COMPLIANCE MEASUREMENTS OF FUEL CELL ELECTRIC VEHICLE EXHAUST

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ABSTRACT

The NREL Sensor Laboratory has been developing an analyzer that can verify compliance to the international United Nations Global Technical Regulation number 13 (GTR 13--*Global Technical Regulation on Hydrogen and Fuel Cell Vehicles*) prescriptive requirements pertaining to allowable hydrogen levels in the exhaust of fuel cell electric vehicles (FCEV) [1]. GTR 13 prescribes that the FCEV exhaust shall remain below 4 vol% H_2 over a 3-second moving average and shall not at any time exceed 8 vol% H_2, as verified with an analyzer with a response time (t_{90}) of 300 ms or faster. GTR 13 has been implemented and is to serve as the basis for national regulations pertaining to hydrogen powered vehicle safety in the United States, Canada, Japan, and the European Union. In the U.S., vehicle safety is overseen by the Department of Transportation (DOT) through the Federal Motor Vehicle Safety Standards (FMVSS) and in Canada by Transport Canada through the Canadian Motor Vehicle Safety Standard (CMVSS). The NREL FCEV exhaust analyzer is based upon a low-cost commercial hydrogen sensor with a response time (t_{90}) of less than 250 ms. A prototype analyzer and gas probe assembly have been constructed and tested that can interface to the gas sampling system used by Environment and Climate Change Canada's (ECCC) Emission Research and Measurement Section (ERMS) for the exhaust gas analysis. Through a partnership with Transport Canada, ECCC will analyze the hydrogen level in the exhaust of a commercial FCEV. ECCC will use the NREL FCEV Exhaust Gas analyzer to perform these measurements. The analyzer was demonstrated on a FCEV operating under simulated road conditions using a chassis dynamometer at a private facility.

1.0 Introduction

The United Nations has published at least several documents pertaining to international safety requirements for hydrogen vehicles. These documents include the United Nations Global Technical Regulation Number 13 (GTR 13) [1] and the United Nations Regulations No 134 (UN R134) [2]. GTR 13 (*Global Technical Regulation on Hydrogen and Fuel Cell Vehicles*) [1] is the defining international document prescribing the safety requirements for light duty hydrogen vehicles, and is to serve as the basis for the national regulations for hydrogen fuel cell electric vehicles (FCEV) safety. UN R134 has nearly identical requirements as GTR 13, but unlike the GTR, UN R134 has not been accepted by many national authorities, including the United States and Canada. The GTR includes prescriptive requirements designed to alleviate potential risks associated with electrical hazards and the gaseous hydrogen fuel in FCEVs. Within the United States, the National Highway Traffic Safety Administration (NHTSA) under the Department of Transportation (DOT) oversees the regulatory safety requirements of vehicles through the Federal Motor Vehicle Safety Standard (FMVSS). An important goal of the GTR is to provide a framework to internationally harmonize FCEV safety requirements so as to facilitate hydrogen vehicle market development and trade. Although vehicle safety regulations are to be implemented and enforced by national authorities, there is to be an effort to harmonize the national regulations with the GTR.

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Transport Canada is the regulatory authority for vehicle safety in Canada, and the prevailing regulatory code is the Canadian Motor Vehicle Safety Standard (CMVSS). Environment and Climate Change Canada (ECCC) is responsible for verification of vehicle exhaust compliance, which will include hydrogen-powered vehicles, such as FCEVs. The NREL Sensor Laboratory has an on-going collaboration with DOT to help assure compliance to safety regulations as they pertain to allowable hydrogen levels within and proximal to hydrogen FCEVs [3], [4], [5]. In order to synergize available resources, DOT/NHTSA, the NREL Sensor Laboratory, along with Transport Canada and ECCC, have agreed to collaborate to develop and implement validated test protocols and required measurement hardware to verify compliance to electrical and hydrogen fuel specifications within the GTR. These protocols are to be demonstrated on commercial FCEVs acquired by Transport Canada.

