SAFETY COMPLIANCE VERIFICATION OF FUEL CELL ELECTRIC VEHICLE EXHAUST

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ABSTRACT

NREL has been developing compliance verification tools for allowable hydrogen levels prescribed by the Global Technical Regulation Number 13 (GTR-13) for hydrogen fuel cell electric vehicles (FCEVs). As per GTR-13, FCEV exhaust is to remain below 4 vol% H_2 over a 3-second moving average and shall not at any time exceed 8 vol% H_2 and that this requirement is to be verified with an analyzer that has a response time of less than 300 ms. To be enforceable, a means to verify regulatory requirements must exist. In response to this need, NREL developed a prototype analyzer that meets the GTR metrological requirements for FCEV exhaust analysis. The analyzer was tested on a commercial fuel cell electric vehicle (FCEV) under simulated driving conditions using a chassis dynamometer at the Emissions Research and Measurement Section of Environment and Climate Change Canada and FCEV exhaust was successfully profiled. Although the prototype FCEV Exhaust Analyzer met the metrological requirements of GTR-13, the stability of the hydrogen sensor was adversely impacted by condensed water in the sample gas. FCEV exhaust is at an elevated temperature and nearly saturated with water vapor. Furthermore, condensed water is present in the form of droplets. Condensed water in the sample gas collected from FCEV exhaust can accumulate on the hydrogen sensing element, which would not only block access of hydrogen to the sensing element but can also permanently damage the sensor electronics. In the past year the design of the gas sampling system was modified to mitigate against the transport of liquid water to the sensing element. Laboratory testing confirmed the effectiveness of the modified sampling system water removal strategy while maintaining the measurement range and response time required by GTR-13. Testing of the upgraded analyzer design on an FCEV operating on a chassis dynamometer is scheduled for the summer of 2021.

1.0 INTRODUCTION

The underlying safety requirements for hydrogen fuel cell electric vehicles (FCEV) are defined in the United Nations Global Technical Regulation 13 (GTR-13) [1]. GTR-13 contains specific performance and prescriptive requirements designed to alleviate potential electrical hazards and hazards associated with the hydrogen fuel in FCEVs. A critical role for GTR-13 is to provide a framework to internationally harmonize FCEV safety requirements 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 individual national regulations with GTR-13. 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). Transport Canada (TCa) is the regulatory authority for vehicle safety in Canada, and the prevailing regulatory code is the Canadian Motor Vehicle Safety Standard (CMVSS).

The NREL Sensor Laboratory has an on-going research program to help assure compliance to safety regulations as they pertain to allowable hydrogen levels within and proximal to hydrogen FCEVs [2], [3],

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[4]. These verification protocols are to be demonstrated on commercial FCEVs acquired by TCa. Within Canada, Environment and Climate Change Canada (ECCC) is responsible for verification of vehicle exhaust compliance to regulatory requirements, which will include exhaust emissions from hydrogen-powered FCEVs. Current efforts by the NREL Sensor Laboratory are focusing on developing test methodology to quantitatively profile the exhaust of commercial FCEVs under different driving conditions. Hydrogen content in FCEV exhaust is rigorously regulated by requirements prescribed in GTR-13, which specifies:

- At the vehicle exhaust system's point of discharge, the hydrogen concentration level shall:
  - Not exceed 4 percent average by volume during any moving three-second time interval during normal operation including start-up and shutdown.
  - And not exceed 8 percent at any time.
  - It was also specified that the response time of the analyzer be less than 300 ms

A prototype FCEV Exhaust Gas Analyzer was developed by NREL to provide a verification tool for regulators and vehicle developers to assure compliance to GTR-13. The prototype Analyzer was tested on a commercial FCEV at the Emissions Research and Measurement Section (ERMS) facility operated by ECCC in Ottawa, Ontario in August 2019. The design and metrological performance of the prototype Analyzer were described at the 2019 International Conference on Hydrogen Safety (ICHS) [4], [5]. Some results on FCEV exhaust measurements obtained during the field deployment were included in the 2019 ICHS conference presentation [5], but were not available for inclusion in the conference paper which was submitted prior to the field deployment. This paper is a follow-up on the work presented in 2019 and will describe recent design modifications of the FCEV Exhaust Gas Analyzer. This recent effort includes the implementation of exhaust gas sampling and delivery methods that preclude transport of liquid water to the hydrogen sensing element while maintaining critical metrological performance specifications.

