

Hydrogen Fuel Consumption Correlation between Established EPA Measurement Methods and Exhaust Emissions Measurements

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ABSTRACT

The development of hydrogen-fueled vehicles has created the need for established fuel consumption testing methods. Until now the EPA has only accepted three methods of hydrogen fuel consumption testing, gravimetric, PVT (stabilized pressure, volume and temperature), and Coriolis mass flow; all of which necessitate physical measurements of the fuel supply [1]. BMW has developed an equation and subsequent testing methods to accurately and effectively determine hydrogen fuel consumption in light-duty vehicles using only exhaust emissions. Known as "Hydrogen-Balance", the new equation requires no changes to EPA procedures and only slight modifications to most existing chassis dynamometers and CVS (Constant Volume Sampling) systems.

The SAE 2008-01-1036, also written by BMW, explains the background as well as required equipment and changes to the CVS testing system. This paper takes hydrogen balance further by testing it against the three EPA established forms of fuel consumption. The instrumentation, testing procedures and results are presented for each of the four fuel consumption methods. The overall goal of the report is to establish the hydrogen-balance method as the default form of hydrogen fuel consumption testing in light-duty vehicles.

INTRODUCTION

Fuel consumption in gasoline and diesel power vehicles is measured on a roller-type chassis dynamometer by way of exhaust emissions. This is known as Carbon-Balance, and uses the principle of conservation of mass. By measuring all exhaust components containing carbon, the amount of fuel consumed can be calculated. Quite simply, what comes in as carbon containing fuel must go out as carbon containing exhaust components [2]. As explained in greater detail in SAE 2008-01-1036, Hydrogen-Balance works in exactly the same way, but with hydrogen containing components replacing carbon. The equation is much simpler, however, because there are only two exhaust components in hydrogen-fueled vehicle exhaust: water and unburned hydrogen.

Hydrogen-balance also has the benefit of leaving the test vehicle completely intact; auxiliary fuel supplies could easily affect fuel consumption and engine performance. In addition, not every vehicle can be easily supplied with hydrogen without major modifications to the car, again affecting test values. From a safety standpoint the hydrogen balance should be much safer than using a custom hydrogen supply system. The danger of hydrogen leaks, among many other considerations such as proper hydrogen bottle handling, is eliminated by the use of hydrogen balance.

To verify the newly developed equation, BMW conducted tests on a specially designed chassis dyno used for testing of hydrogen and other low emission vehicles. As always, safety was the first concern to BMW, as such the test cell features a myriad of hydrogen safety devices. The CVS was a system modified in accordance with the SAE 2008-01-1037. These modifications mostly dealt with accommodation of higher water concentration in the exhaust. These changes to the CVS system are easily completed on most CVS systems, which make hydrogen fuel consumption testing possible everywhere there is a CVS system.

THE CAR

The car used for each of the tests was a BMW Hydrogen7. The Hydrogen7 is the newest generation of the highly modified 7series developed to run on gaseous hydrogen. The engine is a 6.0-liter V12 that can run on both gasoline and hydrogen. The engine is capable of running with continuously changing lambda values. During high load the engine runs slightly rich ($\lambda = 0.97$), meaning there is slightly less oxygen than what is needed for perfect stoichiometric combustion. This region produces small amounts of unburned hydrogen in the exhaust that must be factored into the fuel consumption later. The lean burning region between $\lambda = 0.98$ -1.8 is not used due to NOx emissions. During light load conditions, $\lambda > 1.8$ is used to save fuel, although unburned hydrogen is still present in this operating mode [3].

Unlike many other hydrogen-fueled vehicles, the Hydrogen7 is not a hybrid vehicle. This means no

additional considerations are necessary on the chassis dyno. Normally the hydrogen is supplied to the engine from the cryogenic fuel tank. Super-cooled hydrogen is kept below boiling point until it is supplied to the engine [4]. Unfortunately, this system doesn't easily lend itself to auxiliary external hydrogen supply. Until now the only EPA approved methods require that hydrogen be supplied externally. For safety reasons, this is normally impossible with the BMW Hydrogen7.

