# FUEL CELL VEHICLE HYDROGEN EMISSIONS TESTING

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**ABSTRACT**

The NREL Hydrogen Sensor Laboratory is comprised of researchers dedicated to furthering hydrogen sensor technology and detection methodology. NREL has teamed up with researchers at Environment and Climate Change Canada (ECCC), and Transport Canada (TC) to conduct research to quantify hydrogen emissions from Fuel Cell Electric Vehicles (FCEV). Test protocols will have a large effect on monitoring and regulating the hydrogen emissions from FCEVs. How emissions are tested will play an important role when understanding the safety and environmental implications of using FCEVs. NREL Sensor Laboratory personnel have partnered with other entities to conduct multiple variations of emissions testing for FCEVs. This experimentation includes testing different models of FCEVs under various driving conditions while monitoring the hydrogen concentration of the exhaust using several different test methods and apparatus. Researchers look to support regulatory bodies by providing useful data that can support more consistent and relevant safety and environmental standards. We plan to present on the current test methods and results from recent emissions measurements at ECCC.

## 1.0 INTRODUCTION

The National Renewable Energy Laboratory (NREL) Sensor Laboratory, Environment and Climate Change Canada (ECCC), and Transport Canada (TC) have ongoing research programs to ensure fuel cell electric vehicles (FCEVs) are compliant with safety standards and regulations regarding allowable levels of hydrogen in the exhaust. Earlier, the NREL Sensor Laboratory developed an analyser for the determination of hydrogen concentrations in the exhaust of FCEVs and demonstrated it on a commercial vehicle at the Emissions Research and Measurement Section (ERMS) facility of ECCC in Ottawa Canada [1]. The NREL analyser was based upon a commercial hydrogen sensor with a fast response time ($t_{90}$ < 200 ms) to serve as the hydrogen detector. The ERMS utilizes a so-called full-dilution constant volume sampling system (CVS) to capture, condition, speciate, and eventually vent out the exhaust gases emitted from internal combustion engine vehicles (ICEVs). This type of system is widely used in the industry of vehicle emissions testing, and during the first iteration of this study, the CVS was utilized for the FCEV exhaust as well. Operationally, the analyser collected gas samples for analysis from an exhaust gas transfer line upstream of the ERMS's CVS. The focus of the analysis was to verify that FCEV emissions do not pose a safety risk. The NREL analyser was shown to meet the desired metrological requirements for FCEV exhaust analysis, but because FCEV exhaust is at elevated temperatures and humidity levels and contains liquid water droplets, condensing of liquid water on the hydrogen sensing element was problematic. In addition to physically blocking access of the test gas, condensed water has a proclivity to permanently damage the sensing element. Subsequent efforts of this research were to develop a sample collection system that mitigates against liquid water reaching the sensing element. The updated sample collection system incorporated several water mitigation strategies, including removal of liquid water through condensing coils and a water trap. The sample gas was separated into two gas streams that included a dehumidified stream for analysis and the second stream contained all the remaining liquid water in the sample gas. Both gas streams were vented outside with the primary exhaust stream (carried through the CVS). In addition, supplemental T and RH sensors were used to monitor both gas streams to verify that the dew point of the test gas that was transported to the sensor remained below ambient temperature. The NREL FCEV Exhaust Gas Analyzer with the updated sample collection system was successfully demonstrated at ERMS on an operational FCEV under a variety of driving conditions and test protocols [2].

An outcome of the second deployment at ERMS was the realization that the volume of liquid water emitted in the FCEV exhaust potentially damages the instrumentation and equipment used in the CVS, such as gas analysers, flow controllers and environmental sensors. Accordingly, the ERMS gas transfer line for FCEV testing was modified to both remove entrained water from the FCEV exhaust and bypass the CVS to vent directly outside after sampling.