ECCC is responsible for assuring regulated vehicle exhaust component emission rates comply to the Canadian Environmental Protection Act (CEPA) [6]. The Emissions Research and Measurement Section (ERMS) of ECCC is the national laboratory that undertakes compliance audit testing of both engines and vehicles to ensure they meet these federal emission regulations. In addition, the ERMS participates in multiple correlation programs and research studies that contribute to enhancing the quality of overall testing, advancing regulatory standards and procedures for existing and evolving transportation technologies, and evaluating clean transportation technologies, such as FCEVs. The ECCC's mandate, in part, is to promote the adoption and use of clean transportation technologies, facilitate their evaluations, and continually improve upon test methods; thus, the evaluation of a novel hydrogen sensor for applications in FCEV compliance to emission regulations is of primary interest to ECCC.

As part of the Innovation Centre, Transport Canada's ecoTECHNOLOGY for Vehicles Program (eTV) [7] tests and evaluates the safety and environmental performance of advanced vehicle technologies such as FCEVs, with the goal of advancing key Government of Canada Priorities. Together, TCa and ECCC have leveraged their respective unique resources and capabilities to collaborate on novel and groundbreaking studies related to advanced engines, fuels, and vehicle technologies.

The ERMS laboratory is equipped with environmental chambers, equipment and instruments that allow for the safe operation of test vehicles and engines under simulated real-world loads and driving conditions, all while collecting, speciating, and analyzing numerous vehicle exhaust species. While FCEVs are generally perceived to be zero emission vehicles (ZEVs), their potential to release tailpipe hydrogen has spurred the UN to include regulations on any hydrogen releases in the GTR-13 to assure that the hydrogen content of the exhaust is at all times below dangerous levels. As part of a related TCa-ECCC study, TCa contracted professional drivers to mileage accumulate their FCEV to a minimum of 1600 km to 'break-in' the vehicle (as recommended by SAE J1634) before being evaluated [8]. Once the FCEV has accumulated 1600 km it will be taken to a fueling facility equipped with the manufacturer communication protocols required for safe filling, and then it will be delivered to the ERMS, where it will undergo testing under simulated driving conditions. The ERMS chassis dynamometers are composed of a 48” diameter all-wheel roller assembly and in-line DC motors that can be programmed to specifically load any test vehicle at the resistances it could expect to encounter at a range of speeds on-road. The capability to do this within an environmental chamber allows for controlling the temperature and humidity to which the vehicle is exposed. Further, it allows for the full collection of tailpipe exhaust emissions and equipping the vehicle with various instrumentation that would otherwise be too cumbersome or incompatible with on-road usage. Figure 1 illustrates the ERMS constant volume sampling (CVS) system connected to the tailpipe of a test vehicle from which exhaust samples would typically be extracted and analyzed. For this study, the FCEV exhaust vent will interface with a raw gas sampling tube (Detail A in Figure 1) from which small samples of the exhaust gas will be drawn and transported to the NREL Exhaust Analyzer. A J-type probe ¼ inch diameter will be affixed in an NPT fitting on the raw gas sampling tube (e.g., the Transfer Line in Figure 1) facing upstream, but behind a deflection barrier, which is inserted to mitigate against the collection of condensed water in the test gas stream (the deflection barrier is not shown in Figure 1). The J-type probe is part of the sampling system that integrates the NREL FCEV Exhaust Gas Analyzer to the vehicle exhaust transfer line developed by ECCC.