VEHICLE MODIFICATIONS ALLOWING FOR EXTERNAL FUEL SUPPLY

The modification started with the disabling of the hydrogen fuel tank. After all of the hydrogen was removed from the tank, it was filled with nitrogen and sealed to prevent any moisture from entering. The fuel supply line was then removed up to the engine pressure regulator. This pressure regulator serves as a final conditioning and fail-safe in the event of a tank malfunction. This pressure regulator reduces anywhere from 2.5-9 bar to a working pressure of 2.5 bar. This was the pick up point to the new external fuel supply system. To assure the best connection to the pressure regulator, the original supply line was cut and welded to the new external supply line.

The biggest challenge in modifying the BMW Hydrogen 7 was changing the vehicle software management. Safety is BMW's number one concern when it comes to hydrogen vehicles, and every controller in the car is designed to function only when everything is 100% in working order; this created problems since the hydrogen fuel system was essentially destroyed. A special control module was created to hook up to the cryogenic fuel tank's electrical connections. This controller told the engine management that the tank was full of hydrogen and everything was secure. Beyond that, the motor control modules were changed to ignore any hydrogen system errors that might crop up because of the modifications.

Other, more normal, changes included changing of the street tires to tires specifically designated for test stand use. The boil-off lines that collect any hydrogen lost from the fuel tank were not needed due to the hydrogen tank being inert. The stability control of the 7series also had to be defeated to allow the rear wheels to spin freely. This is done through the onboard computer using the iDrive user interface.

EXTERNAL HYDROGEN SUPPLY SYSTEM

Following the example set by Carl Paulina of the EPA in his report "Hydrogen Fuel Cell Vehicle Fuel Economy Testing at the U.S. EPA National Vehicle and Fuel Emissions Laboratory (SAE 2004-01-2900)," it was decided that using external hydrogen fuel tanks would be the best way to verify Hydrogen-Balance against the other three accepted methods. In his report, Paulina explains how the EPA conducted US fuel economy tests using compressed hydrogen bottles. Mr. Paulina's tests, however, were

carried out on a small, fuel cell equipped Honda hybrid producing 60 kW [1]. The BMW Hydrogen 7 is a large luxury car producing 200 kW of power [3]. Apposed to the relatively constant fuel consumption of fuel cells, the BMW internal combustion engine fuel consumption varies greatly between idling and full load conditions. It was determined that the motor would need a constant supply of hydrogen between 4-5 bar, and at mass flows of up to 5 g/s. Achieving the required pressure would be no problem except that the required mass flow was so great. 5 grams of hydrogen per second is equal to almost 2 cubic feet (55.6 l) of hydrogen flow at standard temperature and pressure. To achieve the required mass flow, two compressed hydrogen tanks were necessary even though one would be enough for most driving cycles. Each tank held around 740 grams of gaseous hydrogen. Figure 1 shows the supply system. The appendix also includes a schematic of the supply system designed by Linde Gas AG.

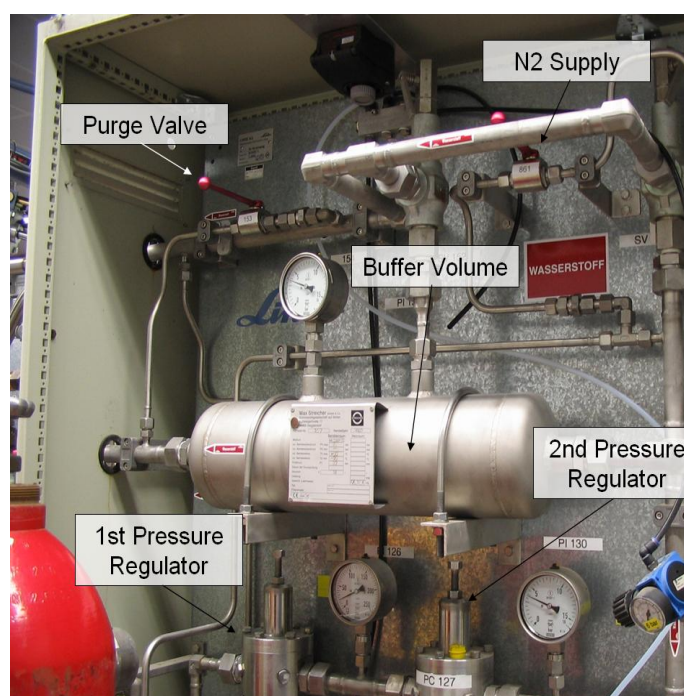


Figure 1: Hydrogen supply system

The tanks used were standard 200 bar hydrogen cylinders with a water volume of around 50 liters supplied by Linde Gas. The hydrogen from the tanks then traveled through two flexible lines to two valves for each of the respective tanks. Opening these two valves along with another single safety valve, allowed hydrogen to flow through two pressure regulators and charge the supply system with hydrogen. To assure the motor was supplied with only pure hydrogen, two valves were built into the system to allow for purging.