Several of the requirements within the GTR pertain directly to the allowable levels of hydrogen external to the fuel system in and around the FCEV. These include allowable hydrogen levels within vehicle compartments during normal operation and following vehicle crash tests. In addition, Section 5.2.1.3.2 of the GT*R prescribes that the FCEV exhaust shall remain below 4 vol% H_2 over a 3-second moving average and shall not at any time exceed 8 vol% H_2 as verified with an analyzer with a response time (t_{90}) of 300 ms or faster. Identical requirements were prescribed in Section 7.2.1.3.2 of UN 134. A verification method must exist that can assure compliance to any prescriptive regulatory requirement in order for that requirement to be binding. Herein is presented a hardware design that can form the basis for a measurement method to verify that the FCEV exhaust meets the hydrogen level requirements as prescribed within the GTR. Within Canada, verification of vehicle emissions, including demonstration of measurement technology, is performed within the Emissions Research and Measurement Section (ERMS) of ECCC. Accordingly, ECCC and Transport Canada are collaborating to investigate, amongst other metrics, FCEV exhaust measurements. The NREL design can integrate into the ECCC gas handling system used to perform vehicle exhaust analysis. This system was developed to analyze emissions from vehicles with internal combustion engines (ICE) but is being adapted for FCEVs. Accordingly, the NREL sensor laboratory, as part of a project supported by DOT [5], has been working with Transport Canada, and by extension with ECCC for these tests. The development of the FCEV exhaust analyzer by the NREL Sensor Laboratory has been on-going [4], with the most recent activity focusing on integrating the system to the ECCC vehicle emission test apparatus for a demonstration test on a commercial FCEV.

2.0 Approach

2.1 The Detector Element for the FCEV Exhaust Gas Analyzer

The detector element (sensor) is often the most crucial component of a chemical analyzer, the properties of which will often define the metrological capability of the analyzer. The critical metrological specifications for the FCEV exhaust gas analyzer application include a fast response time (t_{90} of 300 ms or faster) and a measurement range of at least up to 8 vol% H_2. Although laboratory instruments such as a mass spectrometer may possibly meet these requirements if configured for fast sampling, these instruments tend to be expensive, complicated to operate, and difficult to validate instrument response times, which is necessary to verify compliance to the GTR requirements. Alternatively, a sensor-based analyzer may offer a cost-effective solution with metrological performance metrics that can be conveniently validated. Regardless of approach, it is necessary that the active detector element of the analyzer (e.g., the sensor) have a response time of at least 300 ms. For many years, the availability of hydrogen sensors with response times of less than 1 second was explicitly identified by DOE as a critical metric [6] and a performance gap [7]. Recently however, a microfabricated thermal conductivity hydrogen sensor was commercialized with a manufacturer-specified response time of 250 ms (model

XEN-TCG3880, Xensor Integration, bv, Delft, Netherlands).[2] The 250 ms response time for the sensor was verified using a validated gas sensor response time test apparatus [6].

The ability of the sensor to meet the range and response time requirements was demonstrated in laboratory evaluations, the results of which are illustrated in Figures 1 and 2. Figure 1 shows the sensor signal in response to a series of short hydrogen pulses ranging in duration from 0.7 s to nearly 3 s and demonstrates the ability of the sensor to accurately measure fast hydrogen transients. Regardless of the duration of the hydrogen pulse, the sensor achieved the same final indication as that which would have been obtained with a steady state hydrogen exposure. The test gas (air or air with 2 vol% H_2) continuously flowed over the sensor during the measurements shown in Figure 1. This will be the case when the sensor is deployed for the exhaust gas measurements, such as at the ECCC vehicle test facility. For the laboratory evaluations, a gas sample loop based on ultra-fast gas valves was used to switch from the background gas of air to generate an approximate "square-wave" hydrogen transient in the gas stream passing over the sensor [4]. The duration of the hydrogen transient is controlled by the sample loop volume and gas flow rate. The measurement range of the sensor is illustrated in Figure 2, which shows that the sensor responds linearly from 0 to 10 vol%. The manufacturer specifies that the sensor has a near-linear range up to 100 vol%; laboratory measurements verified the range of the sensor.