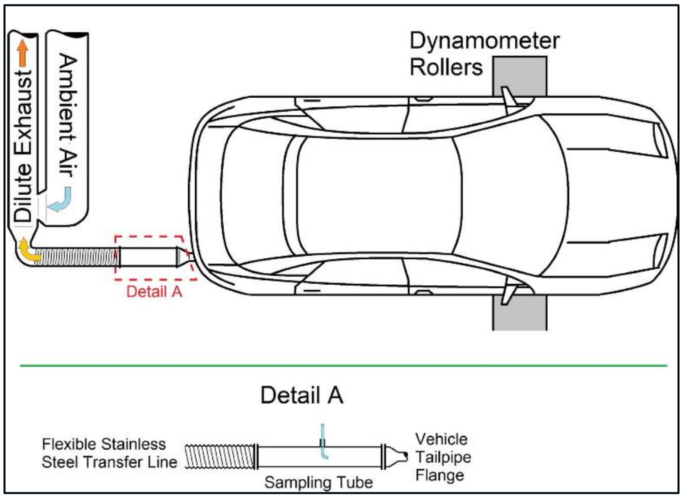

Figure 1: Illustration of the gas handling system developed by ECCC to collect FCEV exhaust for analysis. Detail A shows the gas Transfer Line connected to the vehicle tailpipe. The inlet to the gas Sampling System for the NREL FCEV exhaust analyzer was designed to connect directly to the Transfer Line.

2.0 APPROACH

2.1 Overview of the NREL FCEV Exhaust Analyzer

The NREL FCEV Exhaust Analyzer was developed as a self-contained instrument for the analysis of fast hydrogen transients in a flowing gas stream (such as in FCEV exhaust). It consists of two main subsystems integrated into a specialized gas analyzer designed specifically for the quantitative profiling of hydrogen levels in FCEV Exhaust:

1. The electronic system, which includes the hydrogen sensor element, support sensing elements for monitoring the test gas conditions (e.g., temperature and humidity), and a data acquisition system (DAQ).
2. A Sampling System that extracts sample gas from vehicle exhaust and transport it to a hydrogen sensing element for analysis.

The main features for the electronic subsystem were previously described at the 2019 ICHS [4], including details on the selection and metrological performance metrics of the hydrogen sensing element. The sensing element is the critical component for the Analyzer and must meet crucial performance metrics. The most challenging metric is a verified response time (t_{90}) of less than 300 ms. The hydrogen sensing element is based on a commercial sensor that met this requirement, and has a t_{90} of 200 to 300 ms as verified on response time fixtures at NREL and at the Joint Research Facility [9]. The sensing element also has a broad measurement range (0 to 100 vol% H_2) and thus readily meets the measurement range required by GTR-13. There are also sensors with dual temperature and relative humidity sensing elements (T/RH sensors) installed at multiple points in the sampling system to monitor test gas conditions. The hydrogen sensor and T/RH sensors outputs were logged by a LabView® based DAQ interfaced to a laptop computer. Data files for each exhaust measurement are generated that could be quickly worked up by standard spreadsheet software for analysis and record keeping. For deployments, control elements (e.g., power supplies, electronic interfaces) were packaged into a robust instrument case.

The Sampling System provides a means to transport samples of the exhaust gas to the hydrogen sensor for analysis. It includes a sample inlet (shown in "Detail A" of Figure 1) that is based upon a standard ¼ stainless steel tube configured into a J-probe and mounted on the wall of the ECCC Transfer Line. A critical challenge for the Sampling System is the mitigation of liquid water that may be present in the gas stream and subsequently exposed to the hydrogen sensor. The presence of liquid water could not only corrupt measurement accuracy by physical blockage of the test gas access to the hydrogen sensing element, but could also damage the sensing element, both of which were observed in the 2019 deployment of the prototype FCEV Exhaust Analyzer [5]. Condensed water in the test gas can originate from two main sources:

1. Direct uptake through the sample gas inlet of water droplets and aerosols that are present in the exhaust gas that may then be transported to the sensing element through the Sampling System.
2. Condensation of water vapor to liquid water as the sampled exhaust gas is cooled to ambient temperature during transport through the Sampling System to the sensing element.