An important feature of the system is the 10 liter buffer volume. Looking like a small tank, the buffer assures that the motor always has a supply of hydrogen, even under the hardest acceleration. This was necessary during the US06 tests when a slight pressure drop was seen in the system while the motor was under full load. Although the system pressure could not stay constant, the buffer volume held

enough hydrogen to supply the engine until full pressure could be restored. Unfortunately, the supply line from the buffer volume to the motor pressure regulator could not be purged of air before the test. This small amount of air was quickly evacuated, however, since the engine displacement of 6 liters was much more than that of the line. Internal combustion engines don't require the hydrogen purity of fuel cells; meaning any mixing of hydrogen an ambient air did not affect engine performance. The motor always started easily with only a few cranks.

SUPPLY SYSTEM OPERATING PROCEDURE

Due to the complexity of the supply system, the operating procedure was a multi-step process. Starting with all of the safety valves closed, two hydrogen tanks were brought into the test cell. After being connected, the tanks were opened to allow the flow of hydrogen. The two safety valves were then opened along with a single safety valve directly before the pressure regulator. The first pressure regulator takes the 200 bar pressure and reduces it to 20 bar. The second regulator located directly after the first then reduces the hydrogen pressure to between 2-9 bar. A double stage system, the pressure regulators keep the pressure constant despite the changing bottle pressure. The system is then purged of air by opening a valve located behind the buffer. Finally the valve leading to the motor is opened and the testing is ready to begin. The safety valves and bottles can be seen in Figure 2.

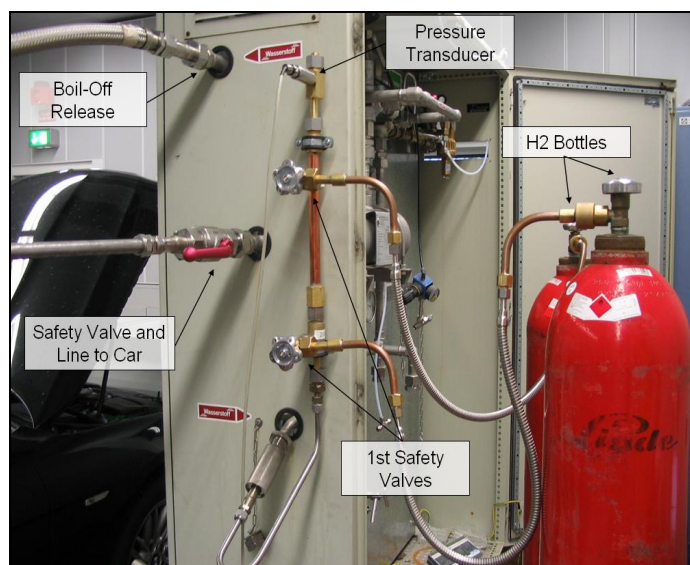


Figure 2: Hydrogen bottles with safety valves and the pressure transducer

After the test, the bottles are closed and the purge valve is opened to release the pressurized hydrogen. To release the hydrogen safely in the test cell, the boil-off lines that were no longer necessary for the Hydrogen7 were used. The lines release the hydrogen outside safely away from the building. The entire system was then supplied with nitrogen from the gas connections already present in the test cell. The nitrogen is supplied at a pressure of 5.2 bar, which is at least 1 bar above the hydrogen pressure. The supply system is then

completely flushed of all hydrogen. The line from the buffer to the motor cannot be purged, however, so another step is necessary to remove all hydrogen from the system. After all the hydrogen has been removed from the buffer, it is filled with nitrogen at a pressure of 5 bar. The motor of the hydrogen7 is then cranked over as if trying to start. During start-up the motor moves a large amount of gas through the valves in attempt to turnover. A couple unsuccessful start attempts and all of the hydrogen left in the line is now safely moved through the exhaust and out the CVS system.

