Onboard Hydrogen/Helium Sensors in Support of the Global Technical Regulation: An Assessment of Performance in Fuel Cell Electric Vehicle Crash Tests

Matthew B. Post, Robert Burgess, Carl Rivkin, and William Buttner
National Renewable Energy Laboratory

Kathleen O'Malley
U.S. Department of Energy and Sentech

Antonio Ruiz
U.S. Department of Energy

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-56177
September 2012

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Onboard Hydrogen/Helium Sensors in Support of the Global Technical Regulation: An Assessment of Performance in Fuel Cell Electric Vehicle Crash Tests

Matthew B. Post, Robert Burgess, Carl Rivkin, and William Buttner
National Renewable Energy Laboratory

Kathleen O'Malley
U.S. Department of Energy and Sentech

Antonio Ruiz
U.S. Department of Energy

Prepared under Task No. HT127110

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5600-56177
September 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Acknowledgments

- Support was provided by the U.S. DOE Energy Efficiency & Renewable Energy, Fuel Cell Technology, Safety Codes and Standards Program.
- Nha Nguyen, Barbara Hennessey and Brian Park of the U.S. Department of Transportation for defining requirements and organizing access.
- Kelsey Chiu of KARCO Engineering for site access and bracket design and fabrication, and on-site logistics for the non-FCEV crash test.
- Andrew Cox and Douglas Pape of Battelle and Jeffery Sankey of Transportation Research Center, Inc., for on-site logistics for the FCEV crash tests.
- Lois Brett of the Institute for Energy and Transport, Joint Research Centre for ongoing collaborations on hydrogen sensor technologies and for helpful discussions on the sensor.
- Scott McWhorter of the Savannah River National Laboratory for comments and suggestions on the project and this report. Currently on assignment at the U.S. Department of Energy Fuel Cell Technologies Program.

Definitions

CAN	Controller Area Network
DAQ	data acquisition system
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
FCEV	fuel cell electric vehicle
FMVSS	Federal Motor Vehicle Safety Standard
G	gravity force
GTR	Global Technical Regulation
H_2	hydrogen
He	helium
IR	instrument response
LDL	lower detection limit
NHTSA	U.S. National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
P_{O2}	partial pressure of oxygen
RH	relative humidity
slpm	standard liters per minute
TC	thermal conductivity
TRC Inc.	Transportation Research Center Inc.

Contents

Figures

Tables

1 Introduction

North American, European, and Asian automobile manufacturers project that commercial hydrogen fuel cell-powered light-duty road vehicles will be released by 2015 for general consumer applications. Initially they will be sold in select markets; a much broader market penetration is expected by 2025, when more than 1 million hydrogen fuel cell electric vehicles (FCEVs) are expected to be on the road in the United States [1]. Significant infrastructure implementation, including production capacity, transport, storage, and dispensing, is ongoing to prepare for the commercial introduction of FCEVs. Even more critical for the release of commercial hydrogen vehicles in the United States is the establishment of the Federal Motor Vehicle Safety Standard (FMVSS) for hydrogen-powered vehicles. To ensure international harmony, North American, European, and Asian regulatory representatives are striving to base their respective national regulations on an international safety standard, the Global Technical Regulation (GTR), Hydrogen Fueled Vehicle [2], which is part of an international agreement pertaining to wheeled vehicles and associated equipment.

1.1 Vehicle Safety Requirements Imposed by the Global Technical Regulation

Although presently the GTR is in draft form, it will likely form the basis for the U.S. FMVSS for FCEVs. The GTR stipulates that commercial hydrogen-powered vehicles achieve a level of safety at least equivalent to that established for conventional petroleum-powered vehicles. This requirement is validated by subjecting the vehicles to independent testing, including crash tests such as those performed under the auspices of the U.S. National Highway Traffic Safety Administration (NHTSA). The GTR stipulates specific performance requirements following crash tests for the FCEV fuel storage system. Specifically, the GTR mandates that for 1 h following crash test impact, the integrity of the fuel storage is maintained such that:

- Hydrogen release rate never exceeds 118 slpm (10.6 g/min).[a]
- The hydrogen concentration within the passenger, trunk, or other vehicle compartments does not exceed 4% by volume.[b]

The hydrogen storage system includes interfaces and hardware associated with:

- The fueling infrastructure
- Safety features
- Storage tank
- All storage media
- Any required insulation or shielding
- All necessary temperature and humidity management equipment
- Regulators, electronic controllers, and sensors

[a] Current regulations for gasoline-powered vehicles limit petroleum leakage rates to 28 g/min, which has an energy equivalent to a hydrogen leak rate of 118 slpm.
[b] The lower flammable limit of hydrogen is 4 vol%.

- All onboard conditioning equipment necessary to store the hydrogen (e.g., compressors, pumps, filters)
- Mounting hardware and hydrogen delivery systems.

The vehicle manufacturer is responsible to comply with the FCEV fuel storage crash test criteria mandated by the Federal Motor Vehicle Safety Standard. To verify compliance, the NHTSA will require vehicles sold in the United States to be subjected to random, independent standardized crash. If the hydrogen release rate or the in-vehicle hydrogen concentration limits are exceeded, the test is considered a failure, and the vehicle may be subject to a mandatory recall. Validated methods compatible with crash test deployment need to be developed to monitor for hydrogen releases from the vehicle fuel storage system and for accumulation within passenger, trunk, and other compartments. Such systems, when implemented in crash tests on FCEVs, will verify whether the test vehicle is in or out of compliance with the GTR requirements. For safety reasons, helium often serves as a surrogate for hydrogen in the crash tests.

1.2 Addressing the Global Technical Regulation Requirements

Compliance with the FCEV fuel storage crash test criteria can be demonstrated via two strategies:

- Release rates can be determined by the temporal monitoring of the pressure and temperature of the high-pressure hydrogen storage system after the crash test. These data can then be used to calculate the volumetric gas release rate using a validated thermodynamic equation of state, such as the hydrogen equation of state developed by the National Institute of Standards and Technology [3]. Although this approach should be sensitive enough to detect releases at the regulated levels, it may not detect slow releases, because the pressure and temperature transducers have limited sensitivity. Although low leak rates do not explicitly violate the integrity requirements set by the GTR, such leaks may form local pockets of enriched hydrogen in or around the vehicle and thereby pose a hazard.

- The work described in this report focuses on developing analytical protocols that will directly measure hydrogen concentration in vehicle compartments. The resulting analytical protocol will ensure that, following impact in a crash test, the hydrogen levels in passenger, trunk, or other vehicle compartments remain below the level regulated by the GTR. Hydrogen (or helium) concentrations in vehicle compartments will be directly measured using appropriately configured chemical sensors.[c] Such a system can also alert site personnel in charge of the crash test of unsafe conditions, such as hydrogen levels exceeding the flammable limit before the 1-h time limit set by the GTR. The sensors can

[c] Adopting the nomenclature developed in ISO 26140 [11] the term *sensing element* will refer to the component (electrochemical, thermal conductivity, etc.) that reacts with or responds to the analyte gas (e.g., hydrogen) to generate an electrical response, which then can be processed, directly or indirectly, into an electrical signal. In this report, *sensor* will refer to an instrumented system composed of a sensing element, control circuitry, and a user interface that provides analytically useful information to the end user.

also be configured for deployment near the hydrogen storage system to detect leaks, including low-level leaks not otherwise detectable by pressure transducers.

The U.S. Department of Transportation (DOT) recognized that hydrogen-sensitive monitors need to be incorporated as part of the crash test instrumentation, and recently sponsored a market survey of commercial hydrogen and combustible sensors for possible consideration as in-vehicle hydrogen monitors in crash tests [4]. This survey, however, focused on detecting combustible gases and hydrogen, and thus was of limited value for any test that used helium as a surrogate.

In separate work, Sandia National Laboratories and SRI International evaluated a procedure to indirectly determine the hydrogen concentration in vehicle compartments by using oxygen sensors to monitor the displacement of oxygen in air [5]. This approach applies to helium and hydrogen, but has potential drawbacks, including a marginal lower detection limit (LDL) and limited analytical resolution, which lowers the accuracy of monitoring slight changes in hydrogen concentration. There would also be ambiguity in directly correlating the displaced oxygen to incoming hydrogen, as displaced gas will likely be a mixture of hydrogen and air. Alternatively, if displacement is impeded, the influx of hydrogen will tend to increase the total internal pressure of the vehicle compartment, but will not affect the partial pressure of oxygen (P_{O2}). Because the oxygen sensor response is controlled primarily by P_{O2}, the hydrogen influx in a closed system may not be detected.

This report describes work performed in the National Renewable Energy Laboratory (NREL) Hydrogen Sensor Testing Laboratory to identify specific sensor technologies that are compatible with the GTR crash test requirements and the demonstration of the viability of the identified technology to perform the required measurements in real-world FCEV crash tests. This work can form the basis of a validated analytical method, deployable in crash tests to verify hydrogen safety in FCEVs.

2 Methods

NHTSA collaborated with a vehicle original equipment manufacturer (OEM) to acquire two similar models of demonstration FCEVs for deployment in crash tests, which were scheduled in late March to early April 2012. The available time allotment and limited budget precluded extensive development of the analytical method and pretest demonstrations. Fortunately, from earlier discussions with DOT personnel and in-house experience, a strategy was quickly formulated for deploying sensors in the FCEV crash tests:

- Identify critical performance parameters and assign corresponding specifications that are compatible with the proposed crash test plan. These specifications were guided by the GTR requirements.
- Identify technology types that would meet (or nearly meet) the identified metrics. This step leveraged the extensive sensor testing performed in the NREL Hydrogen Safety Sensor Test Laboratory.
- Identify a short list of specific sensor models that would potentially be compatible for the crash test environments. This was performed by reviewing manufacturer-published specifications, and by further leveraging the NREL sensor test laboratory experience in sensor evaluations.

For actual deployment, five units of an identified sensor were obtained and subjected to laboratory evaluations that were specifically designed to ascertain response factors to both hydrogen and helium. The sensors were then subjected to two series of standard crash tests:

- The first series was performed in conventional gasoline-powered vehicles to verify survivability of the sensors selected for deployment in real crash tests.
- The second series was performed on actual hydrogen FCEVs and thus provided an opportunity for a real-world validation of the proposed technology.[d]

Laboratory assessments were performed in the NREL sensor test laboratory before and after each field deployment to verify sensor integrity.

[d] By agreement with DOT and the vehicle OEM, the vehicle models deployed in the crash tests will not be identified.