Thus, to protect the sensing element, a water mitigation strategy must address both direct water uptake at the sample inlet and the internal generation of liquid water from condensation out of the elevated temperature, high humidity FCEV exhaust gas as it cools in the Sampling System. Several elements for liquid water mitigation were incorporated into the updated Sampling System to address both of these issues. There is a deflection barrier at the sample gas inlet to minimize direct liquid water uptake with the exhaust stream into the Sampling System. The Sampling System includes a cooling coil immersed in an ice bath to lower the test gas temperature to below ambient as a means to condense water vapor to produce a gas stream with a low dew point. There is also a novel liquid water removal system that includes a water trap and a gas stream separator to produce a separate dehumidified test gas stream that is analyzed by the hydrogen sensor. T/RH sensors are installed at various points in the Sampling System to monitor the condition of the gas streams and to verify that the test gas reaching the hydrogen sensor is at a near-ambient temperature and a non-condensing RH. Specific locations for the T/RH sensors include within the Transfer Line at the inlet to the Sampling System, downstream from the water trap, and at the hydrogen sensor. The main features are shown in Figure 2, but details of the Sampling System design are currently treated as proprietary and a subject of an internal record of invention [10].

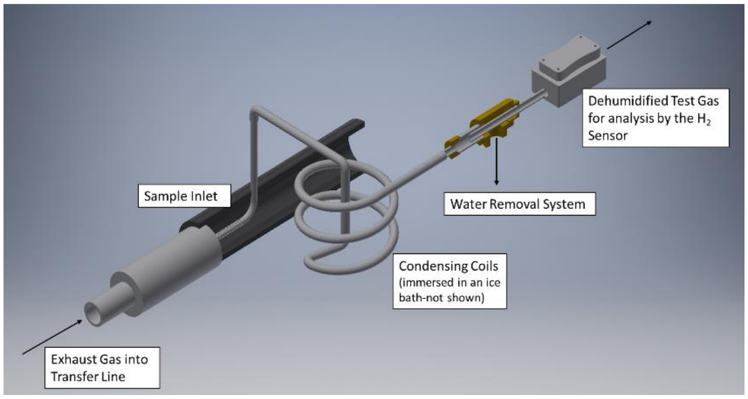

Figure 2: Key features of the gas Sampling System to collect gas samples for the FCEV Exhaust and transport them to the hydrogen sensor for analysis. A downstream pump, vent, and flow controllers are not shown. A water trap (not shown) is just downstream from the Water Removal Section.

2.2 Assessment and Deployment of the NREL prototype FCEV Exhaust Gas Analyzer

Validation testing of the hydrogen sensing element used in the Analyzer has been described previously [4]. Laboratory assessment of the assembled prototype FCEV Exhaust Gas Analyzer has been performed on a simulated tailpipe fixture designed to provide test gas up to 60 L/min at elevated temperatures up to 70ºC and condensing humidity levels (Figure 3), which simulate conditions within an FCEV exhaust pipe. A heated water bubbler bath was used to generate test gases at elevated temperatures and high humidity levels and entrained with water droplets. Flow rate through the bubbler and into the simulated tailpipe fixture are controlled by rotameters. The simulated tailpipe fixture was adapted to accommodate the Sampling System for the prototype FCEV Exhaust Gas Analyzer. Testing with the simulate tailpipe verified the effectiveness of the water mitigation strategy incorporated into the Sampling System