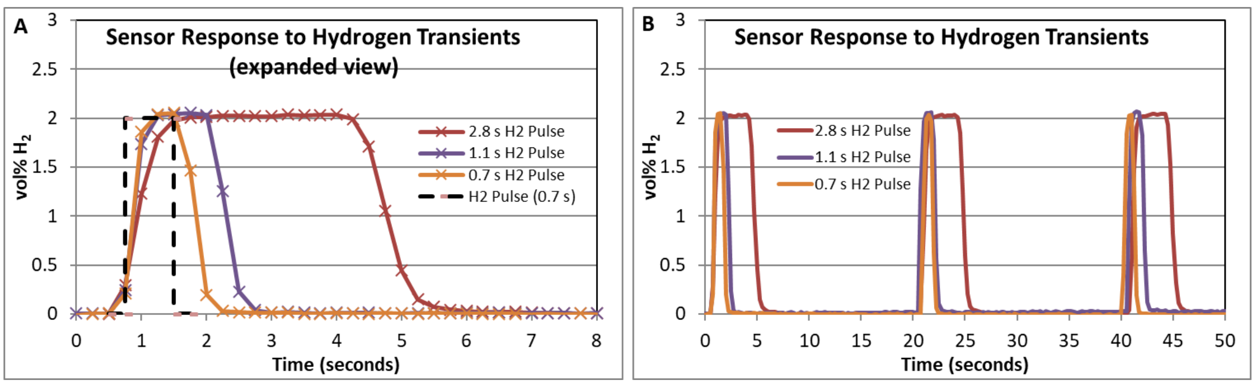

Figure 1: Net sensor response to hydrogen pulses of variable duration (0.7 to 2.8 s are shown) as generated from a gas sample loop pre-purged with 2 vol% H_2. The sample loop generates a near-square wave hydrogen pulse, albeit with some broadening at the pulse edge due to diffusion that occurs during transit. (A) Expanded view the sensor response for hydrogen pulses of different duration to demonstrate the sensor fast response time and its ability to quickly achieve a stable final indication. (B) Illustration of the sensor reproducibility as demonstrated by a series of multiple gas exposures.

[2] Other sensor types could be used for the FCEV exhaust gas analyzer providing they meet the required response time and measuring range requirements as specified in GTR Number 13.

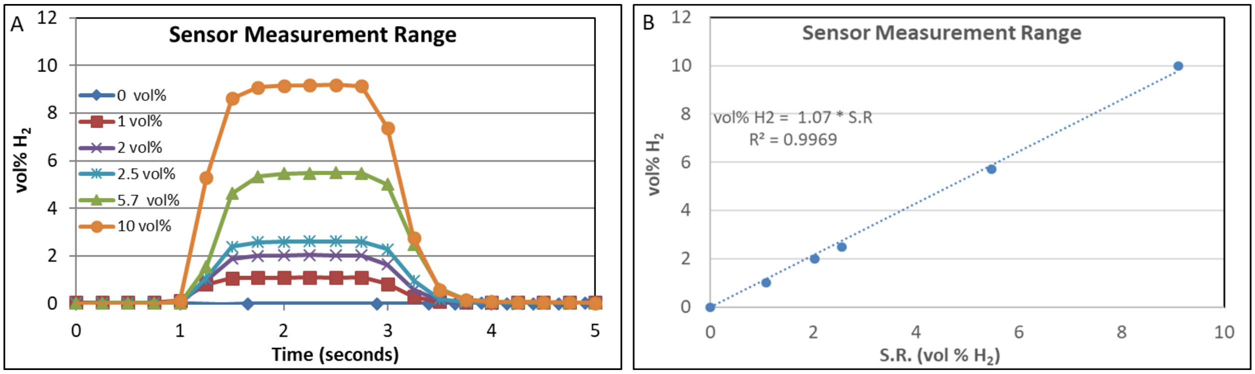

Figure 2: (A) Net sensor response to different hydrogen concentrations (0 to 10 vol% H_2) for an approximate 2-second hydrogen pulse. (B) Test gas concentration vs. sensor response (S.R), demonstrating a linear sensor response for the range 0 to 10 vol% H_2.