3 Results

3.1 Sensor Requirements for Onboard Vehicle Crash Test Deployment

The selection of a sensor technology (or any other analytical system) should be based on an assessment of performance parameters (or metrics) as they pertain to a specific application. A discussion of major sensor parameters, along with numerous hydrogen applications, was previously presented by NREL [6]. The parameters can be divided into three main categories—analytical characteristics, deployment parameters, and operational parameters. The most important and obvious performance parameters pertain to the analytical characteristics of the device. These parameters are directly related to the ability of the proposed technology to perform the analytical measurements required by the application, which in this case is to determine hydrogen or helium concentration. However, deployment and operational parameters can also have significant impact on the compatibility of a sensor for the specific application. These parameters do not pertain to a sensor's ability to accurately detect the target analyte, but rather on other factors that can ultimately determine the suitability of a technology for a specific application. The deployment parameters pertain primarily to installing or incorporating the sensor technologies into a specific system; the operational parameters pertain to operating and maintaining the installed sensors. The critical performance parameters must be identified and assigned specifications. Of the nearly 40 parameters identified and previously discussed in the NREL report [6], the following, with the assigned specifications, were identified as most critical for deployment in FCEV vehicle crash tests.

- **Analytical**
    - Target analyte: H_2 or He (but not simultaneously)
        - Preferable to have a single system responsive to both H_2 and He
        - Minimal impact by other parameters (chemical, environmental)
    - Linear range: to 4 vol% in air (preferably to 8–10 vol%)
    - LDL: Better than 0.4 vol% (10% of designated action level of 4 vol%)
    - Analytical resolution: Better than 0.4 vol% (10% of the mandatory range)

- **Deployment**
    - Commercially available
    - Operable by battery for test duration (up to 4 h)

- **Operational**
    - Shock resistant (to withstand impacts associated with crash tests)
    - Electronic output for electronic logging of response
    - Output in or easily converted to engineering units (e.g., vol% H_2)

3.2 Platform Identification

To ensure the availability of reliable safety sensors, the U.S. Department of Energy (DOE) set up a sensor test facility at NREL in Golden, Colorado [7]. Numerous hydrogen sensor platforms are commercially available. Many of the platform types have been evaluated in the NREL facility [8], and their relative performance traits recently reviewed [9, 10]. Of the various hydrogen sensor platform types, the thermal conductivity (TC) sensor offered the best potential for meeting the requirements to verify hydrogen safety compliance as defined by the GTR.

TC sensors rely on a temperature-induced change of resistance in an electrically heated sensing element following exposure to the analyte. In addition to the input power, which is controlled by the sensor control circuit, the thermo-conductivity of the surrounding gas affects the device temperature. A higher TC coefficient (λ) leads to a greater transfer of heat to the surrounding environment. The TC coefficient for hydrogen of 174 $mWm^{-1}K^{-1}$ is the highest TC of any known gas. TC sensors exploit this property to detect and monitor hydrogen in air or in other matrixes. Although often marketed as a hydrogen sensor, the TC sensor is actually sensitive to a broad range of chemical vapors. The TC sensor is, in fact, often deployed as a nonspecific detector in a gas chromatograph. However, the sensitivity of the TC to changes in hydrogen concentration is significantly greater than for any other gas or vapor. For comparison, λ for helium is 142 $mWm^{-1}K^{-1}$, methane is 30.0 $mWm^{-1}K^{-1}$, and for nitrogen it is 24.3 $mWm^{-1}K^{-1}$.

Furthermore, because the concentration range of interest is in the percent range (0.4%–10% in air based on the target specifications), as opposed to the ppm levels associated with many other vapors, the sensor will not be significantly impacted by likely interferents (e.g., any vapors that induce a measurable response on the sensor). Fortuitously, helium is the second most sensitive gas on the TC sensor. Thus the TC sensor can be used to detect either helium or hydrogen. However, the response from a TC sensor cannot quantify both vapors simultaneously, nor can it distinguish between the two analytes in a test gas of unknown composition. Neither issue is significant, because by experimental design, the target analyte will be known, and it is unlikely that any crash test will be performed with hydrogen/helium mixtures of unknown composition.

Leveraging the NREL sensor test laboratory experience in the evaluation of hydrogen safety sensors, several commercial TC sensor models were identified. Of the models so far identified by NREL, one model, the AppliedSensor model HLS-440P, shown in Figure 1, had the best physical design so as to have the best chance to survive vehicle crash tests, and as such, was down-selected for deployment in the NHTSA FCEV crash test.[e] The power requirement for this sensor is 10–24 VDC and approximately 70 mA, and thus is readily compatible with operating off a 12-V battery. The electronic output of the model HLS-440P thermal conductivity sensor was

Figure 1. The AppliedSensor Model HLS-440P

Applied Sensor, Used with permission

[e] NREL typically treats data as proprietary. In this report, we present data that verify the identified technology successfully met the unique requirements for a specific application, and may ultimately be used in further publically accessible deployments. Other technologies that demonstrate compatibility to the listed requirements could be substituted in future crash tests for the one identified here.

designed explicitly for use in Controller Area Network (CAN) output interfaces. The CAN output is a standard but specialized platform, but is within the capability of the NREL sensor test laboratory that was used for pre- and post-crash test evaluations. CAN requires a specialized interface for data acquisition, but these are readily available. Although a major feature of a CAN outputs is that multiple devices (nodes) can share a single interface, this particular feature was not available for sensors available for the crash test.[f] Figure 2 illustrates the basic analytical performance of this TC sensor. The response of the sensor is shown for 0, 0.2, 1.0, and 2.0 vol% hydrogen and helium in air. The TC sensor shows a linear response for both analytes, although the helium response is approximately 10% less than hydrogen for the same test gas concentration. The direct readout of the instrument provides the helium or hydrogen concentration to an accuracy of better than 10%. Accuracy can be further improved by adjusting the instrument readings using the sensor calibration factors. Specific sensor calibrations for the two analytes are:

Unit 1:	$\%H_2 = 1.048 * IR$;	$\%He = 1.082 * IR$
Unit 2:	$\%H_2 = 1.053 * IR$;	$\%He = 1.064 * IR$
Unit 3:	$\%H_2 = 0.996 * IR$;	$\%He = 1.104 * IR$
Unit 4:	$\%H_2 = 1.069 * IR$;	$\%He = 1.046 * IR$
Unit 5:	$\%H_2 = 1.079 * IR$;	$\%He = 1.027 * IR$

Where IR represents the instrument response as logged by the data acquisition system. Further testing in the NREL sensor test laboratory confirmed that this linear sensor response extended to an IR of 10%.

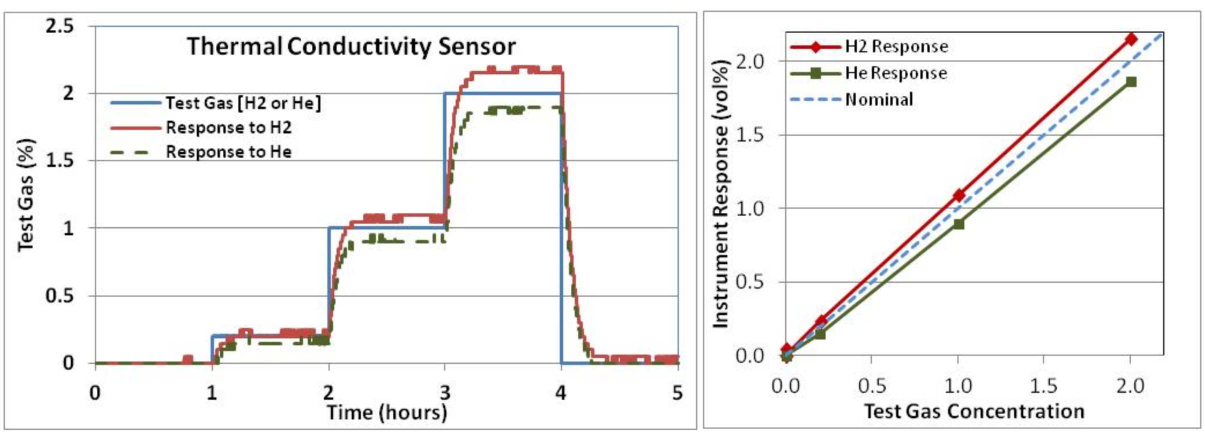


Figure 2. Left: Response of a TC sensor to hydrogen and to helium. The sensor was exposed to test gas concentrations of 0.2, 1.0, and 2.0 in air. Right: Plots of instrument response versus test gas concentration.

[f] Subsequent discussions with the manufacturer verified that different configurations of the HLS-440P are available, and units can be obtained that can be operated such that multiple sensors can connect to a single CAN interface. This configuration was not incorporated into the specific sensor units deployed in the crash tests described in this report.

To support field use of the sensors, NREL acquired two transportable CAN module interfaces (National Instruments Model USB-8473) to interface the sensors to a portable data acquisition system (DAQ). These CAN modules, however, were not robust enough to be implemented for onboard deployment in vehicle crash tests, but were initially used to perform onsite "bump" tests on the sensors (e.g., a brief exposure to helium following a crash test to verify sensor survivability). Ruggedized CAN modules that would be compatible with the crash test environment are commercially available, but were not obtained because of time and budget constraints.

3.3 Demonstration of Sensor Survivability—Deployment of Sensors in Non-Fuel Cell Electric Vehicle Crash Tests

The analytical performance of the sensor was well characterized by laboratory analyses. However, limited data on their vibration and shock stability were available. Furthermore, although vibration and shock measurements are routinely performed in vehicle crash tests, data that represent the conditions likely to be encountered for the planned FCEV crash tests were not readily available to NREL personnel before deployment. Nor was there sufficient time to develop an adequate vibration evaluation test plan, although ultimately vibration and shock specifications should be developed. Thus, owing to the short time and limited opportunity to deploy sensors in FCEV crash tests, it was decided to empirically verify the survivability of the sensors by actual deployment in crash test vehicles.

Rather than FCEVs, the initial crash test sensor deployment was in conventional gasoline-powered vehicles at the KARCO Engineering facility in Adelanto, California. The test vehicles were commercial full-size pickup trucks of the same make and model. Three standard crash tests were performed during the demonstration phase: the Frontal Impact Test, the Side Impact Moving Deformable Barrier Test, and the Side Impact Rigid Pole Test. The primary goals of this deployment were to develop mounting protocols for the sensors and to demonstrate the crash test survivability of the sensors, as before this deployment, it was not clear if the sensors would be capable of withstanding the shock and vibrational stresses associated with crash tests.