Aside from safety concerns, there is a need to optimize hydrogen utilization to minimizes both product loss and to mitigate against possible adverse environmental impacts of hydrogen. Thus, manufacturers should aim to limit the amount of hydrogen released into the atmosphere. These concerns also pertain to stationary fuel cells. In addition to developing tools for verifying that FCEV emissions comply to safety regulations, the research team is developing methodology to quantify overall hydrogen emissions from FCEVs during simulated driving tests performed on a chassis dynamometer. The NREL Sensor Laboratory has extensive expertise in hydrogen detection and gas sensing for a variety of applications. ECCC performs regulatory testing for newly manufactured vehicles to ensure that the vehicles meet emissions requirements. These tests are conducted by utilizing a chassis dynamometer system to simulate real world driving loads and temperatures integrated with an exhaust gas collection and analysis system. In addition to their confirmatory compliance audit program, ECCC and TC regularly partner together to conduct research on advanced vehicle technologies, fuels and emission reduction technologies. TC also leads vehicle crash safety regulatory development and research programs in Canada.

### 1.1 Global Technical Regulations 13 and Hydrogen Safety

Many safety requirements for FCEVs are defined by the United Nations Global Technical Regulations 13 (GTR-13) [3]. The GTR-13 strives to accelerate FCEV market growth and public acceptance by internationally harmonizing safety requirements for FCEVs. The GTR-13 defines the allowable limits of hydrogen in the exhaust of an FCEV, and it also defines the requirements for the analyser that is to be used to verify the hydrogen concentration. These specifications include:

- 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 a start-up and shutdown procedure as defined later in the GTR.
  - And not exceed 8 percent at any time.
- The response time of the analyser must be <300 ms.
- Measurements from the analyser must be taken 10cm away from the exhaust tip.

It is further stipulated in GTR-13 that the FCEV must be on and warmed up to normal operating temperature. An acceptable analyser must be placed in the centreline of the exhaust gas flow within 10cm of the exhaust outlet. The car is then turned off, immediately started again, then turned off again after one minute [3].

These requirements were established to ensure the safe operation of FCEVs. Although these metrics may not be all-encompassing, they provide reasonable certainty that there will not be a build-up of hydrogen in enclosed areas such as parking garages, at-home garages, or tunnels due to repeated start-up and shutdown processes. The GTR-13 does not specify any kind of regulations regarding emissions while driving. It has been argued that even if there were to be a release of hydrogen while driving, the turbulence around the vehicle should quickly disperse and dilute any flammable concentrations of hydrogen.

### 1.2 Environmental Considerations

Although using hydrogen as an alternative to fossil fuels will almost certainly be helpful to the environment due to hydrogen's renewable characteristics, recent studies have indicated that hydrogen in the atmosphere may be contributing to climate change [4]. Hydrogen is not a greenhouse gas, but it is thought that hydrogen will react with hydroxyl radicals in the atmosphere that would have otherwise been used to decompose methane, and methane is a strong greenhouse gas. Thus, hydrogen may be considered a potential secondary greenhouse gas. If increased levels of hydrogen in the atmosphere contribute to global warming, then it is imperative to monitor and limit the amount of hydrogen being released from FCEV while driving. Currently, the largest emitter of carbon dioxide is the transportation sector [5]. Replacing ICE vehicles with FCEVs provides a way to drastically cut back on overall greenhouse gas emissions. However, since hydrogen could be a secondary greenhouse gas, there is a need develop methodology to quantify overall hydrogen emissions, including those from FCEVs. The GTR-13 prescribed testing method is not sufficient for quantifying overall FCEV emissions under driving conditions. New testing methods must be developed and implemented to track overall FCEV hydrogen emissions during normal driving operations.

## 2.0 Methods of Testing

All FCEV exhaust gas testing, except when noted otherwise, was performed at the ECCC Emissions Research and Measurement Section (ERMS) facility in Ottawa Canada and utilized the NREL FCEV Exhaust Gas Analyser (the Analyser) as previously described [2]. The Analyser was shown to meet the metrological requirements as prescribed in the GTR-13. The Analyser was configured to allow integration to the ERMS vehicle exhaust handling system. The Analyser was then deployed at ERMS and measured FCEV exhaust using protocols analogous to the procedure described in the GTR and under simulated driving conditions.