2.2 The ECCC Vehicle Exhaust Gas Handling System

ECCC is responsible for assuring regulated vehicle exhaust constituent emission rates comply to the Canadian Environmental Protection Act (CEPA). For conventional ICE vehicles, the vehicle exhaust regulations frequently pertain to environmental standards; hence within Canada this activity is spearheaded by ERMS. The ECCC has a vehicle test facility that can safely operate vehicles under simulated vehicle loads and driving conditions using chassis dynamometers, while analyzing the vehicle exhaust gas composition. FCEVs are recognized as zero emission vehicles, hence environmental concerns are minimal, but the exhaust requirements as prescribed by the GTR were formulated to assure non-flammability. The ECCC has developed and regularly use exhaust gas handling systems for safely collecting and measuring vehicle emissions. This testing is performed under simulated vehicle load conditions using a chassis dynamometer, which uses a roller assembly and DC motor to allow the vehicle drive-axle(s) to rotate under load, simulating the losses experienced on-road, in a controlled, indoor environment. Figure 3 illustrates the ECCC exhaust gas handling system. It provides an interface between the exhaust vent of the test vehicle (typically a tailpipe for an ICE vehicle but in this case the vent of the FCEV) and the test facility constant volume sampler (CVS) system. The ECCC exhaust gas handling system interface includes a slip-stream (the Sampling Tube highlighted in Detail A of Figure 3) that can siphon raw test gas to a chemical analyzer, such as the NREL FCEV exhaust analyzer. The ECCC system has been adapted to operate with hydrogen powered vehicles.

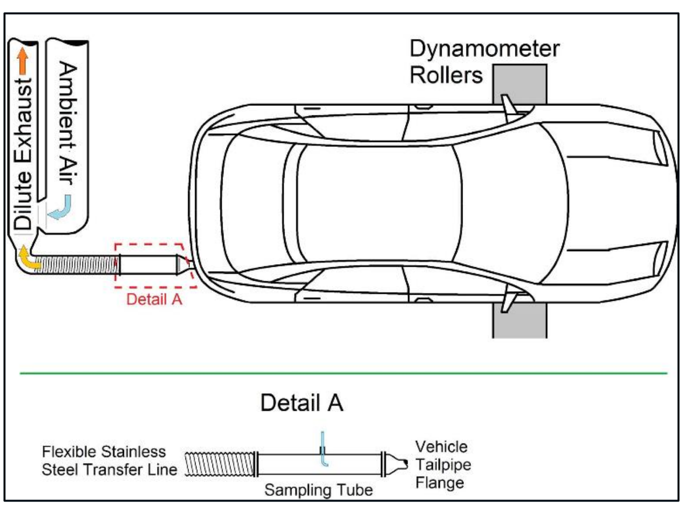

Figure 3: Illustration of the gas handling system developed by ECCC to collect FCEV exhaust for analysis. The NREL FCEV exhaust analyzer was adapted to connect directly to the sampling tube shown in Detail A. Illustration provided by ECCC.

2.3: Integration Exhaust Analyzer to the Gas Handling System

The Sampling Tube illustrated in Detail A of Figure 3 provides a convenient way to collect gas samples from the exhaust stream for analysis. The sensor described in Section 2.1.1 was mounted in a hermetically sealed housing of in-house design to assure leak-free sample collection and analysis integrity (Figure 4). A miniature gas pump draws gas through the sampling tube to the hydrogen sensor. The sensor output was continuously monitored and stored in an electronic data file using the software supplied by the sensor manufacture. The sensor response was logged every 250 ms. The gas flow rate over the sensor was maintained to approximately 1 slpm (standard liter per minute) as measured with a mass flow meter (MFM); the MFM responds to the mass flow rate of the sample gas over the sensing element but is converted to a volume by assuming standard conditions for an ideal gas. Laboratory evaluation verified that the sensor response is not affected by variations in the gas flow rate.

Figure 4: Left: A commercial thermo-conductivity hydrogen sensor. This sensor has been incorporated into the NREL FCEV Exhaust Analyzer. Right: A low-dead volume, custom built hermetically-sealed housing that includes a gas tight electrical feedthrough for the sensor for power and to allow data collection.