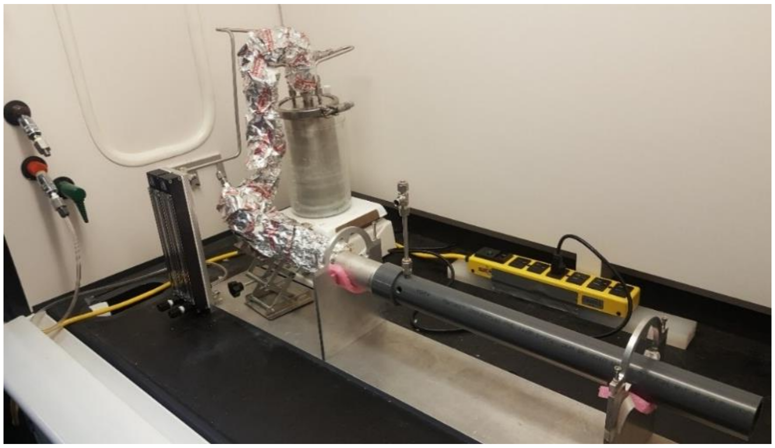

Figure 3: The Simulated Tailpipe Fixture used to evaluate key operational features of the NREL FCEV Exhaust Gas Analyzer.

The prototype FCEV Exhaust Gas Analyzer with a simple gas sampling system was deployed at the ERMS of ECCC in July 2019. The deployment served to:

- Verify compliance of a commercial FCEV to the exhaust requirements as prescribed in GTR-13.
- Demonstrate operation of the NREL Exhaust Gas Analyzer and to identify improvements in its design and operation.
- Verify the effectiveness of the current GTR-13 requirements on FCEV exhaust and to provided recommended modifications.
- Develop documented protocols for verification of the GTR-13 requirements for possible incorporation into upcoming revisions of the GTR.

The first two bullets were successfully completed, although verification of improvements in the design and operation of the FCEV Analyzer (with the modified sampling system) still need to be validated outside the laboratory and on an actual operational FCEV; this is planned for the summer of 2021. The remaining bullets are part of the on-going collaboration with TCa and ECCC and will be addressed following the field deployment of the Analyzer.

3.0 RESULTS

3.1 Outcomes of the Exhaust Gas Analyzer Deployment at ECCC (2019)

Members of the NREL Sensor Laboratory made a site visit to ERMS of ECCC in 2019 to deploy the prototype Analyzer on a commercial FCEV Vehicle (Figure 4). The vehicle was provided by TCa to support this deployment. Over 20 FCEV exhaust gas profiles were measured with the vehicle operating on a chassis dynamometer to subject the vehicle to simulated driving conditions. Exhaust gas measurements were also performed during vehicle start up and shutdown. Figure 5 illustrates the hydrogen profiles obtained from several of these tests. A brief discussion of the deployment results were presented at the 2019 ICHS [5]. Figure 5 shows plots of the hydrogen levels (in vol% H_2) as measured by the prototype FCEV Exhaust Gas Analyzer for various simulated driving tests. The data in Figure 5 was obtained with the DAQ logging the hydrogen sensing element response at a sampling rate of 10 Hz and is presented both as a temporal plot of the direct output of the hydrogen sensing element along with a plot of the 3-second moving average for the same data. Various test methods that simulate different driving conditions were performed on the vehicle operating on the chassis dynamometer, including urban driving (LA4 and 505), and aggressive driving (US06) along with monitoring of the exhaust during FCEV shutdown. In all cases, the FCEV Exhaust Analyzer confirmed the compliance of the FCEV to the GTR requirements.

Figure 4: NREL and ECCC team members interfacing the prototype FCEV Exhaust Gas Analyzer to a commercial FCEV

Operation of the prototype FCEV Exhaust Gas Analyzer was demonstrated, but not the robustness of the hydrogen sensing element. At least one hydrogen sensor suffered catastrophic failure due to water entrainment in the sampling line that made its way to the sensing element. Although there were water mitigation strategies in place in this field deployment, these were found to be inadequate for reliable long-term operation. This necessitated upgrades to the Sampling System as described above. Laboratory evaluations of the upgraded Sampling System is presented below.