Figure 1 is an illustration of the current Analyser configuration and the ECCC vehicle exhaust handling system as previously reported [2]. Vehicle exhaust testing at ECCC requires the use of a gas transfer line as a conduit to transport exhaust to chemical analysers as well as to safely vent the exhaust gas. For FCEV exhaust gas analysis as per Figure 1, the sample gas is pulled from the transfer line and is directed through condensing coils. Because the FCEV exhaust is at an elevated temperature and is very humid (typically around 60 °C and nearly saturated with water vapor), the dew point of the gas must be dropped to below ambient temperatures to prevent liquid water from condensing on the hydrogen sensing element. After exiting the condensing coils, the two-phase flow is then separated into a partially dehumidified sample gas stream that is ideally free of liquid water and a “wet” stream that is composed of gas and all of the liquid water that was condensed in the coils. The dehumidified sample gas is directed over the hydrogen sensor for analysis and is then merged with the wet stream and vented. T and RH sensors were installed to measure the condition of the dehumidified gas stream just after the hydrogen sensing element, the wet gas stream, and the state of the exhaust gas in the ECCC Gas Transfer line. Details of the Analyser were described previously [2].

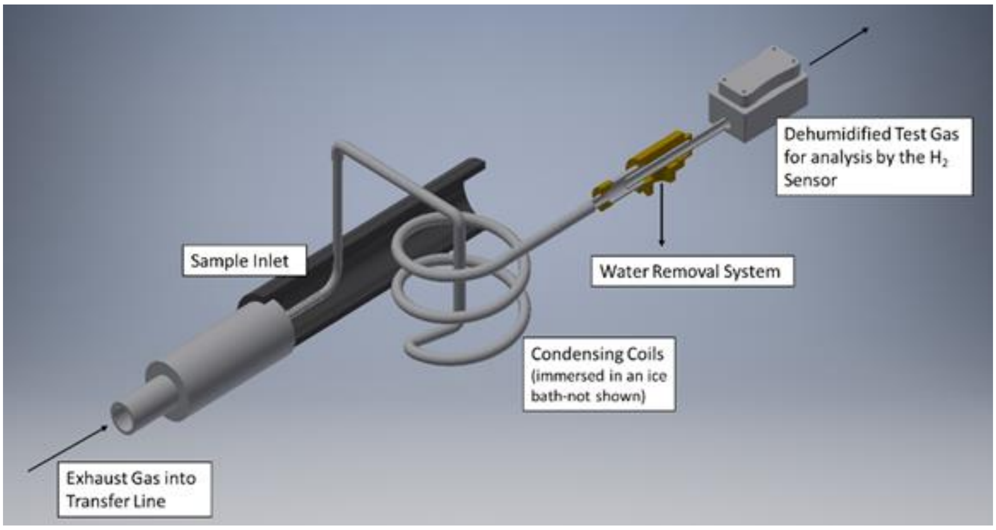


Figure 1: An illustration of the flow path to transport gas from the FCEV exhaust outlet to the hydrogen sensor.

This method of sample collection is highly versatile because samples can be taken while performing a GTR-13 prescribed test or testing under simulated driving conditions. Figure 2 shows the overall experimental design during the most recent testing at ECCC. An inline reservoir was added in the exhaust transfer line to remove liquid water in the exhaust, prior to the sample reaching the analyser. The volume of liquid water, if not first removed from the exhaust gas, would otherwise cause the hydrogen sample probe and transfer line to become entrained with large amounts of liquid water that would compromise the NREL Analyzer’s ability to provide a water-free sample to the sensor. The Analyser is contained on the H2 Bench. The vehicle is mounted on the chassis dynamometer which is used to perform simulated driving tests such as the US06, the Highway Fuel Consumption test, the LA4, and others [6].