3.3.1 Sensor Installation and Vehicle Instrumentation

Multiple sensors were deployed in each crash test to produce some statistical survivability data. Specifically, three of the five available sensors were installed in the vehicle for each crash test. In this manner, three sensors could be set aside so as to be deployed only once (e.g., one for each crash test), whereas the other two sensors were deployed in all three crash tests. This distribution of sensor deployment was performed to ensure availability of at least one sensor for the third and final crash test and to identify which crash test scenario would result in device failure. To facilitate installation, a ruggedized fixture (Figure 3) was, at the request of the DOT program manager, designed and built by KARCO engineers to accommodate the sensors during the crash tests. The fixture was securely bolted to the floor of the test vehicle, just behind the driver's seat, as indicated in Figure 4. During the crash test, the sensors were powered by an onboard 12-V battery. Although powered, the sensor signals were not logged, because a compatible DAQ was not available. The vehicle was also instrumented with accelerometers, whose output was logged and provided vibration and shock data. Accelerometers were mounted in various locations on the vehicle, including one adjacent to the sensor mounting bracket and one attached directly to the top of the bracket. (The accelerometer data are shown in Appendix A.) The accelerometer data "X" component was in line with the sensor axis, whereas the Y and Z components are tangential to the main sensor axis. Sensor survivability was verified by a short exposure to helium (e.g., a bump test), performed onsite at the KARCO facility.

KARCO Image, used with permission

Figure 4. Sensor mounting bracket (custom built by KARCO Engineering)

KARCO Image, used with Permission

Figure 3. Mounting of the sensor bracket and sensors in the test vehicle

3.3.2 Crash Test Conditions and Sensor Performance

3.3.2.1 Frontal Impact

The vehicle was instrumented with three sensors (Units 1, 2, and 4) as described in Section 3.3.1. The vehicle was then subjected to the standard frontal impact crash test, in which the vehicle was accelerated to a speed of 35 mph (56 km/h) prior to a front end impact into an immovable barrier. The sensors remained mounted and powered before and after impact. The maximum output of the accelerometer mounted on the floor adjacent to the sensors was 27.3 G for 17.4 ms, whereas the maximum output of the accelerometer mounted on the bracket was 51.7 G for 26.7 ms. All three sensors survived the crash test, as confirmed by a bump test performed onsite after the crash test. Unit 4 was not deployed in any further crash tests, and thus was used only in the Frontal Impact Test.

3.3.2.2 Side Impact Moving Deformable Barrier Test

The vehicle was instrumented with three sensors (Units 1, 2, and 5) as described above. The vehicle was then subjected to the standard Side Impact Moving Deformable Barrier Test, in which a mobile barrier was accelerated to a speed of 38 mph (61 km/h) prior to a driver's side door impact at 90°, while the test vehicle was stationary. The sensors remained mounted and powered before and after impact. The maximum output of the accelerometer mounted on the floor was 66.0 G for 19.4 ms, whereas the maximum output of the accelerometer mounted on the bracket was 70.8 G for 15.8 ms. All three sensors survived the crash test, as confirmed by a bump test performed onsite after the crash test. Unit 5 was not deployed in any further crash tests, and thus was used only in the Side Impact Moving Deformable Barrier Test.

3.3.2.3 Side Impact Rigid Pole Test

The vehicle was instrumented with three sensors (Units 1, 2, and 3) as described above. The vehicle was then subjected to the standard Side Impact Rigid Pole Test, in which a mobile barrier was accelerated to a speed of 20 mph (32 km/h) prior to a driver's side rear quarter panel impact into a stationary test vehicle. Although the projectile was angled relative to the direction of motion, the target vehicle was also angled such that impact between the target and projectile was at 90°. The sensors remained mounted and powered before and after impact. The maximum output of the accelerometer mounted on the floor was 38.3.0 G for 78.4 ms, whereas the maximum output of the accelerometer mounted on the bracket was 35.0 G for 56.7 ms. All three sensors survived the crash test, as confirmed by a bump test performed on-site following the crash test. Unit 3 was deployed only in the Side Impact Rigid Pole Test.

3.3.2.4 Overall Sensor Performance

Three sensors were deployed in each crash test. Three of the five available sensors were deployed in only a single crash test and two were deployed in all three crash tests. Bump tests performed onsite on each sensor immediately following the crash test confirmed that no sensor failed as a result of crash test deployment. Analyses identical to that shown in Figure 2 were performed in the NREL sensor test laboratory following the crash test deployment, and confirmed that the calibration of the sensors also remained intact. The crash tests subjected the TC sensor to forces of up to nearly 80 G, without any degradation of sensor performance, thus demonstrating the sensor crash test survivability.

3.4 Deployment of Sensors in Fuel Cell Electric Vehicle Crash Tests

The exemplary performance of the sensors during the demonstration deployment in the non-FCEV provided strong impetus to deploy them in an actual FCEV crash test. Accordingly, between April 9 and April 15, 2012 NREL personnel field deployed the five units of the AppliedSensor Model HLS-440P TC sensor in FCEV crash tests. The specific crash tests were the rear impact test and the side impact test and were performed at the Transportation Research Center Inc. (TRC Inc.) in East Liberty, Ohio, under a subcontract from Battelle (Columbus, Ohio) with support from DOT/NHTSA. The test vehicles were two similar models of midsize hydrogen fuel-cell powered sport utility vehicles. The vehicles were provided by the automotive OEM; an OEM representative was present during each test. One vehicle was subjected to a rear impact crash test and the other to a side impact crash test. The two tests were performed on separate days. Specific test conditions were based on crash tests for FMVSS and were patterned after the associated NHTSA compliance test procedures [12, 13].

3.4.1 Sensor Installation and Fuel Cell Electric Vehicle Instrumentation

The vehicles were fully instrumented, including the helium/hydrogen sensors, on the day(s) prior to each crash test, although final preparation was necessarily performed on the day of the test. The vehicles were placed at the impact location on the morning of the test for final preparation.

Vehicle instrumentation included the installation of three sensors on the inside ceiling of the vehicle passenger compartment and two on the external underbody of the vehicle. Performance of the mounted sensors was demonstrated prior to the crash test by a bump test. For the rear impact test, three sensors were installed on the ceiling in the passenger compartment and two in the driver's side rear wheel well near the storage tanks. For the side impact test, three sensors were installed on the ceiling in the passenger compartment and two on the vehicle underbody near the storage tanks. The mounting of the sensors is shown in Figure 5.

Battelle Images, Used with permission

Figure 5. Mounting of the sensors in a FCEV

Left: Three sensors were mounted in the passenger compartment, above the rear seats for the rear and side impact tests. Center: In the rear impact test, two sensors were mounted in the left rear wheel well. Right: In the side impact test, two sensors were mounted on the vehicle underbody near the storage tanks.

During the FCEV crash test, the sensors were powered by an onboard 12-V battery. The two transportable, but not ruggedized, CAN interface modules were used to interface the sensors to the DAQ. Because these specific sensor units were configured such that each required its own

CAN interface, the output of only two sensors could be logged, although five sensors were installed in the vehicle. Thus, the outputs of one sensor installed on the ceiling and one on the vehicle underbody or wheel well were logged. These were interfaced to a remote CAN interface and DAQ system via a custom-built 200-ft long wire umbilical. TRC Inc. also instrumented the vehicle with accelerometers, whose output was logged with an onboard DAQ. The accelerometers provided vibration and shock data. Accelerometers were mounted in various locations on the vehicle, including one on the floor adjacent to the mounted sensors. The accelerometer data for the FCEV are shown in Appendix B. The accelerometer “X” component was in line with the sensor axis, whereas the Y and Z components were tangential to the main sensor axis. Sensor survivability was verified by a short exposure to helium (e.g., a bump test), performed onsite at the TRC Inc. facility.

3.4.2 Crash Test Conditions and Sensor Performance

The generalized crash test protocol consisted of a final preparation, which included a final check of the test vehicle and the helium fill to the required test pressure (indicated as “A” in Figure 8). Nonessential personnel were not allowed access to the vehicle once the final preparation was initiated. Therefore, sensor logging was initiated during the final preparation (but before the onboard storage tanks were pressurized). Following the final preparation, a 1-h pressure hold was performed (indicated as “B” in Figure 8) to verify that the storage tanks were holding at the prescribed pressure for the test. After the 1-h hold, the actual impact occurred (indicated in Figure 8 as the vertical line separating sections “B” and “C”). Following impact, there was a 1-h post impact hold in which helium/hydrogen levels were to be monitored in passenger compartments (indicated as “C” in the Figure 8). At the end of the post crash 1-h wait, the gas storage tanks were depressurized (indicated as “D” in Figure 8) and site personnel were allowed access to the vehicle. NREL personnel responsible for the sensor DAQ were allowed access only after TRC Inc. personnel verified that the vehicle was safe to approach.

3.4.2.1 Rear Impact Test

The test vehicle was stationary and was impacted by a moving rigid (“billboard”) barrier traveling at a nominal speed of 30 mph (48 km/h) as shown in Figure 6. Five sensors were installed in the vehicle, and two were interfaced to the remote DAQ via the wire umbilical. Impact was directed into the rear of the vehicle with both target and projectile in line with each other. Accelerometer data (shown in Appendix B) indicated the sensors were subjected to forces of up to nearly 30 G for about 35 ms. The target vehicle was filled to nominally 500 psi helium 1 h before the impact. The storage tanks were depressurized 1 h after impact. Access to the vehicle was tightly restricted until the storage tank was depressurized. Although test standards require it to remain operational in the rear impact crash test, the vehicle battery, which was used as the power supply to the sensors, failed on impact. Once depowered, the sensors discontinued communicating to the remote DAQ.

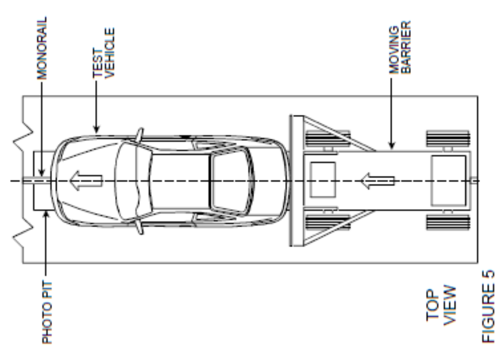


Figure 6. Illustration of the rear impact test

From [12], no permission required

Sensor data were obtained for the final vehicle preparation step and the 1-h pressure hold step only; no data were obtained on and after impact. No helium was detected, however, in the data obtained before impact (not shown). At the time of the crash test, the prevailing weather conditions were breezy but dry. The temperature was 40.9°F (4.9°C) with a 62% relative humidity (RH) based on the TRC Inc. weather data [14]. The sensor's calibration curves were obtained under laboratory conditions at a temperature of about 77°F (25°C) and 50% RH. Thus, deployment was at a lower temperature. Sensors can be impacted by changes in ambient temperature. However, previous laboratory evaluations demonstrated that this sensor model was negligibly affected by changes in ambient temperature in the range of 5°F (–15°C) to +185°F (+85°C). More specifically, defining the sensitivity (slope of the calibration curve) at 77°F (25°C as unity (1), the sensitivity at 5°F (–15°C) and +185°F (+85°C) were 1.00 and 1.04, respectively. Changes in RH, however, had a larger impact on sensor accuracy. However, the RH difference between the test conditions in the laboratory and the deployment site was slight and therefore would have a negligible impact.