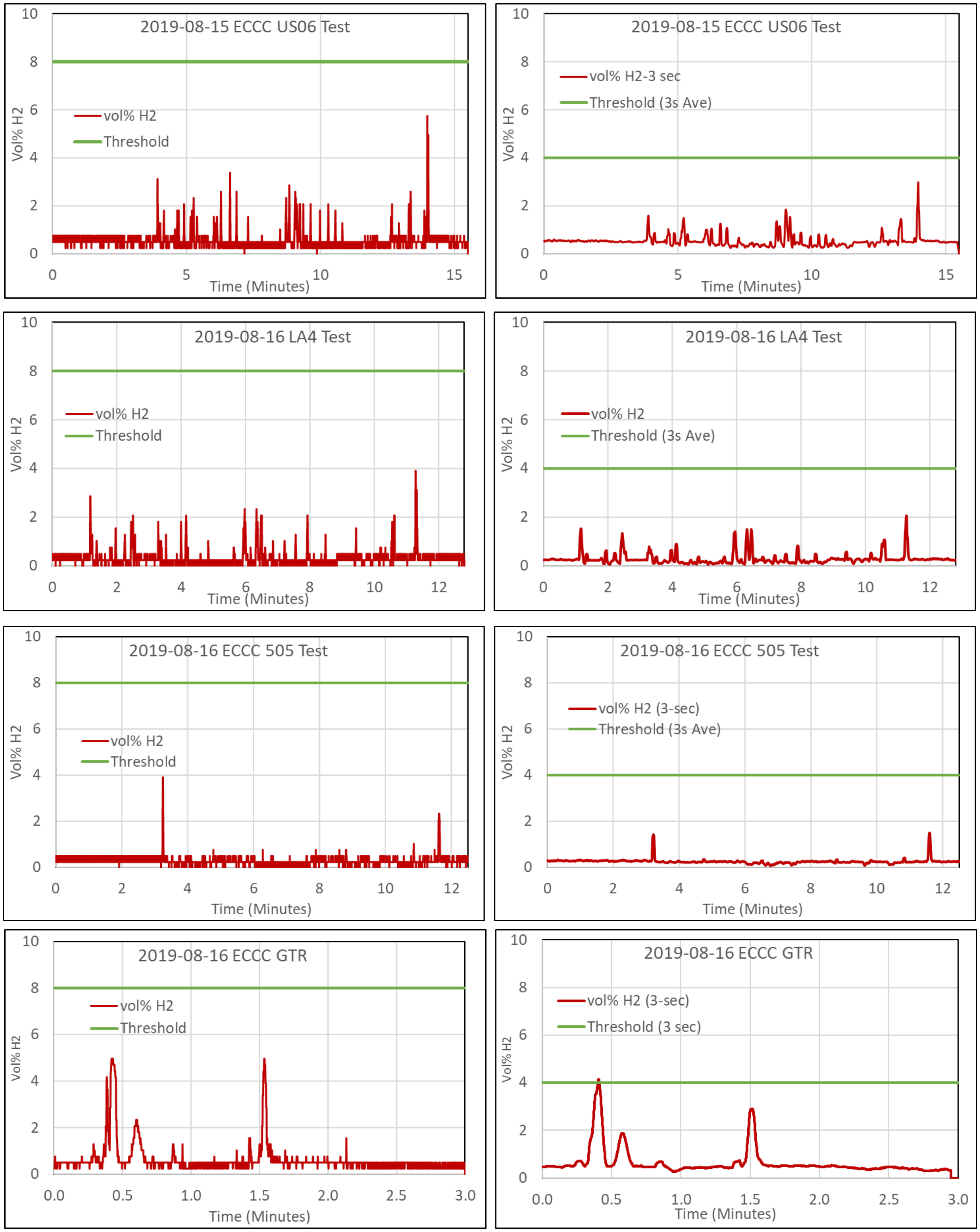

Figure 5: Exhaust Gas Analyzer results to various simulated driving test protocols including aggressive (US06) and urban (LA4 and 505) and during FCEV Shutdown as per GTR-13 requirements. Results are shown (LEFT) as the direct output of the sensor (10 Hz sampling rate) and (RIGHT) as a 3-second moving average of the same data. The Analyzer confirmed compliance of the FCEV exhaust requirements as prescribed by GTR-13