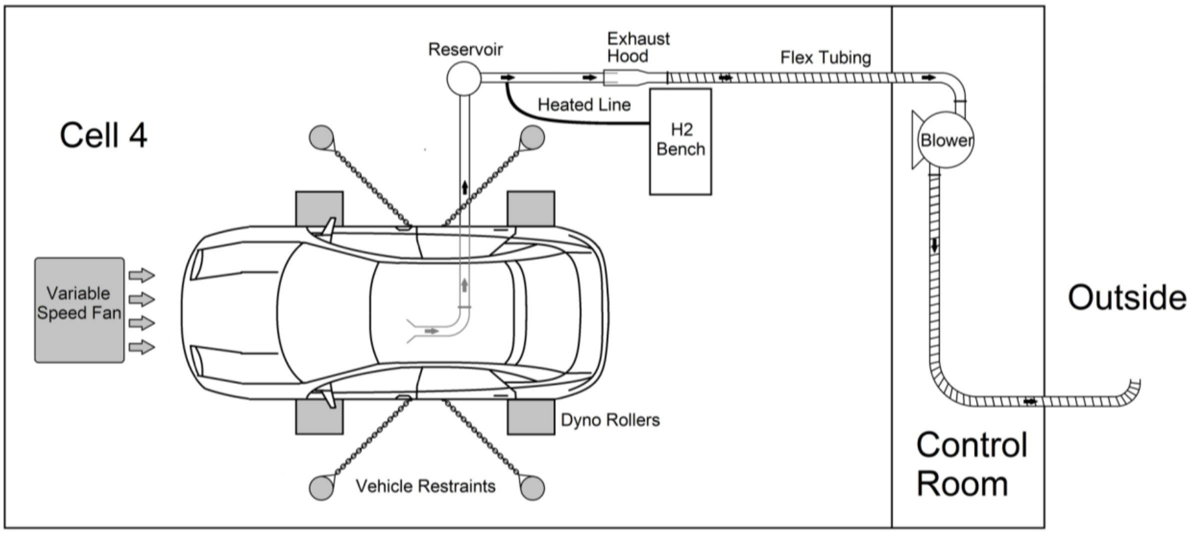


Figure 2: A top-down view of how the vehicle and analyser are arranged in the test cell at ECCC.

The hardware for measuring FCEV exhaust that is shown in Figures 1 and 2 has multiple benefits. First, this approach for testing improves consistency between repeated tests. Because all the exhaust gas is being collected, the sample stream that is pulled from the transfer line is a good representation of the hydrogen concentration at the tailpipe. Testing for emissions as prescribed by the GTR-13 may allow the sensor to be placed in open air 10cm away from the exhaust tip, which could easily produce variabilities when testing. For example, when performing the test outdoors, environmental factors such as wind could influence what concentration the sensor detects by diluting the exhaust gas with ambient air. When performing the GTR-13 test indoors, the room must be ventilated to ensure no hydrogen accumulation occurs; the ventilation could have the same effect as outdoor testing in the wind. The methodology developed by NREL and ECCC also protects personnel and facilities from being exposed to potentially flammable environments. As data will show, flammable concentrations of gas exiting the FCEV could exist and have been observed. Collecting all of the exhaust gas and taking a sample for analysis provides increased precision and accuracy and provides an extra layer of safety when compared to the GTR-13 prescribed method of testing.

The methodology developed by NREL and ECCC as per Figure 2 also allows for the opportunity to monitor the hydrogen concentration in the exhaust while conducting driving tests. With the addition of a flow meter, concentration measurements can be easily converted to the mass of hydrogen vented. Thus, researchers can quantify the overall emissions of an FCEV during a driving cycle as well as determine the occurrence of flammable concentrations. Emissions quantification can be important to track hydrogen utilization efficiency as well as to address concerns that hydrogen could act as a secondary greenhouse gas.

Figure 3 shows a testing configuration that can measure real-time hydrogen concentrations and can track overall emissions during a drive cycle. The main difference between the test setups shown in Figures 2 and 3 is the addition of an inline flow meter that allows for the calculation of hydrogen mass emitted.