3.4.2.2 Side Impact Test

The test vehicle was stationary and impacted by a moving deformable barrier traveling at nominal speed of 33.5 mph (54 km/h), as shown in Figure 7. Impact was to the driver's side of the vehicle in the region near the rear passenger door. The direction of motion was at an angle of 63° to the longitudinal axis of the vehicle, but the target and projectile face were at 90° to each other, as shown in Figure 7. Accelerometer data (see Appendix B) indicated the vehicle was subjected to forces of up to slightly more than 15 G for about 20 ms. The target vehicle was filled to nominally 5,000 psi helium 1 h before the impact; this was explicitly designed to be a high-pressure test. To achieve pressure with the available helium, the onboard tanks were filled with nitrogen, but the fill was primarily helium. The storage tanks were depressurized by remote operation 1 h after impact. Access to the vehicle was tightly restricted until the storage tank was depressurized.

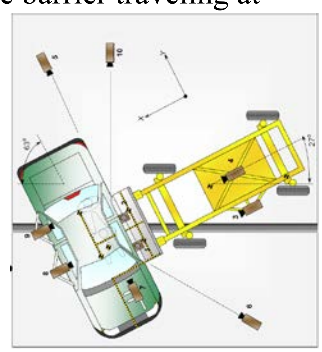


Figure 7. Illustration of the side impact test

From [13], no permission required

Five sensors were installed in the vehicle, and two were interfaced to the remote DAQ via the wire umbilical. Prevailing weather conditions at the time of the crash tests were inclement and windy. The temperature was 56.1°F (13.4°C) with 93% RH based on TRC Inc. weather data [14]. As discussed in Section 3.4.2.1, the sensor was negligibly impacted by differences in ambient temperature relative to the calibration temperature. However, laboratory evaluations indicate that high RH, such as that encountered during the side impact test, could increase the sensor sensitivity by about 10%, thus overestimating the gas concentration. This, however, is not overly significant as it is within the stated overall accuracy of the sensor. In future deployments, sensor output can be compensated for temperature and humidity variations.

3.4.2.3 Overall Sensor Performance

Five sensors were deployed in each of the two crash tests performed on FCEVs: three in the passenger compartment and two on the vehicle underbody. Bump tests performed onsite on each sensor immediately following the crash test confirmed that no sensor failed as a result of crash test deployment. Thus, all sensors survived both crash tests performed at the TRC Inc. facility. These sensors were the same as those subjected to crash tests performed on conventional gasoline-powered vehicles at KARCO Engineering. The sensor survivability is summarized in Table 1. Thus, these five sensors were deployed in up to five crash tests without a single incident of device failure! Laboratory analyses performed following the FCEV crash test deployment verified the integrity of the calibration curve.

Table 1. Sensor Deployments and Performance for DOT Crash Test

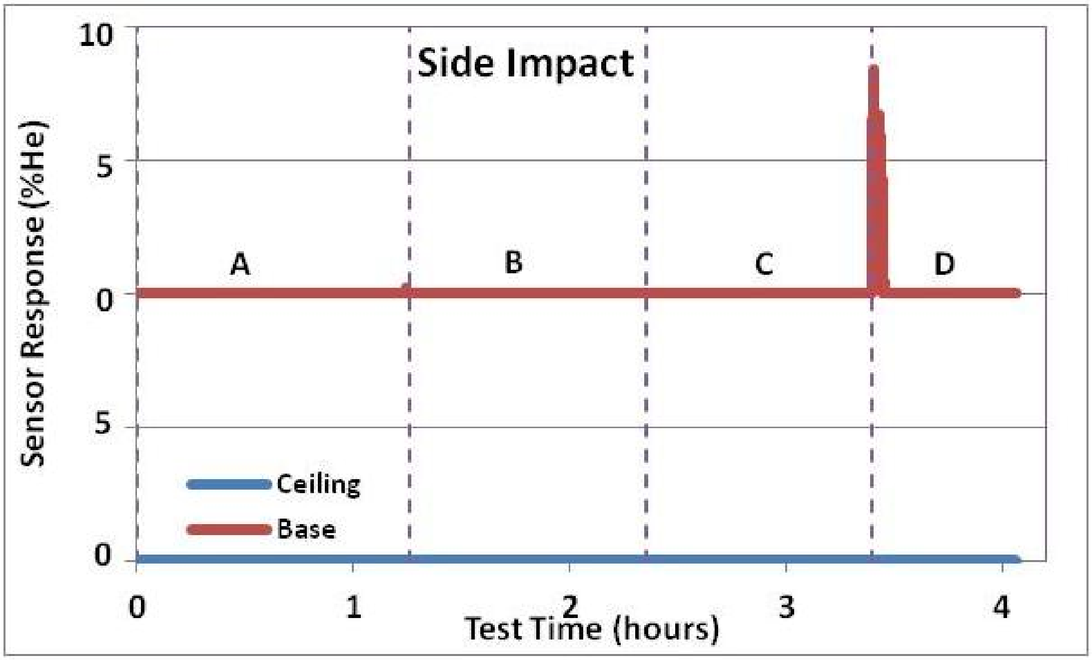
	March 5–9 Deployment							April 9–15 Deployment				
Sensor ID	**Pretest Functionality[1]**	**Frontal Impact[2]**	**Bump Test[3]**	**Side Impact[2]**	**Bump Test[3]**	**Side Impact Pole[2]**	**Bump Test[3]**	**Post test Functionality**	**Rear Impact**	**Bump Test**	**Side Impact**	**Bump Test**
401	CAL	X	+	X	+	X	+	CAL	X	+	X	+
403	CAL	X	+	X	+	X	+	CAL	X	+	X	+
404	Bump					X	+	CAL	X	+	X	+
405	CAL	X	+					CAL	X	+	X	+
406	CAL			X	+			CAL	X	+	X	+

[1] Sensor functionality was confirmed by laboratory calibration (CAL) or by on-site bump test (bump)
[2] "X" indicates which sensor was used for the indicated test
[3] "+" indicates the sensor survived the crash test (as confirmed by the bump test), "-" indicates a sensor failure

Figure 8 shows the measured response from the two onboard sensors in the side impact test. No helium was observed in the vehicle compartment. However, the sensor mounted on the vehicle underbody detected helium at various points in the test sequence, as indicated by the small sensor responses shown in Figure 8 (Section D). A trace amount of helium was observed at the vertical line demarcating Sections A and B; this corresponds to the point at which the helium fill was discontinued and the connector was removed from the tanks. We believe this was due to some fugitive release associated with the disconnection of the fill pneumatics. A helium spike was also observed at the vertical line demarcating Sections C and D. Prior to allowing access to the test vehicle following impact, site safety protocols required that the high-pressure system be depressurized. This spike was considerably larger than the one demarcating Sections A and B and corresponded to the start of the storage tank depressurization, which was performed by opening a shutoff valve to allow free venting of pressurized helium through a gas line plumbed from the tanks through the passenger compartment to the top of the vehicle roof.

Turbulent flow apparently backflushed helium under the vehicle and was detected by the underbody sensors. No backflow into the vehicle passenger compartment was observed. The observed gas concentration was in excess of 8% after pressure release around the vehicle underbody. Because helium was used as a surrogate, this posed no risk; however, a comparable concentration of hydrogen could be dangerous. Thus, it may be necessary to develop improved pressure release scenarios. Periodic small "pulses" of helium were also observed during Section

C of the test; these correspond to the 1-h monitoring period to track the integrity of the high-pressure storage system following impact. These pulses, which correspond to helium concentrations of 0.05%, were *not* observed prior to impact. Thus, the impact apparently induced some helium releases, albeit very small, and would not likely pose a risk. These small releases were much smaller than could have been detected by the pressure transducers [15]. Overall, the vehicle storage system was compliant with the GTR requirements. However, the test vehicle fuel storage system was modified by crash test personnel in preparation for the crash test. Modifications included the incorporation of a remotely activated vent system to depressurize the storage tank. Therefore, the results shown in Figure 8 do not necessarily pertain to the original design of the fuel storage system. The storage tanks, which were not modified, survived the crash tests.



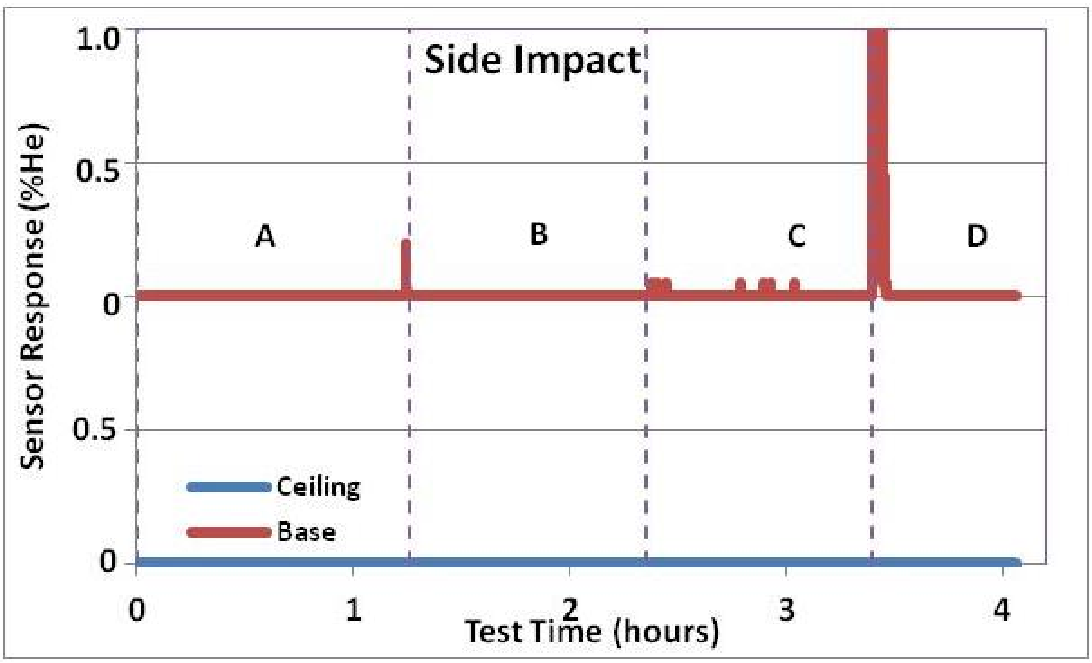


Figure 8. Response of the sensors installed on the vehicle subjected to the side impact crash test performed on April 14, 2012 on a midsize sport utility vehicle powered by a hydrogen fuel cell

One sensor was installed on the ceiling in the passenger compartment and one on the vehicle underbody near the storage tanks. Top: Full-scale display of the sensor response. Bottom: Expanded view of the same data. The sensor test was demarcated into four sections: (A) final vehicle preparation, including tank pressurization (5,000 PSI) and initiation of sensor logging; (B) pressure hold for 1 h, performed to verify that the storage tanks maintained pressure following the helium fill (5,000 psi); (C) post crash period (1 h minimum); and (D) post crash test during which time the vehicle was inspected prior to access by NREL personnel. The actual impact occurred at the time indicated by the vertical line separating steps B and C.