SAFETY

Two 50-liter bottles of hydrogen hold around 1.5 kilograms of hydrogen, which at standard temperature and pressure is almost 590 cubic feet (16,685 liters) of volume. Not an insignificant amount considering explosion can happen at anywhere from 4 - 70% hydrogen in air. For this reason all necessary precautions were taken to assure the safety of the workers and equipment. The supply system itself was built almost entirely from high grade, 316L/T stainless steel. A BMW hydrogen certified welder completed all welds, and where welding was not possible or logical, only Swagelok connectors were used. The high-pressure side connections were custom made from the company Linde, and were brazed for hydrogen impervious connections. The system proved to be exceptionally leak-proof despite hydrogen being the smallest element in the periodic table. In the event of a pressure regulator malfunction, two emergency valves were used to evacuate the pressurized hydrogen. The valves were automatically set to spring open when system pressure exceeded 10 bar. In the event of an emergency, the supply system operator would first shut off the tanks. Secondly, the valve leading to the engine would be closed and nitrogen would be used to quickly purge the system of hydrogen. The BMW fire department was notified before every test, and signs were hung alerting personnel to the presence of hydrogen tanks.

HYDROGEN FUEL CONSUMPTION TESTING EQUIPMENT AND PROCEDURES

In Carl Paulina's report, he outlined how the EPA has conducted fuel economy tests in the past. It was decided that BMW's tests would be carried out in similar fashion to those of the EPA. Mr. Paulina also made some suggestions for increased accuracy, which were also taken into consideration. Initial goals were to have all forms of measurement having accuracy under or around $\pm 1\%$ of value. The procedure was changed slightly from the EPA tests since two large compressed bottles would be used for more than one test.

STABILIZED PRESSURE, TEMPERATURE AND VOLUME

In another report written by Marcia Huber and others, they explain how to calculate the hydrogen massing.  **Documents**
hydrogen massing

fixed volume vessel using only temperature and pressure measurements. The hydrogen mass equation described in "Standardized Equation for Hydrogen Gas Densities for Fuel Consumption Applications (2006-01-0434)" was used by BMW to calculate the hydrogen mass before and after each test [5]. The equation is seen later in this paper.

The biggest difference in procedure between BMW and the EPA test procedures was the use of two tanks at the same time for an entire test instead of one tank per individual driving cycle. This was a compromise in accuracy since making one measurement before and after each test cut down on the variability of measuring once every cycle. However, using two bottles for one test also made the system of hydrogen much larger overall. This complicated the temperature measurements since one or two measurements would not be adequate to describe the system as a whole.

Temperature was measured with a NiCr-Ni type thermocouple. The signal was read by a multimeter with a 0.1 C readability. To get an accurate temperature reading of the system, the temperature was measured twelve times before and twelve times after each test. This was necessary because the temperature of the bottles at the top was slightly different than at the bottom. This was due to the cooling effect of releasing the hydrogen. The pressure drop caused the hydrogen inside the bottle to expand and thus cool. Since the two bottles were taken as a system as a whole, the temperature had to be an average temperature. The bottles were measured each two times on top, two times in the middle and two times at the bottom. Twelve readings in all were used to create an average temperature of the system. In the pressure, volume, temperature equation, pressure and volume play the most important role. For example a temperature deviation of 2 degrees Celsius on a 100-liter system at 200bar made a difference of under 0.65% of final value. The bottles were also kept inside the environmentally controlled test stand, which cut down on test variability.

Since pressure was the single most important part of the PVT equation, great care was taken to make it the most accurate part of the measurements. Pressure was measured with an Althen sourced pressure transducer. The Silicon-on-Sapphire strain gauge construction provides excellent resistance to temperature and vibration effects with effectively zero hysteresis. Made of titanium, the device was approved for operation up to 400 bar. The accuracy was certified at $\pm 0.2\%$ of full value, and the inspection certification was included. The measurement point for pressure was where the two bottles came together before entering the first pressure regulator. Since both bottles were open and connected, hydrogen could flow freely between them creating a single uniform pressure for the entire system. This pressure was measured before and after each test. The pressure transducer can be seen at the top of the bottle connection point in Figure 2.