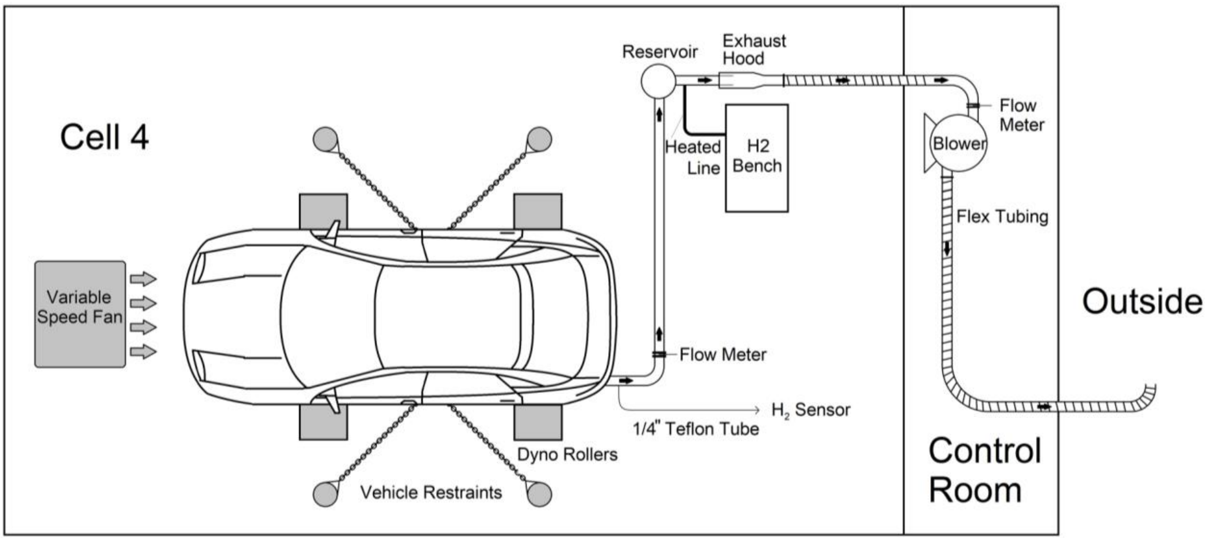


Figure 3: An illustration of a test configuration to track real-time hydrogen concentration and exhaust flow rates. These measurements can be used to calculate overall hydrogen emissions during a driving cycle.

## 3.0 Results from Testing

### 3.1 GTR Method for FCEV Exhaust Measurement

Multiple FCEVs were tested using the GTR-13 method and using the sampling configuration shown in Figure 3. The team has also conducted tests that follow the startup/shutdown procedures described in GTR-13 while monitoring the exhaust hydrogen concentrations using NREL's Analyser. Figure 4 shows results from a test conducted in 2022 at ECCC's test facility. This test was conducted using the testing procedures for vehicle startup/shutdown described in GTR-13 and the configuration for gas sampling shown in Figure 2.

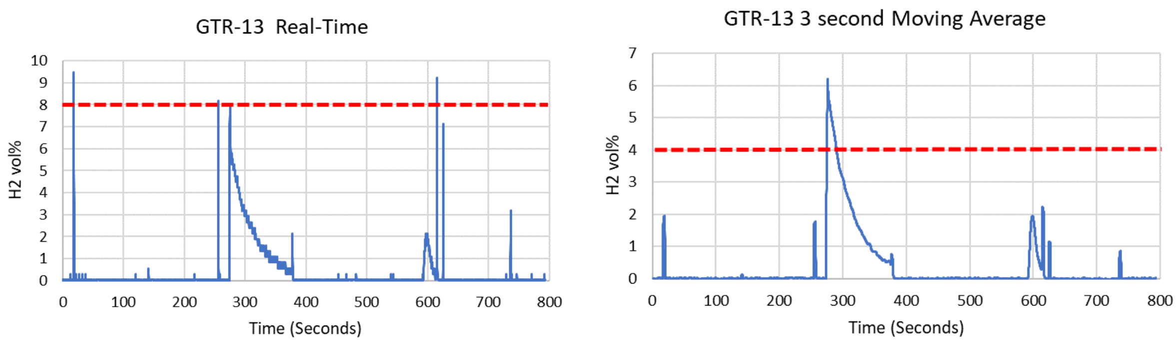


Figure 4: Real-Time (Left) and 3-Second Moving Average (Right) data from testing on an FCEV. The FCEV was put through a simulated driving condition then shut down and restarted multiple times.