4 Conclusions and Recommendations

- The selected sensor technology (AppliedSensor model HLS-440P) was compatible with FCEV crash tests and works for helium and hydrogen.
- Laboratory assessments confirmed that the detection limit and linear range of the selected sensors meet crash test requirements (linear to 10% with an LDL of 0.05–0.1% hydrogen [or helium] in air).
- Sensor utilization during FCEV crash test should include deployment in all vehicle compartments (passenger, trunk, etc.). In addition, although not part of the GTR, sensor utilization should also include deployment around components associated with the high-pressure storage system. Gas concentrations in excess of 8% were observed following pressure release around the vehicle underbody. As a corollary, improved pressure release scenarios should be developed.
- Future sensors acquired for crash test deployments should be more readily compatible with current DAQs to properly handle multiple nodes into a single CAN input. The ability to handle multiple nodes (e.g., sensors) to a single interface was a main feature for development of CAN and should be a standard feature. This would simplify installation in test vehicles.
- A DAQ with a CAN interface that is compatible with a crash test should be obtained and implemented in future crash tests.
- Remote interrogation of the sensors via telemetry is strongly urged for any hydrogen test.
- An automated, self-contained sensor module system should be developed to facilitate sensor deployment and pretest and post test performance validation (or calibration).
- Sensor accuracy can be readily improved by incorporating temperature and RH compensation.

References

1. U.S. Department of Energy. (2011). The Department of Energy Hydrogen and Fuel Cells Program Plan – An Integrated Strategic Plan for the Research, Development, and Demonstration of Hydrogen and Fuel Cell Technologies. www.hydrogen.energy.gov/pdfs/program_plan2011.pdf.
2. GRSP. (2011).United Nations Global Technical Regulation (Draft) Hydrogen Fuelled Vehicle. Working Party on Passive Safety. www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29grsp/GRSP-50-19r1e.pdf
3. NIST Equation of State Calculator, see: http://webbook.nist.gov/chemistry/fluid/
4. DOT. (2011). *Comparison of Available Portable Combustible Gas and Hydrogen Sensors*. Washington, D.C.: U.S. Department of Transportation, Federal Motor Carrier Safely Administration, Report Number FMCSA-RRT-11-005/. www.fmcsa.dot.gov/facts-research/research-technology/report/Hydrogen-Sensors.pdf
5. Ekoto, I.W.; Merilo, E.G.; Dedrick, D.E.; Groethe M.A. (2011). "Performance-Based Testing for Hydrogen Leakage Into Passenger Vehicle Compartments." *International Journal of Hydrogen Energy* 36:10169–10178.
6. Buttner, W.; Burgess, R.; Post, M.; Rivkin C. (2012). *Summary and Findings from the NREL/DOE Hydrogen Sensor Workshop (June 8, 2011)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5600-55645. www.nrel.gov/docs/fy12osti/55645.pdf
7. NREL. (2011). NREL Safety Sensor Testing Laboratory, www.nrel.gov/hydrogen/facilities_hsl.html (accessed December 1, 2011).
8. Black, G., Boon-Brett, L., Harskamp, F.,Moretto, P., Buttner, W. J., Post, M. B., Burgess, R., Rivkin, C., Interim report of the SINTERCOM project, JRC Technical Notes (EUR 24854 EN – 2011) http://iet.jrc.ec.europa.eu/sites/default/files/documents/scientific_publications/2011/ld-na-24-854-en-n_pdf.pdf
9. Buttner, W.J.; Post, M.B.; Burgess R.; Rivkin C. (2011). "An Overview of Hydrogen Safety Sensors and Requirements." *International Journal of Hydrogen Energy* 36:2462–2470.
10. Hübert, T.; Boon-Brett, L.; Black, G.; Banach, U. (2011). "Hydrogen Sensors – A Review." *Sensors and Actuators* (B) 157:329–352.
11. ISO. (2010). Hydrogen Detection Apparatus – Stationary Applications. Geneva: International Organization for Standards. ISO 26142:2010. www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=52319.
12. NHTSA. (1995). *Laboratory Test Procedure TP-303-00: FMVSS 212 Windshield Mounting, FMVSS 219 Windshield Zone Intrusion, FMVSS 303 Fuel System Integrity of Compressed Natural Gas (CNG) Vehicles*. Washington, D.C: National Highway Traffic Safety Administration. www.nhtsa.gov/search?q=Laboratory+Test+Procedure+TP-303-00
13. NHTSA. (2006). *Laboratory Test Procedure TP-214D-08: Side Impact Protection – Dynamic, Standard Regulation on Dynamic Side Impact Protection*. Washington, D.C:

National Highway Traffic Safety Administration. http://www.nhtsa.gov/DOT/NHTSA/Vehicle%20Safety/Test%20Procedures/Associated%20Files/TP214D-08Part1.pdf

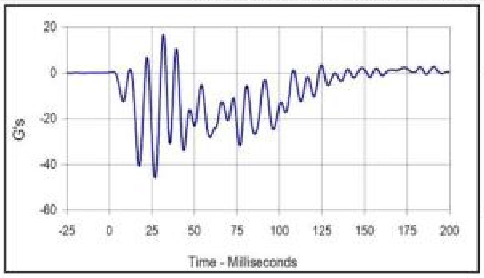
14. http://trcpg.com/weather/trcbulletin.htm

15. Battelle. (2012). Douglas Pape and Andrew Cox, personal communication, to be published in: Battelle, Draft Project Report, Task Order 7: Crashworthiness Research of Hydrogen Fuel Cell Vehicles Contract No. DTNH22-08-D-00080 Task Order 7 June 11, 2012

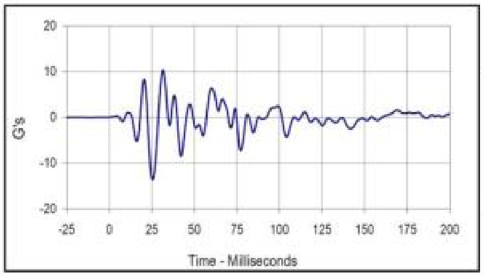
Appendix A

Accelerometer Data
Sensor Deployment in Conventional Vehicles
(provided by KARCO Engineering, used with permission)

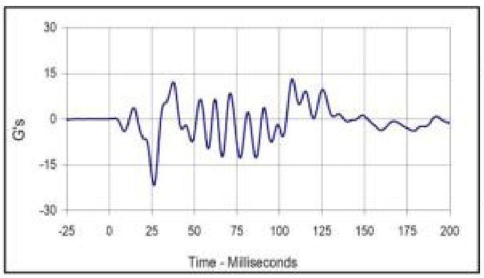
Accelerometer Data – 56 km/hr Frontal Impact Test – On Bracket



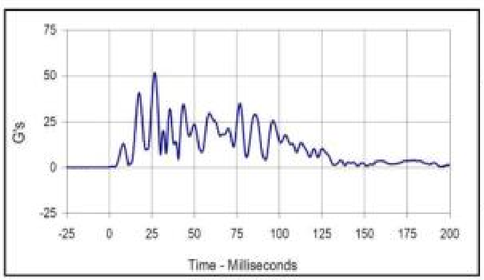
Curve Description			
On Sensor Bracket X			
Plot No.	Type	SAE Class	Units
001	FIL	60	G's
Max	Time	Min	Time
16.8	31.7	-45.9	26.8



Curve Description			
On Sensor Bracket Y			
Plot No.	Type	SAE Class	Units
002	FIL	60	G's
Max	Time	Min	Time
10.3	31.5	-13.6	25.4

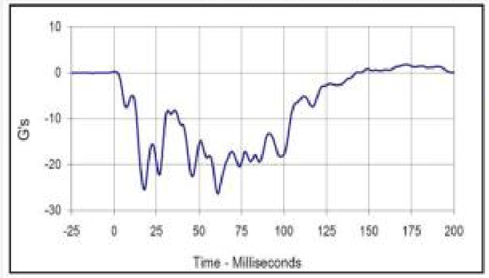


Curve Description			
On Sensor Bracket Z			
Plot No.	Type	SAE Class	Units
003	FIL	60	G's
Max	Time	Min	Time
13.1	107.5	-21.7	26.3

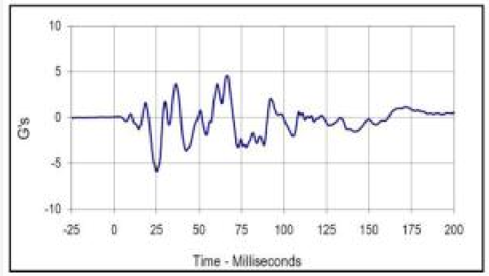


Curve Description			
On Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
004	RES	60	G's
Max	Time	Min	Time
51.7	26.7	0.2	0.0

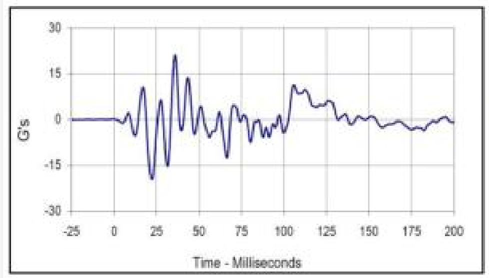
Accelerometer Data – 56 km/hr Frontal Impact Test – Near Bracket



