Existing Light-Duty Hydrogen Refueling Stations In-Use Study Report

Vapor Recovery and Fuel Transfer Branch
Monitoring and Laboratory Division

November 22, 2024

Contents

List of Acronyms

ANSI	American National Standards Institute
APRR	Average Pressure Ramp Rate
CARB	California Air Resources Board
CEC	California Energy Commission
CHSS	Compressed Hydrogen Storage System
DOE	US Department of Energy
FCEV	Fuel Cell Electric Vehicle
HGV	Hydrogen Gas Vehicle
HyStEP	Hydrogen Station Equipment Performance Device
IrDA	Infrared Data Association
LCFS	Low Carbon Fuel Standard
LD	Light-Duty
MAT	Mass Average Temperature
MAT30	Mass Average Temperature after 30 seconds of fueling
MC	Combined Mass and Specific Heat Capacity
OEM	Original Equipment Manufacturer
SNL	Sandia National Laboratories
SOC	State of Charge

Executive Summary

Over the past decade, the State of California has supported the development of retail hydrogen refueling stations for light-duty (LD) fuel cell electric vehicles (FCEV) using grant funding, low carbon fuel standard (LCFS) credits, and direct assistance with station testing to incentivize private investments in the fueling network. The California Air Resources Board (CARB) utilizes a mobile test device, called the Hydrogen Station Equipment Performance (HyStEP) device, to test new light-duty hydrogen refueling stations before they are opened for public use. Testing is based on the CSA Group/ANSI Hydrogen Gas Vehicles (HGV 4.3), which evaluates station conformance to SAE J2601, the industry standard hydrogen fueling protocols.

Until now, CARB has only tested new hydrogen stations, and no data has been collected on how well stations have adhered to the standard fueling protocols since first opening to the public. Concurrently, there have been discussions among California state agencies, industry, and other stakeholders that there is a need for a regulation to include periodic testing to support adherence to SAE J2601. For this study, CARB staff tested 22 existing in-use hydrogen refueling stations with the HyStEP (test device) to determine adherence to SAE J2601. Participation in this study was voluntary and two of four station operators in California agreed to participate. Testing occurred between October 2023 and May 2024. Although not all station operators participated in the study, the findings are representative of all stations operating in California because most stations share technology, programmable logic control, and have a similar age distribution as those tested in the study.

Limitations prevented CARB staff from uniformly testing every station. For example, many of the tests in HGV 4.3 require station data logs which some older stations are not equipped with and/or could not provide for these assessments. Other tests require station technicians to alter station sensor readings or operational settings to induce fault conditions, and these tests could not be performed due to either station design limitations or technician knowledge. Additionally, regional fuel supply shortages resulted in testing delays and prevented certain stations from being tested. Summary reports were created for each station tested, which include a general station description, dispenser fueling protocol, operating characteristics, a summary of fault and communication test results, and graphs and analyses of fueling tests.

Findings and Recommendations

Finding 1: All stations fell short of fully adhering to SAE J2601.

Most stations fell short of fully adhering to SAE J2601 when they were originally commissioned. At that time, not achieving full compliance was allowed if there were no safety issues present. For these stations, FCEV manufacturers agreed that fueling performance was adequate during commissioning and requested that the station operator correct any deficiencies. During in-use testing conducted for this study, failing to achieve a complete fill was the most common fueling performance issue. In addition, CARB staff witnessed many customers having fueling issues (incomplete fueling, no fueling, etc.) at the hydrogen dispensers open to the public. Many of these issues were identified during initial station commissioning and have not yet been addressed. Data suggests a periodic testing program could identify and resolve these deficiencies and maintain a positive customer refueling experience.

Finding 2: Stations that were not initially validated with the testing device failed multiple fault tests.

There were six stations tested in the in-use study that were not previously tested during station commissioning. Five of the six stations failed multiple general fault and communication tests, and testing was terminated early at the sixth station due to a dispenser communication issue. These tests are primarily designed to prevent overheating or over-pressurizing, thereby protecting the longevity of the FCEV tanks. The stations that were tested during commissioning passed all the general fault and communication tests that could be performed at the time of in-use testing. This suggests that initial validation testing of stations supports safe operation and reliability of hydrogen refueling stations.

Finding 3: Most stations fuel in the T30 fuel delivery temperature category.

Most stations are now set to operate in the T30[1] fuel delivery temperature category. These stations were originally set to T40 as was contractually required by California Energy Commission (CEC) grant funding opportunity and stipulated by FCEV automakers. Fueling in the T30 fuel delivery temperature range results in a slower fill compared to fueling in the T40 range.

Finding 4: Changes were made to numerous stations between original commissioning and in-use study testing.

The most common changes made to stations include updating fueling protocols from the table-based to the MC formula-based, changing fuel delivery temperature categories, implementing category D[2] fueling (>10 kg), and modifying dispenser logic.

Finding 5: Many stations lack a data acquisition system capable of recording the HGV 4.3-required fueling data.

Many stations were unable to record and/or provide fueling data or allow technicians to simulate station fault testing due to outdated hardware or programming. The ability to record and provide data and simulate fault tests is required and necessary to analyze station performance and confirm adherence to the fueling protocols. Dispenser upgrades/modifications are needed to record fueling data for test evaluation and to simulate fault conditions per HGV 4.3 requirements.

Recommendation 1: Periodic testing should be considered to ensure a safer and more reliable hydrogen fueling experience.