3.2 Development and Testing of the Modified Sampling System

The modified Sampling System with advanced water mitigation elements developed for the FCEV Exhaust Gas Analyzer was tested with humidified test gas at elevated temperature flowing up to 60 L/min through the simulated tail pipe. T/RH sensors monitored the test gas at three points in the Sampling System, including:

1. Within the Transfer Line (e.g., the exhaust gas) proximal to the inlet of the Sampling System.
2. Just downstream from the water trap to measure the T and RH of the “moisture line” within the Sampling System.
3. Just downstream from the hydrogen sensing element to measure the T and RH of the dehumidifed gas stream flowing over the hydrogen sensing element.

Results illustrating the effectiveness of the modified Sampling System for removing water from the test gas are shown in Figure 6. The temperature of the gas steam in the simulated tailpipe fixture ranged between 70ºC and 80ºC and with a near-saturated RH. RH data are not shown for the transfer line due to damage to the RH sensing element caused by condensed water prior to this test, however, earlier tests confirmed a near-saturated humidity in the test gas. We have a way to preclude water damage to the RH sensing element by deflecting water droplets away from the T/RH sensor in the transfer line. T/RH sensors also measured test gas conditions within the Sampling System. The temperature of the gas stream just downstream from the water trap was near-ambient (25ºC) but with a high RH (about 90%). However, downstream from the water trip, the gas temperature was 25ºC but at 50% RH; this is the gas stream that is analyzed by the hydrogen sensing element. At this temperature and relative humidity, there is no chance of water droplets interfering with the hydrogen sensing element. Long-term operation (several hours) did not show any evidence of condensed water in the analysis line (e.g., the gas stream that is passed over the hydrogen sensing element), either as the presence of droplets on the walls of the pneumatic line or the observation of a RH greater that 50% to 60%. This demonstrates that the modified Sampling System is effective in removing water from the gas sample line and that the sensor will likely not be plagued by condensed water.

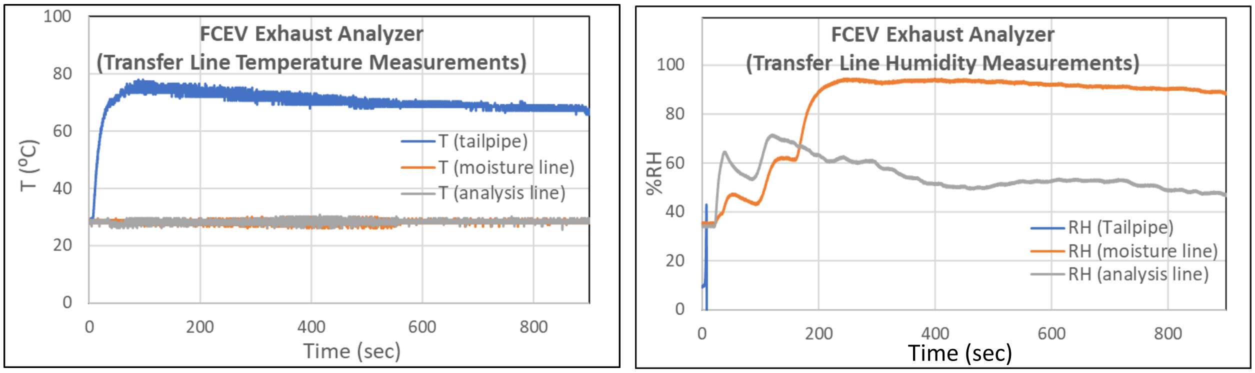

Figure 6: T (left) and RH (right) measurements at various points in the Sampling System including within the tailpipe transfer line (blue), just downstream from the water trap (orange), and near the hydrogen sensing element (gray). High humidity levels were present at all locations within the Sampling System except downstream of the water removal system, which is the gas stream analyzed by the hydrogen sensing element.