GRAVIMETRIC MEASUREMENTS AND PROCEDURE

The bottles were weighed using a Sartorius QA150FEG-S scale. Extremely flexible, the scale had a maximum weight limit of 150 kilograms, but with ± 2 -gram accuracy. The procedure proved to be the only shortcoming of the gravimetric system. On the grounds of safety, only two bottles of hydrogen could be allowed in the test cell at one time. This meant that purging the system of air had to be done with hydrogen from one of the test bottles. The original procedure had weighing coming before flushing the system, which meant a small amount was lost to charging of the system. This small amount of hydrogen, however, created fuel consumption differences as large as 10%. The first handful of tests were thus corrected with a correction factor of 31.33 grams. The factor was developed by calculating the volume of the entire system, most notably the buffer volume, and determining how much hydrogen was necessary to fill the volume. This calculation was further corrected experimentally by filling the system volume with hydrogen and then flushing with nitrogen and filling again. This was done three times and an average value was calculated. It was determined that the correction factor made the results seem less substantial despite good agreement before and after use of the correction factor. The first tests using the correction factor, therefore, are not included in this report. The procedure was amended so that purging of the system took place before the weighing. One bottle was connected to the system and the nitrogen was purged from the lines with pure hydrogen and the bottle was then disconnected again and weighed. Figure 3 shows a hydrogen cylinder being weighed. There a holder that is in place to insure the bottles do not fall when being weighted, their tare weight was subtracted before weighing.

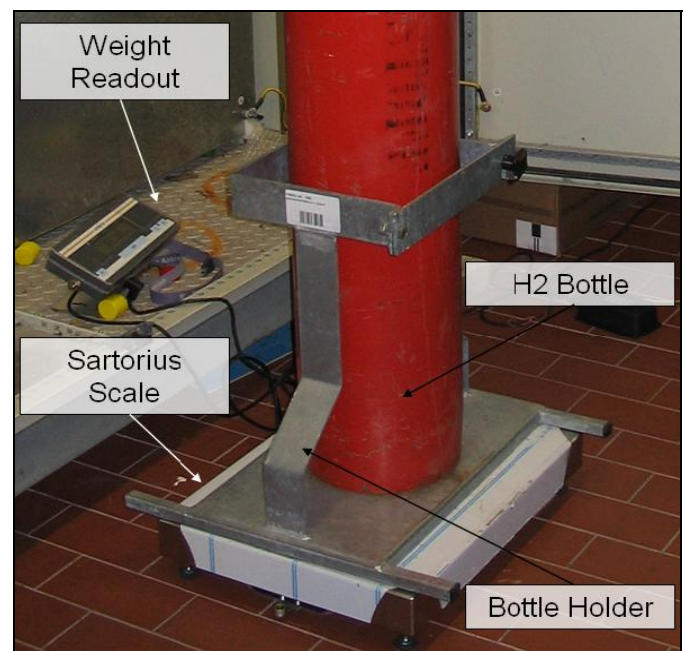


Figure 3: Scale and hydrogen bottle being weighed

CORIOLIS MASS FLOW METER MEASUREMENTS AND PROCEDURE

Coriolis measurements were the hardest to optimize during testing. The system was set up with two Emerson Micro-Motion Coriolis mass flow meters of different sizes in series. The Micro-Motion CFM-025 measured up to 10 g/s, and CFM-010 worked up to 2 g/s. Beside each device was a ball valve that, when closed, forced the hydrogen to run through the Coriolis device. The EPA had problems during idle with the flow dropping to an indicated zero. For this reason BMW chose to have two sizes of Micro-Motion, one for idle and one for the dynamic parts of the test cycles. The mass flow meters were configured to send a 10-volt signal corresponding to hydrogen flow to the CVS system computer. This signal enabled BMW engineers to see the fuel consumption for every second of the test. The data clearly showed that even at idle the larger CFM-025 meter was adequate to measure the hydrogen flow. This was important because the pressure drop over the smaller device was too large (almost 4 bar) for the motor. The CFM-025 is shown on the left in figure 4; the smaller CFM-010 is shown on the right.