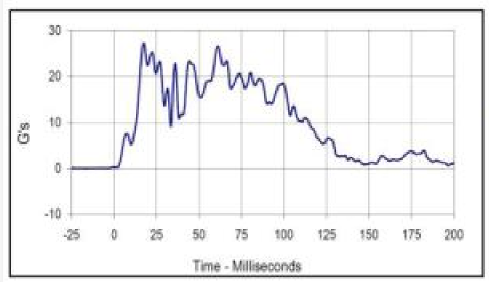
Curve Description			
Near Sensor Bracket X			
Plot No.	Type	SAE Class	Units
001	FIL	60	G's
Max	Time	Min	Time
1.8	172.1	-26.4	61.2



Curve Description			
Near Sensor Bracket Y			
Plot No.	Type	SAE Class	Units
002	FIL	60	G's
Max	Time	Min	Time
4.6	66.4	-5.9	25.0

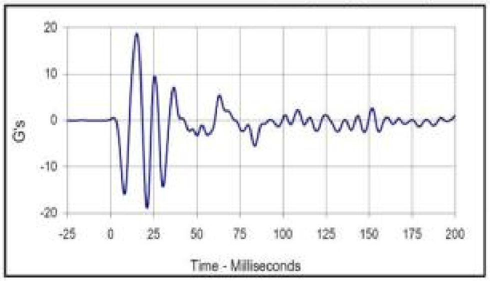


Curve Description			
Near Sensor Bracket Z			
Plot No.	Type	SAE Class	Units
003	FIL	60	G's
Max	Time	Min	Time
21.1	35.9	-19.6	22.4

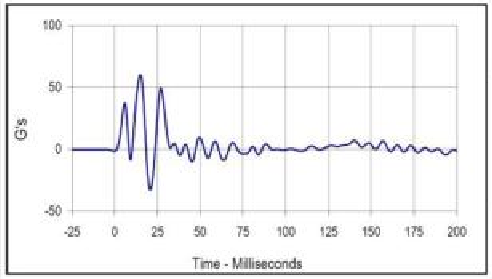


Curve Description			
Near Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
004	RES	60	G's
Max	Time	Min	Time
27.3	17.4	0.2	1.8

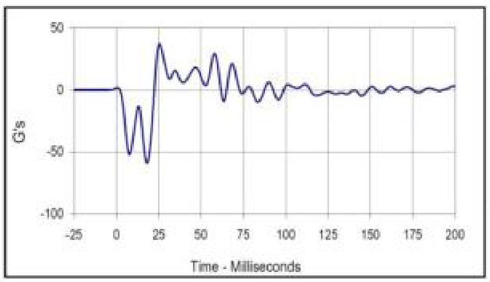
Accelerometer Data – 61 km/hr (38 mph) Side Impact Moving Deformable Barrier Test – On Bracket



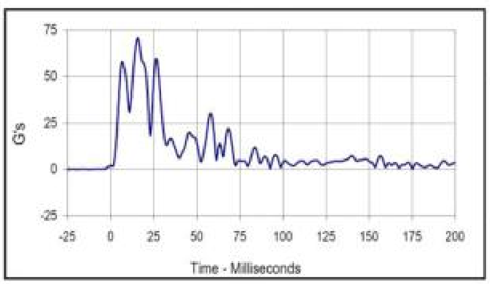
Curve Description			
On Sensor Bracket Acceleration X			
Plot No.	Type	SAE Class	Units
001	FIL	60	G's
Max	Time	Min	Time
18.7	15.2	-18.9	21.1



Curve Description			
On Sensor Bracket Acceleration Y			
Plot No.	Type	SAE Class	Units
002	FIL	60	G's
Max	Time	Min	Time
60.0	14.9	-32.5	20.7

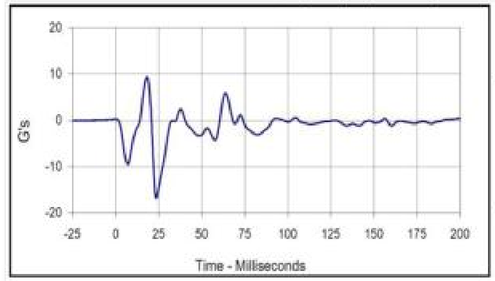


Curve Description			
On Sensor Bracket Acceleration Z			
Plot No.	Type	SAE Class	Units
003	FIL	60	G's
Max	Time	Min	Time
37.3	25.4	-58.7	18.0

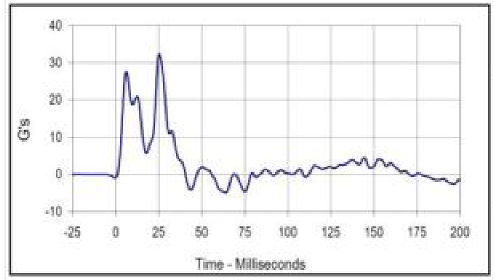


Curve Description			
On Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
004	RES	60	G's
Max	Time	Min	Time
70.8	15.8	0.3	175.2

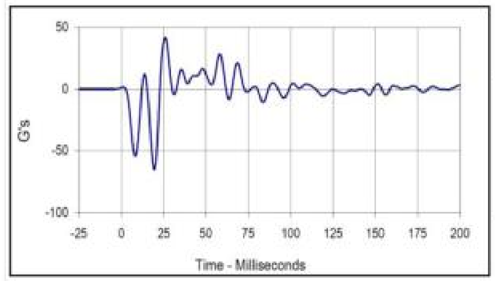
Accelerometer Data – 61 km/hr (38 mph) Side Impact Moving Deformable Barrier Test – Near Bracket



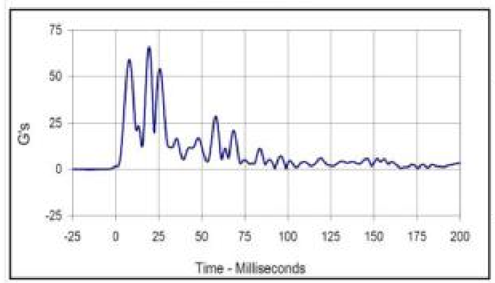
Curve Description			
Near Sensor Bracket Acceleration X			
Plot No.	Type	SAE Class	Units
005	FIL	60	G's
Max	Time	Min	Time
9.4	18.2	-16.8	23.6



Curve Description			
Near Sensor Bracket Acceleration Y			
Plot No.	Type	SAE Class	Units
006	FIL	60	G's
Max	Time	Min	Time
32.4	25.3	-5.0	63.9

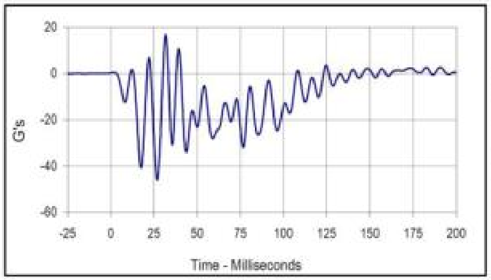


Curve Description			
Near Sensor Bracket Acceleration Z			
Plot No.	Type	SAE Class	Units
007	FIL	60	G's
Max	Time	Min	Time
41.7	25.9	-65.1	19.4

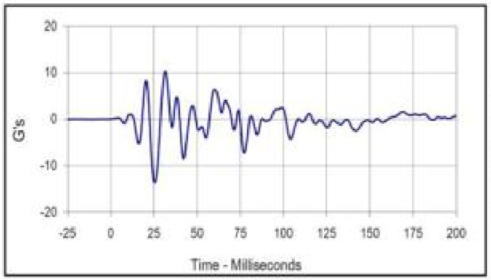


Curve Description			
Near Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
008	RES	60	G's
Max	Time	Min	Time
66.0	19.4	0.4	92.6

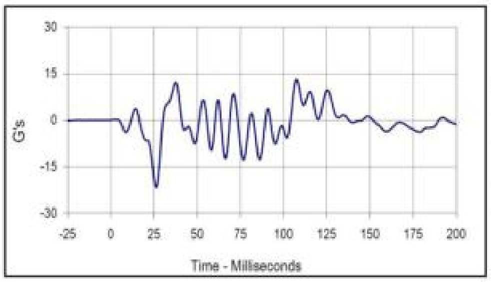
Accelerometer Data – 56 km/hr Frontal Impact Test – On Bracket



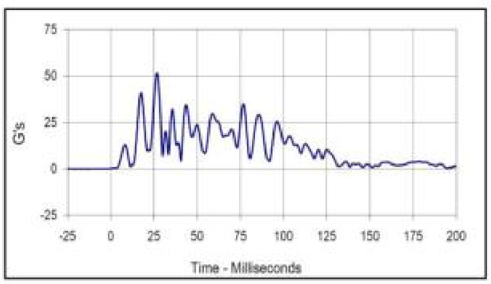
Curve Description			
On Sensor Bracket X			
Plot No.	Type	SAE Class	Units
001	FIL	60	G's
Max	Time	Min	Time
16.8	31.7	-45.9	26.8



Curve Description			
On Sensor Bracket Y			
Plot No.	Type	SAE Class	Units
002	FIL	60	G's
Max	Time	Min	Time
10.3	31.5	-13.6	25.4

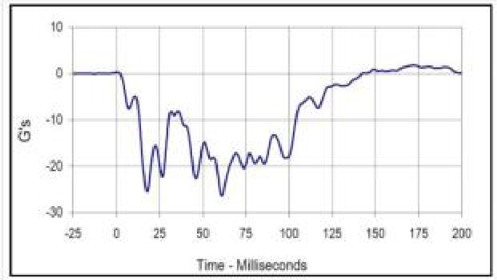


Curve Description			
On Sensor Bracket Z			
Plot No.	Type	SAE Class	Units
003	FIL	60	G's
Max	Time	Min	Time
13.1	107.5	-21.7	26.3

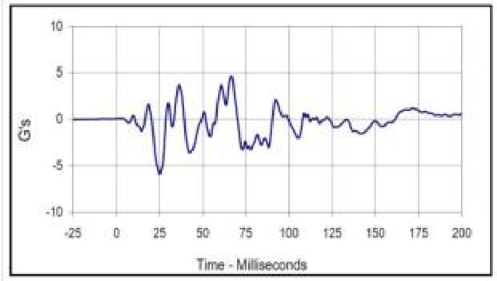


Curve Description			
On Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
004	RES	60	G's
Max	Time	Min	Time
51.7	26.7	0.2	0.0

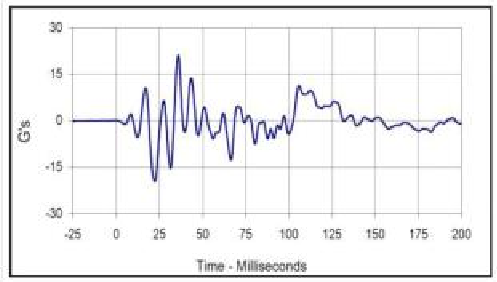
Accelerometer Data – 56 km/hr Frontal Impact Test – Near Bracket