A gas handling system analogous to the ECCC design was constructed at NREL and deployed on an FCEV. NREL was given access to a developmental FCEV with an on-board hydrogen sensor to test out the exhaust gas analyzer (the vehicle type and on-board sensor were proprietary). Measurements made by the NREL analyzer on a FCEV are shown in Figure 5. Figure 5 (left) was a set-up test (i.e., a functionality test) with the NREL FCEV analyzer connected to the FCEV exhaust vent, in which the output of the exhaust analyzer is compared to data provided by the on-board hydrogen sensor. The agreement between the proprietary on-board sensor response and the NREL exhaust analyzer was excellent. Minor deviations in the on-board sensor and the NREL exhaust analyzer were observed that were probably due to differences in sensor response times; the NREL exhaust analyzer uses a very fast sensor. Furthermore, the GTR requirements prescribe that exhaust gas analyses are performed downstream from the vehicle exhaust pipe, thus there is a delay time between the measurement by the on-board sensor and off-vehicle sensor associated with the NREL analyzer. This delay allows time for more diffusion of the hydrogen, which would tend to dampen out transient spikes. The exhaust analyzer was then used to monitor FCEV exhaust as the vehicle operated under two simulated vehicle load conditions. The load conditions were developed by the developer to support internal research and development activities. The specifics on the simulated vehicle load conditions are proprietary but were designed to subject vehicles under test to conditions that mimic highway and urban driving environment. The data from the on-board sensor was not available from these tests. Overall, the NREL FCEV exhaust gas analyzer performed as desired. However, a few design modifications of the gas collection design are proposed to minimize impact of condensation on the gas collection system.

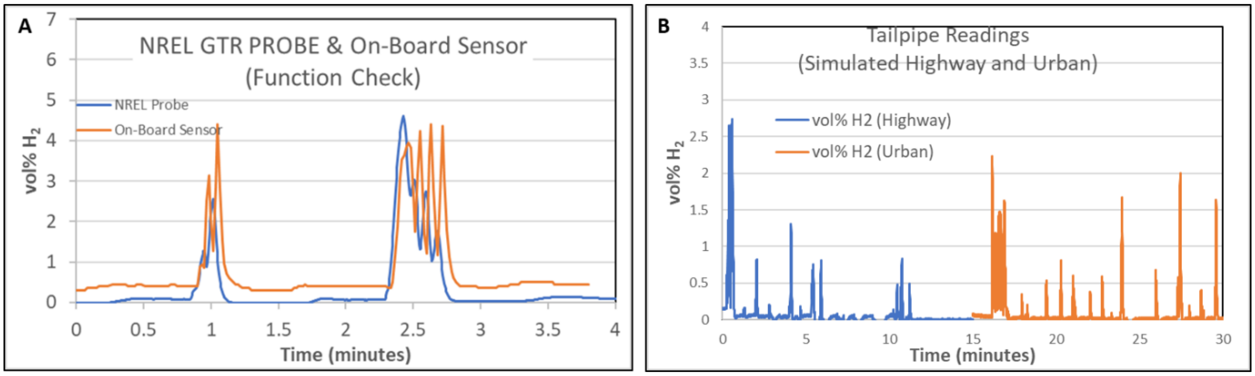

Figure 5: (A) Preliminary measurement of the NREL FCEV Exhaust Analyzer on a FCEV using the gas handling system analogous to the ECCC design. For comparison, the reading of a (proprietary) on-board sensor is shown. (B) Measurement of a developmental FCEV exhaust under simulated highway and urban driving conditions through the use of a dynamometer. Data from the on-board sensor was not available.

3.0 Future Plans--Testing of the NREL Exhaust Gas Analyzer on a Commercial FCEV

Transport Canada has acquired two commercial FCEV for safety testing. This testing, which is in partnership with the U.S. DOT will be guided by the GTR requirements. As indicated, the exhaust gas analysis will be performed at the ERMS facility operated by ECCC. Although the deployment of the NREL Exhaust Gas Analyzer on a commercial FCEV at the ERMS-ECCC was planned for fiscal year 2018, it was delayed, primarily for logistical reasons. Presently, this testing is being scheduled and will be completed by September 2019. The results of which and the performance of the analyzer will be presented in the corresponding lecture section at the ICHS.

4.0 Acknowledgements

The development and deployment of the prototype FCEV Exhaust Gas Analyzer was supported through the DOE Fuel Cells Technology Office, Hydrogen Safety Codes and Standards Program (Laura Hill, Program Manager and Anthony Belvin assistant sub-Program Manager). Additional support was provided by the U.S. DOT through Interagency Agreement IAG-17-02046: Hydrogen Detection Technology.

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