More importantly, the Sampling System can be operated in a manner that complies with the GTR measurement requirements, including measurement range and response time (see Figure 7). A plug of a test gas sample with 2 vol% H_2 was injected into the sample inlet of the Sampling System. The gas was transported to the hydrogen sensing element through the sampling system. The sensor responded to the test gas with a t_{90} of 250 ms.

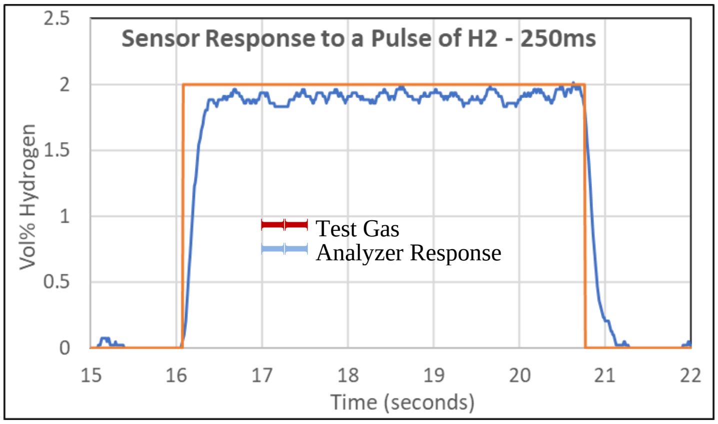

Figure 7: Metrological performance of the NREL FCEV Exhaust Gas Analyzer to a short pulse of 2 vol% H_2 in air as transported through the Sampling System. The sensing element accurately measured the concentration of the test gas. The sensor response time (t_{90}) was 250 ms, which was compliant to the GTR requirements.

4.0 SUMMARY and FUTURE WORK

The NREL Sensor Laboratory has developed a prototype FCEV Exhaust Gas Analyzer that meets crtical metrological metrics prescribed by GTR-13 for allowable hydrogen levels in FCEV Exhaust, including an appropriate measurement range and t_{90} response time. Performance was demonstrated on a commercial FCEV at ERMS. However, while the prototpye Analyzer met the metrological specifications needed for verificaton to the GTR-13 requirements, the overall system was plagued with condensed water issues which could corrupt measurement accuracy or even permanently damage the hydrogen sensing element [5]. A novel Sampling System was recently develped to mitigate condensed water issues and was successfully demonstrated at NREL using an in-house laboratory fixture that simulatte FCEV exhaust conditions. With the Sampleing System, simulated FCEV exhasut test gas that was collected at approximately 70º C and saturated humidity levels with water droplets reached the hydrogen sensing element at ambient temperature and 50% RH, while maintaining sample integrity and appropriate response time.

The NREL FCEV Exhaust Gas Analyzer (the Electronic Subsystem and the modified Sampling System) now needs to be demonstrated on operational FCEVs. NREL, ECCC, and TCa have agreed to test and deploy the updated Exhaust Gas Analzyer and test it on a commecial FCEV at the ERMS. This deployment is planned for the summer of 2021, although there may be delays because of COVID related restrictions. TCa has several candidate commercial FCEVs for this demonstration, including the Toyota Marai and Hyundi Nexo (Figure 8), which will be supplied to ECCC to support this proposed testing. ECCC will make available ERMS resources to support the on-site testing of the Analzyer on the FCEV operating under simulated driving conditions using a chassis dynanometer.

Upon successful demonstration of the Exhaust Analyzer with the updated Sampling System, NREL will work with TCa, ECCC and other stakeholders to develop a validated method for using the Analyzer for testing hydrogen concentration in for FCEV exhaust. NREL will also work with instrument developers to assure availability of the Analyzer.

Figure 8: Commercial FCEVs acquired by TCa for safety testing and compliance to GTR-13, including demonstration of the NREL FCEV Exhaust Analyzer at ECCC.

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