isolation at this time, both with and without hydrogen onboard the vehicle at the time of the test. Following selection of the most appropriate of these methods, the contractor will draft a test procedure and validate its efficacy through bench top testing. A draft work plan will also be developed for potential full scale demonstration testing at a later date. The results will be documented in a comprehensive report which will be published in 2007.

Project 4: Compressed Hydrogen Fuel Container Integrity Testing

As a key early step in its strategy for ensuring safety of hydrogen fuel cell vehicles, NHTSA desires to conduct component level integrity testing of the cylinders used to store high pressure hydrogen on HFCVs. FMVSS 304 *Compressed natural gas fuel container integrity*, specifies performance, labeling, and inspection requirements for compressed natural gas (CNG) motor vehicle fuel containers [3]. Typically CNG containers are rated up to 3,600 psi service pressure. Hydrogen containers are typically rated from 5,000 to 10,000 psi service pressure, but, although industry standards exist, NHTSA currently imposes no regulatory requirements on their performance.

In order to generate performance data on HFCV storage integrity, research oriented testing of hydrogen cylinders will be performed in general accordance with FMVSS 304, and any applicable or draft industry standards and test specifications analogous and/or supplemental to those requirements, and specific to hydrogen storage. Testing is being conducted at Southwest Research Institute by the Department of Fire Technology under contract to NHTSA, and the proposed test matrix is currently under review.

As mentioned earlier, hydrogen vehicle components, including the storage cylinders used on prototype vehicles, are not readily available on the open market. However, four different models of “off the shelf” cylinders have been identified for NHTSA’s first round of integrity testing. It is hoped that as the HFCV safety program progresses, more test articles that are actually in use on state-of-the-art vehicles will become available.

The four models that will be tested initially are NGV2-2000 certified cylinders of type 3, composite metallic full wrapped, or type 4, composite non-metallic full wrapped.

The draft test matrix is shown below in table 4.

Table 4: Hydrogen Cylinder Test Matrix

Test Type	Pass/Fail Criteria	Test Description	Reference Std/Reg	Test condition/ comments	
Bonfire	20 minutes or vent	Position longitudinal axis of cylinder horizontally over uniform fire source 1.65 meters in length, > 430 degrees Celsius	FMVSS 304	100% fill	10% fill
Pressure Cycling	No leakage	13,000 cycles between 100% and $\leq$10% SP, and 5,000 cycles between $\leq$ 10% and 125% SP	FMVSS 304	Fleet cycle, 4 refuelings/day, 300 days, 15 years.	
Penetration Test	No rupture	Penetration of at least one cylinder wall with a .30-in. caliber bullet	ISO 15865	100% fill	10% fill
Hydrostatic Burst	2.25x service pressure	Increase pressure to minimum prescribed burst pressure at a rate up to and including 200 psi per second and hold constant for 10 seconds	FMVSS 304	Test to failure Cylinders that survive other tests will be tested to failure	

Tests may include instrumentation beyond the requirements of the certification test procedures, e.g., addition of strain gauges, pressure transducers, thermocouples, and any cylinders that pass the test criteria will be hydrostatically burst-tested to failure.

Testing will be documented in a final report that should be made available in May 2007.

Plans for FY 2007 HFCV Research and Testing

HFCV technology is developing rapidly as evidenced by the recent announcements by GM and Honda that they will be releasing wholly new vehicles for demonstration in the near future. GM plans to begin placing its new Equinox FCV with customers in the fall of 2007, and Honda plans limited introduction in 2008 of a new FCV based on its FCX Concept.

To aid in planning follow-on research to the projects discussed in this paper, NHTSA published a Request for Information (RFI) in December 2006, to identify potential sources, costs, and schedule estimates for obtaining hydrogen and fuel cell vehicles, fuel system components, and test facilities with the capabilities to conduct fuel system integrity research testing.

Specifically, this RFI sought the following information:

- Availability and cost of hydrogen fueled vehicles and fuel system components for destructive testing.
- Availability of facilities, personnel, expertise, material and equipment to perform fuel system integrity testing and evaluation of hydrogen fuel systems and fuel system components.
- Schedule estimates and costs for component, systems level, and full scale vehicle fuel system integrity testing.
- Information concerning likely fuel system packaging configurations and test methods to assess failure mitigation strategies for hazards imposed by crash or fire exposure.
- Information concerning the value of using purpose-built, generic hydrogen fuel systems to collect baseline performance data in crash or fire exposure testing.
- Suggestions for evaluating fuel system safety in prototype or preproduction vehicles, through non-destructive assessment or testing.

The responses to this RFI are being analyzed and will help define the scope and scheduling of near and long term projects assessing HFCV safety. In the near term, NHTSA plans on expanding physical testing from single cylinders to plumbed cylinder assemblies to assess deceleration and crash performance at the subsystem level. It also plans to subject cylinders and plumbed arrays to flame impingement testing to assess pressure relief device performance with remote, localized heating. NHTSA also hopes to obtain vehicles from manufacturers for testing, which could include non-destructive assessments such as hydrogen sensor sensitivity testing, leak detection while garaged or parked, and electrical isolation testing during normal operation.

Future Work

As the industry matures, NHTSA will continue to monitor the progress of vehicle and standards development, and assess each through testing and analysis. Although most manufacturers are utilizing high pressure hydrogen storage at this time, it is likely that the industry will continue to explore cryogenic and low pressure hydrides as options for the future, so that as those systems come closer to utilization, they will have to be assessed for safety performance as well.

References

[1] U.S. Department of Transportation Docket Management System, http://dms.dot.gov/search/searchFormSimple.cfm, Docket No. NHTSA-2004-18039

[2] Hennessey, B., Hammel-Smith, C., Koubek, M., "NHTSA's Four-Year Plan for Hydrogen, Fuel Cell, and Alternative Fuel Vehicle Safety Research," 19th International Conference on the Enhanced Safety of Vehicles, Washington, DC, 2005

[3] CFR 49 Transportation, Chapter V - National Highway Traffic Safety Administration, Part 571—Federal Motor Vehicle Safety Standards, §571.301, §571.303, §571.304, §571.305, http://www.access.gpo.gov/nara/cfr/waisidx_05/49cfr571_05.html