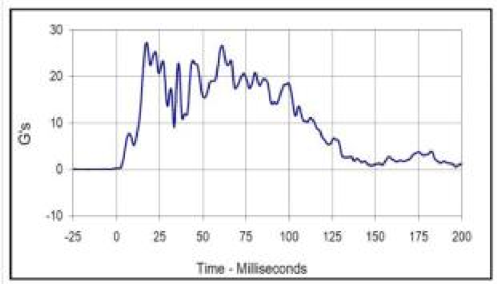
Curve Description			
Near Sensor Bracket X			
Plot No.	Type	SAE Class	Units
001	FIL	60	G's
Max	Time	Min	Time
1.8	172.1	-26.4	61.2



Curve Description			
Near Sensor Bracket Y			
Plot No.	Type	SAE Class	Units
002	FIL	60	G's
Max	Time	Min	Time
4.6	66.4	-5.9	25.0



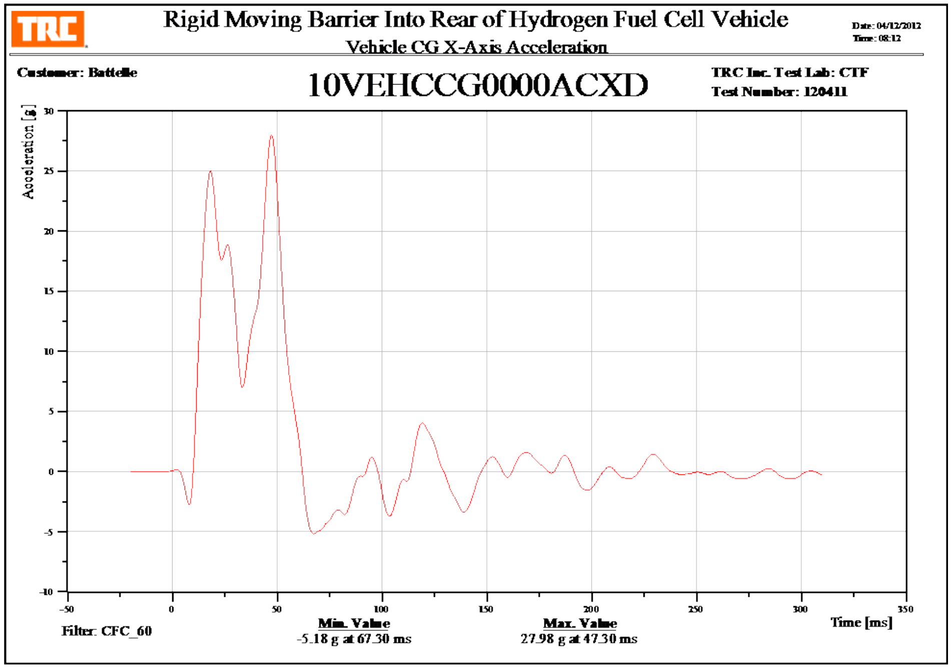
Curve Description			
Near Sensor Bracket Z			
Plot No.	Type	SAE Class	Units
003	FIL	60	G's
Max	Time	Min	Time
21.1	35.9	-19.6	22.4

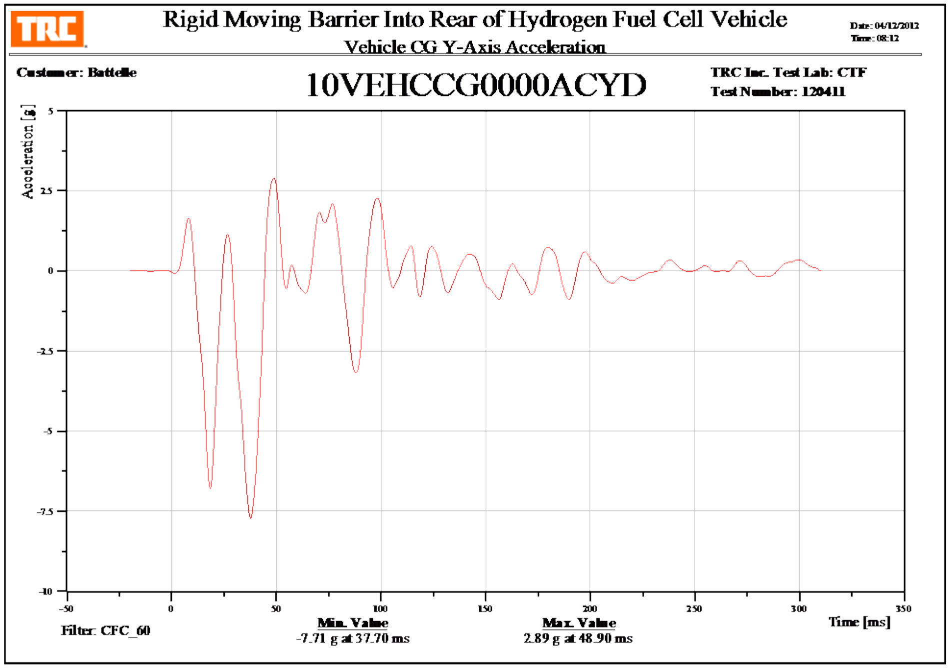


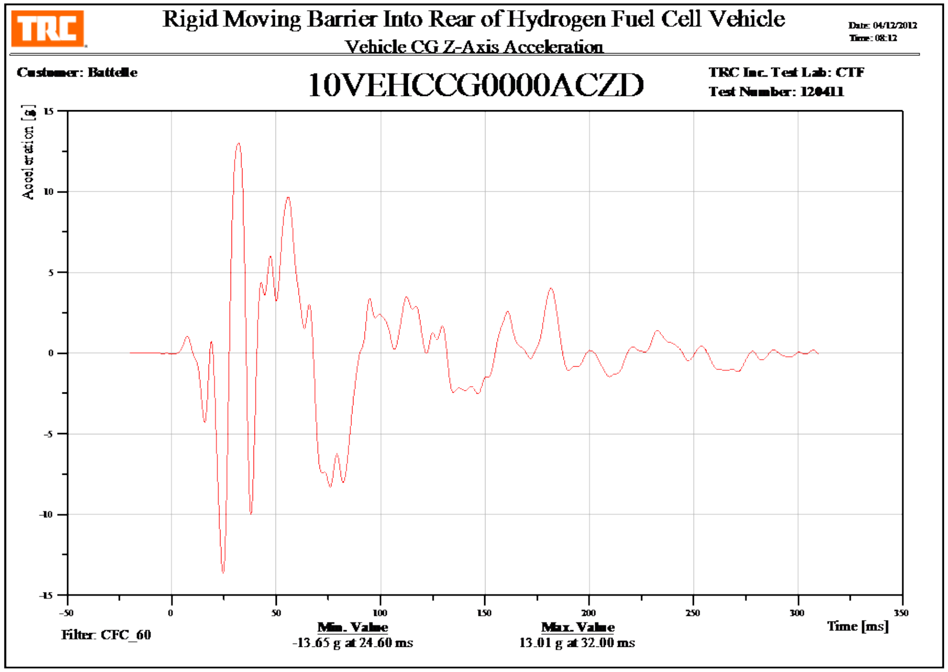
Curve Description			
Near Sensor Bracket Acceleration Resultant			
Plot No.	Type	SAE Class	Units
004	RES	60	G's
Max	Time	Min	Time
27.3	17.4	0.2	1.8

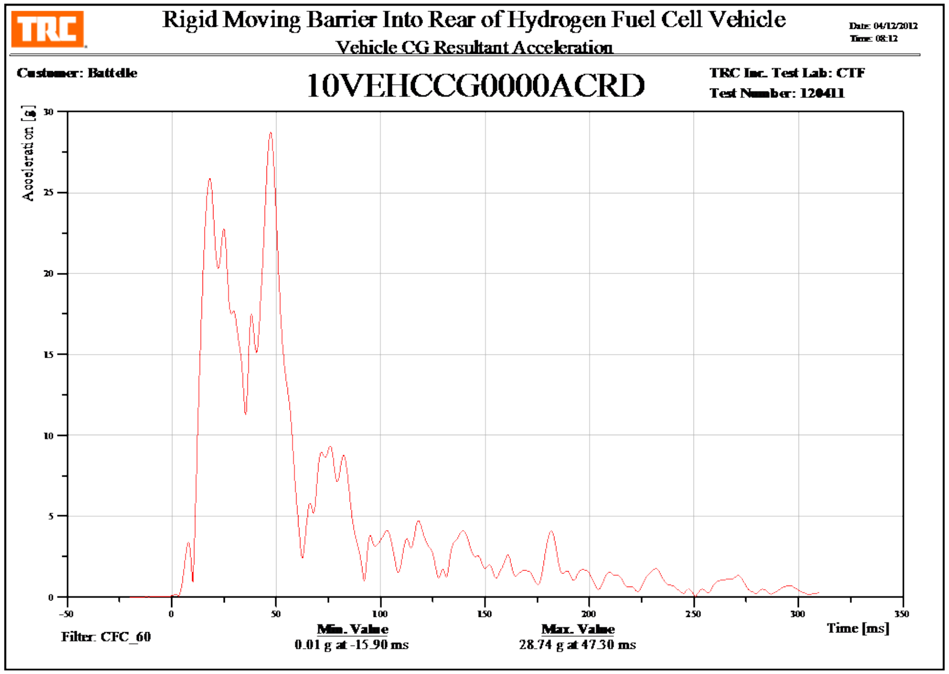
Appendix B

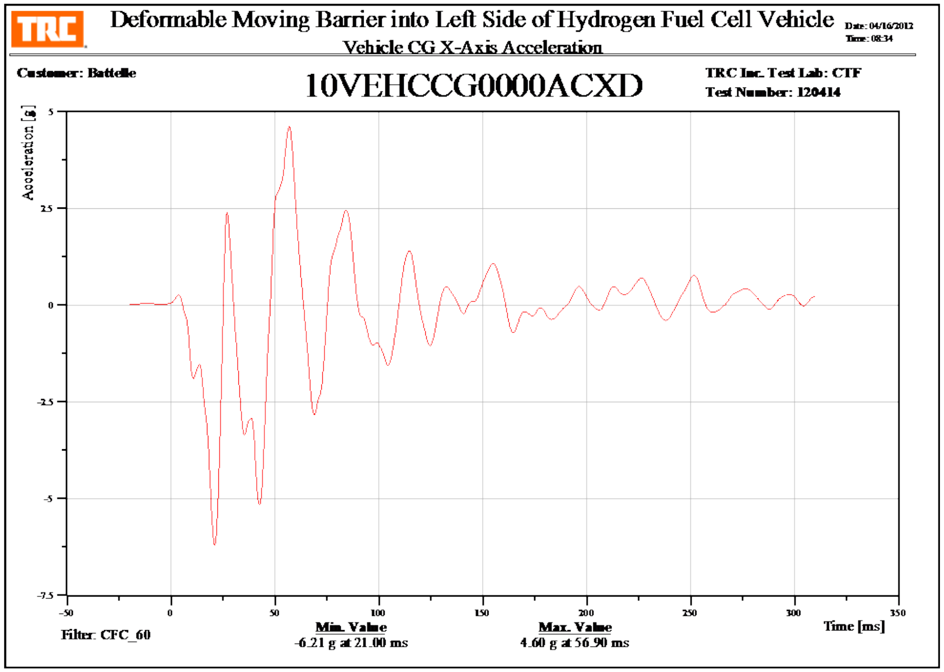
Accelerometer Data
Sensor Deployment in Fuel Cell Electric Vehicles
(provided by Battelle, used with permission)