As shown in the graphs of Figure 4, hydrogen concentrations above the GTR-13 allowable levels were observed in the exhaust during portions of this tests. Keep in mind that although the team was following the GTR-13 protocol for operating the vehicle, a modified sample handling methods was used. Analysis by placing the sensor 10 cm from the point of release as per the GTR-13 method will be prone to variable levels of dilution from wind or ventilation effects. In contrast, the sampling and method illustrated in Figures 2 and 3 may result in more mixing of the sample gas due to turbulence from flow in the transfer line. This mixing will result in shorter, wider concentration peaks than what is truly present at the exhaust outlet. The recent testing will give the team insight as to how the different sample handling configurations compare.

After this testing was conducted and the data was analysed, the results were shared and discussed with the vehicle manufacturer. The manufacturer pointed out that they have followed the GTR-13 testing protocol and detected hydrogen concentrations on the order of a tenth of a volume percent. Because their results differ by multiple orders of magnitude, the NREL, ECCC, and TC team finds it imperative that extra testing be conducted before solid conclusions can be reached. This extra testing and data will be presented during the 2023 ICHS conference. The team also conducted the GTR-13 test but instead held the sensor directly at the tailpipe (0cm) in addition to the prescribed 10cm away. This test will show the amount of dilution that occurs directly after the exhaust exits the tailpipe.

Related to safety, there was a question that arose during the 2022 testing at ECCC as to whether hydrogen emissions released during the start-up and shutdown of a drive cycle test be considered for safety. In real-world use, an FCEV could be started in a garage or other confined spaces and then driven on the roadway. As stated before, there is not much of a safety concern for hydrogen releases while driving on roadways, but there is a safety concern when cars are pulling out of home garages or parking garages. Likewise, when a car has just finished driving on the roadway and is going to be parked, there is a concern with releases that happen as the car is being stopped or shut off. Figure 5 shows a driving test where high concentrations of hydrogen was emitted upon start-up of the FCEV just as a driving test was about to commence. All drive cycles mentioned here are defined by the United States Environmental Protection Agency [6].

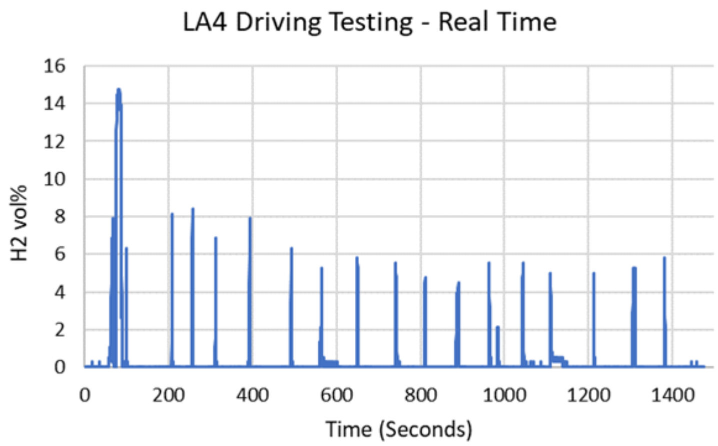


Figure 5: Just as the LA4 drive cycle starts, the FCEV emits hydrogen concentration that are nearly four times the lower flammable limit of hydrogen.

It should also be noted that this drive cycle was the first test conducted that day, which means this would almost perfectly simulate a real-world situation. An FCEV user could park their car at the end of the day, begin their commute at the beginning of the next day, and emit a plume of gas that is nearly 15% hydrogen into a home garage or parking garage before their commute begins. Large concentration spikes at the beginning and end of a driving test were a regular occurrence and should be examined further for safety considerations.