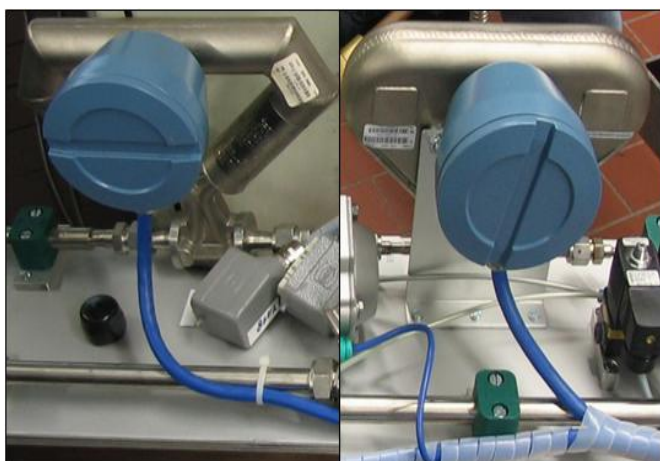


Figure 4: Micro-Motion Coriolis mass flow meters

Although the fuel consumption curves fit together well, the end fuel consumption deviation between Coriolis and Hydrogen-Balance was up to 20%. This was initially thought to be simply device limitations. After calibration of the zero point using the Micro-Motion software, it was discovered that what was received over the 10-volt signal was not what the Micro-Motion software was indicating. This may have been a timing issue since the Coriolis meter send a flow signal every second and the CVS computers measured ten times a second and created an average. What ever the reason, the Micro-Motion signal was not recorded correctly during dynamic parts of the cycle. After this discovery, Micro-Motion software was used for final fuel consumption, but the second by second fuel consumption comparison with the Hydrogen-Balance was no longer possible. Just before the test, the mass would be zeroed and after the test the mass value indicated was the amount of hydrogen consumed during the test. Some of the tests do not include Coriolis measurements, the system computer did not function for these tests.

HYDROGEN-BALANCE MEASUREMENTS AND PROCEDURE

A full explanation of the modifications done to the CVS system can be found in SAE 2008-01-1037. Most of the new features are in place to avoid water condensation since water is the exhaust component of hydrogen fuel. If condensate water were to collect in the exhaust testing lines, for example, it would not be measured and fuel consumption would be too low. Heated lines and a heated environment for the bags were necessary to avoid all water condensation. The water analyzer and hydrogen analyzer are also obvious necessary upgrades to the testing system.

The Hydrogen-Balance equation is seen below [6]. This equation can only be used for gram results. The equation using concentrations is more complex. The fuel consumption on the left hand side is simply the hydrogen consumed and expressed in grams of Hydrogen. The right side is the water content, 0.1119 is the factor that reduces water mass to mass of hydrogen. Unburned hydrogen is also a part of the equation.

$$FC = [(0.1119 \cdot H_2O) + H_2]$$

Water content of the exhaust is measured in the NDIR (Non-Dispersive Infrared) water analyzer every second during the test. This is in contrast to how the CVS usually works by filling bags and analyzing the sample after the test is completed. Due to the relatively high water content of the exhaust, modal measurement is the best way to determine water content. Logically, this value has to be corrected for dilution air water concentration since the dilution air also contains a fair amount of water even after running through a dryer. This value is calculated by reading a background sample bag. After some questionable background measurements, it was found that the Tedlar® bags used for sample collection allowed water diffusion. If the water concentration inside the bag was greater than the concentration outside, then water would escape through the bag walls. Similarly, higher concentrations in the test cell would cause diffusion into the bag. To avoid this phenomenon, a new bag was conceived by BMW that is essentially two bags in one. The inner bag is used for sample collection, and the outer bag has the same dilution air constantly cycling through it. Since the dilution air should have the same water concentration as the sample, the water should not diffuse between the inner bag sample and the dilution air in the outer bag. It is possible that some water content from the outer bag may diffuse, but this will not affect the sample inside the inner bag. In this way the sample is protected from diffusion without changing the sampling method.

The Hydrogen-Balance equation is not complete without first measuring the exhaust for hydrogen. This hydrogen is a result of a slightly rich fuel mixture where the amount of oxygen is not adequate to fully combust all of the fuel.