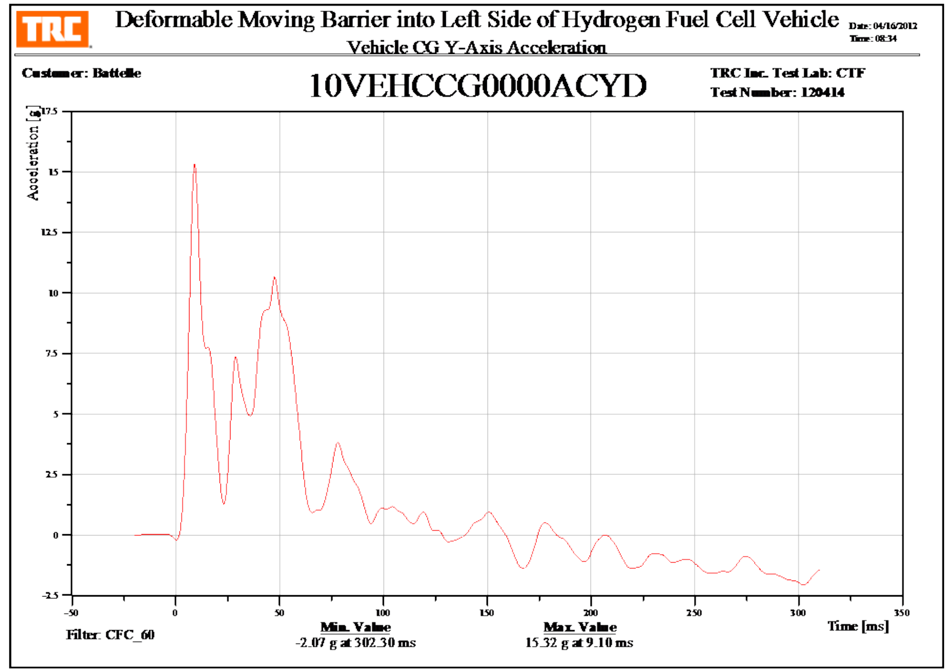

Rigid Moving Barrier Into Rear of Hydrogen Fuel Cell Vehicle
Vehicle CG X-Axis Acceleration
Date: 04/12/2012
Time: 08:12
Customer: Battelle
10VEHCCG0000ACXD
TRC Inc. Test Lab: CTF
Test Number: 120411
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-5.18 g at 67.30 ms
Max. Value
27.98 g at 47.30 ms

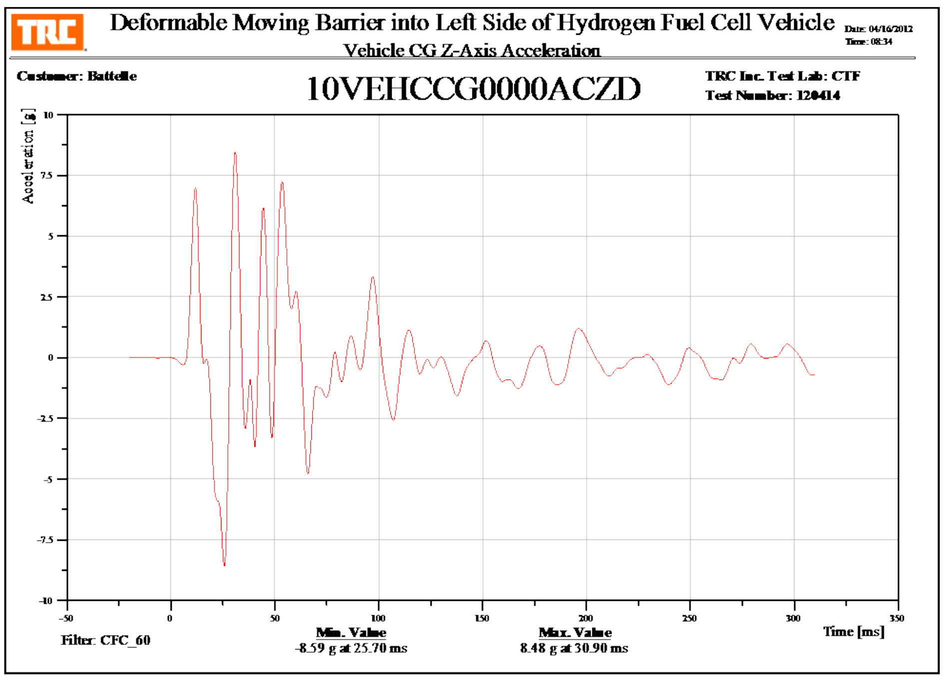

Rigid Moving Barrier Into Rear of Hydrogen Fuel Cell Vehicle
Vehicle CG Y-Axis Acceleration
Date: 04/12/2012
Time: 08:12
Customer: Battelle
10VEHCCG0000ACYD
TRC Inc. Test Lab: CTF
Test Number: 120411
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-7.71 g at 37.70 ms
Max. Value
2.89 g at 48.90 ms

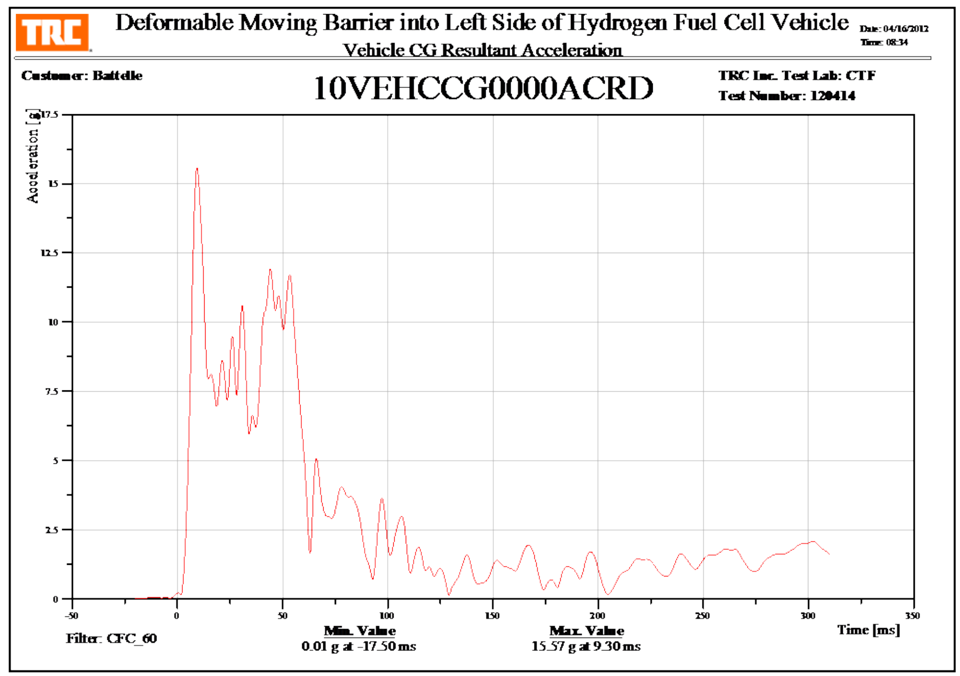

Rigid Moving Barrier Into Rear of Hydrogen Fuel Cell Vehicle
Vehicle CG Z-Axis Acceleration
Date: 04/12/2012
Time: 08:12
Customer: Battelle
10VEHCCG0000ACZD
TRC Inc. Test Lab: CTF
Test Number: 120411
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-13.65 g at 24.60 ms
Max. Value
13.01 g at 32.00 ms


Rigid Moving Barrier Into Rear of Hydrogen Fuel Cell Vehicle
Vehicle CG Resultant Acceleration
Date: 04/12/2012
Time: 08:12
Customer: Battelle
10VEHCCG0000ACRD
TRC Inc. Test Lab: CTF
Test Number: 120411
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
0.01 g at -15.90 ms
Max. Value
28.74 g at 47.30 ms


Deformable Moving Barrier into Left Side of Hydrogen Fuel Cell Vehicle
Vehicle CG X-Axis Acceleration
Customer: Battelle
10VEHCCG0000ACXD
TRC Inc. Test Lab: CTF
Test Number: 120414
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-6.21 g at 21.00 ms
Max. Value
4.60 g at 56.90 ms


Deformable Moving Barrier into Left Side of Hydrogen Fuel Cell Vehicle
Vehicle CG Y-Axis Acceleration
Customer: Battelle
10VEHCCG0000ACYD
TRC Inc. Test Lab: CTF
Test Number: 120414
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-2.07 g at 302.30 ms
Max. Value
15.32 g at 9.10 ms


Deformable Moving Barrier into Left Side of Hydrogen Fuel Cell Vehicle
Vehicle CG Z-Axis Acceleration
Customer: Battelle
10VEHCCG0000ACZD
TRC Inc. Test Lab: CTF
Test Number: 120414
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
-8.59 g at 25.70 ms
Max. Value
8.48 g at 30.90 ms


Deformable Moving Barrier into Left Side of Hydrogen Fuel Cell Vehicle
Vehicle CG Resultant Acceleration
Customer: Battelle
10VEHCCG0000ACRD
TRC Inc. Test Lab: CTF
Test Number: 120414
Acceleration [g]
Time [ms]
Filter: CFC_60
Min. Value
0.01 g at -17.50 ms
Max. Value
15.57 g at 9.30 ms