### 3.2 NREL's Exhaust Gas Analyzer

Test using NREL's exhaust gas analyser showed surprisingly high hydrogen concentrations while performing many driving tests. As shown above, the data from figure 5 shows high concentration peaks during start-up with multiple significant peaks spread throughout the driving cycle. Figure 6 shows similar data for a simulate driving test.

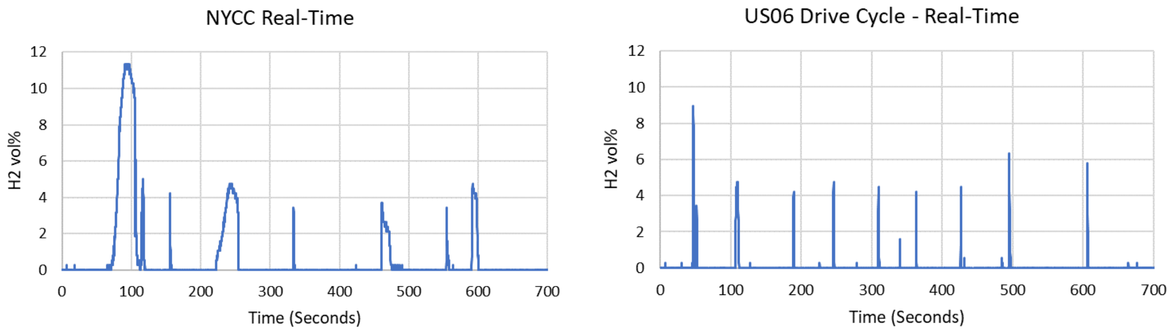


Figure 6: Data from the New York City Cycle and the US06 Drive Cycle show a large concentration peak at the beginning of the test followed by more hydrogen releases throughout the rest of the cycle.

Because the exhaust flow rate was not measured during testing, it is impossible to conclude the mass of emitted hydrogen that was vented during the test, although it is known that there is some amount vented. The addition of a flow meter during similar tests will allow researchers to accurately determine the mass of hydrogen that is venting during a particular drive cycle. As stated above, this new testing method as per Figure 3 (drive cycles with concentration and flow measurements being collected simultaneously) has recently been used in a test and the results will be presented at the 2023 ICHS conference.

## 4.0 Summary

With the increasing uses of FCEVs as a cleaner alternative to vehicles powered by fossil fuels, the safety and potential environmental concerns must be considered. Safety should always be at the forefront of innovation for the good of the public. Furthermore, safety-related incidents involving hydrogen could have a major impact on the implementation of renewable energy and public acceptance of new technologies. There should also be concerns with overall FCEV hydrogen emissions due to the possible adverse effects on the environment.

The exhaust gas concentration requirements as prescribed in GTR-13 are likely sufficient for safety consideration, but the currently required test protocol could be improved to produce more accurate and repeatable results. Measuring exhaust gas in an open space as prescribed in the GTR could easily lead to inconsistency in the measured hydrogen concentrations and therefore, inappropriate verification of compliance. For instance, testing an FCEV using the GTR-13 protocol could produce vastly different results when conducted in a well-ventilated room versus a stagnant garage versus outdoors. The GTR-13 standard could also consider the exhaust hydrogen concentrations when a vehicle is taking off just after starting the FCEV or when coming to rest and shutting down. Often, the highest hydrogen concentration observed in a simulated driving test was right at the beginning and end of the drive cycle. Neglecting these potentially hazardous situations could lead to real-world safety consideration being overlooked.

Since personal and commercial vehicles currently contribute to a large portion of the earth's greenhouse gas emissions due to the number of vehicles on roadways, it follows that FCEVs could be a main source of hydrogen emissions in the future and as such, FCEV emissions should be quantified. Currently, there are no standards or regulations around overall hydrogen emissions from FCEVs while driving. There are also no standard test methods for quantifying these emissions, but using the protocol described above in Figure 3 could quantify hydrogen emissions. Such analysis is ongoing. The emissions mass and concentration data from FCEVs subjected to different driving tests will be presented at the 2023 ICHS.

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