Many stations were unable to fully adhere to the applicable standards, including failing general fault and performance tests. Additionally, changes to station programming, fueling protocols, and fuel delivery temperatures were noted at many stations between the time of station validation and in-use study testing. There is currently no regulation that mandates testing or oversight, which means station performance may decline over time, negatively impacting customer satisfaction. Periodic testing would promote confidence that

[1] The three ranges of fuel delivery temperature are T40, T30, and T20 which correspond to temperature ranges of -40 °C < T < -33 °C, -33 °C < T < -26 °C, and -26 °C < T < -17.5 °C, respectively.

[2] The CHSS Categories are A (2-4 kg), B (4-7 kg), C (7-10 kg), and D (>10 kg).

stations maintain a satisfactory level of fueling performance and that customers have a safe and reliable fueling experience.

Recommendation 2: A test device is needed to test CHSS Capacity Category D fueling.

Testing confirmed that the fueling protocol logic on some stations has been updated to allow filling of compressed hydrogen storage system (CHSS) Capacity Category D (>10 kg). However, during the initial commissioning process for these stations, the light-duty FCEV automakers approved stations based on Category D fueling being disabled. The current test device is only able to perform tests for CHSS capacity categories A, B, and C[2], with no capability to test category D fueling. Therefore, a new test device is needed to confirm conformance with the fueling protocols for CHSS capacity category D.

Study Description

The objective of this study was to assess in-use conformance of California's existing light-duty hydrogen refueling stations with SAE J2601. SAE J2601 is the industry standard light-duty FCEV fueling protocol in the United States. The existing station population ranges in operating age from about 10 years since opening to recently opened. This study assesses conformance as a function of operational age. A representative sample of stations were tested using the testing device and an abbreviated version of the HGV 4.3 test method. HGV 4.3 is the test method used to verify stations conformance with SAE J2601 requirements.

The purpose of this study is to provide test data to help policy makers assess the need for periodic station testing. CARB tests most light-duty stations prior to opening to the public in order to meet the CEC Grant Funding Opportunities (GFOs) and/or FCEV automakers' requirements. This is an informal process in which the CARB test device assists FCEV manufacturers and station operators in the opening of publicly or privately funded stations. There is currently no regulation requiring stations to fuel FCEVs using a particular fueling protocol, or for stations to pass fueling protocol testing to operate. CARB has not retested any stations after opening. In addition to assessing whether the safety requirements of SAE J2601 are met, this study assesses station fueling performance for three vehicle CHSS categories (A, B, and C).

Of the approximately 55 operational (not including 7 non-operational) light-duty hydrogen refueling stations in California, 22 stations (40%) were tested. Stations were selected with the goal of testing a representative sample of station characteristics, including operational age, manufacturer, operator, model, hydrogen storage and delivery technology (gaseous or liquid hydrogen), and dispenser technology and programming. An abbreviated adaptation of the HGV 4.3 test method matrix was performed at each station (see Appendix B).

SAE J2601 Description

SAE J2601 establishes the protocol and process limits for hydrogen fueling of light-duty FCEVs. Vehicles can be filled in as little as three minutes following the SAE J2601 fueling protocols. Factors such as ambient temperature, CHSS size, and initial tank pressure affect the process limits that dispensers must stay within while fueling. The standard contains two different protocols, a look-up table-based fueling protocol (table-based protocol) and a formula-based fueling protocol (MC formula-based protocol). The primary difference between the two protocols is the way in which the pressure ramp rate is determined throughout the fill. Many general requirements are shared by both protocols.

Fueling is normally conducted with Infrared Data Association (IrDA) communication between the vehicle and dispenser, although fueling without communication is possible following a more conservative process. SAE J2799 defines the IrDA communication protocol that is used in SAE J2601. Communicated signals from the vehicle allow the dispenser to read the vehicle tank temperature and pressure, respond to vehicle signals such as abort or halt, and read important vehicle specifications such as tank volume and pressure class. During fueling, the dispenser monitors for errors in the communicated data.

Vehicle storage systems can be designed for a nominal working pressure of either 35 MPa or 70 MPa (categorized as H35 and H70, respectively). In practice, all light-duty FCEVs on the market have been designed for H70 fueling. Fuel delivery temperature (the temperature of the hydrogen gas as it is delivered into the vehicle) is a critical factor in how quickly the station can fuel the vehicle and assuring the long-term integrity of the fuel tank. SAE J2601 splits fuel delivery temperature into three categories, T40, T30, and T20. T40 is the coldest category and allows the quickest fueling rates, with H70 fills completed as quickly as three minutes. For the table-based protocol, T30 fueling is roughly half (depending on the ambient temperature) as fast as T40 fueling and T20 fueling is roughly half as fast as T30 fueling. For the MC formula-based protocol, the pressure ramp rate can change throughout the fill as fuel delivery temperature and ambient temperature changes. In general terms, the fueling time does not increase as much with T30 fueling using the MC formula-based protocol when compared to the table-based protocol.

Test Methodology

Station Selection

A database was compiled of all light-duty retail hydrogen stations in California, which included important station characteristics, operational status, station opening date, and whether the station was initially tested by CARB.

After compiling the station database, an invitation was sent to each station operator with operational stations to participate in the study. The invitation included a study description and assurance that study results would be presented anonymously. Following the email invitations, CARB staff held numerous webinars with station operators, automakers, and state agencies to describe the study and solicit feedback. Initially, all major station operators (four) agreed to participate, but only two operators ended up participating in the study. The participants were asked to identify which of their stations would be available for testing and any anticipated difficulties at each station. Difficulties noted for testing stations included:

- uncooperative site owner (most stations lease property at gasoline stations).
- constrained access where our test device would block access to gasoline dispensers.
- high utilization stations where testing would interfere with FCEV drivers fueling their vehicles.
- stations located where there is no nearby alternative station.

To test an even distribution of station ages, stations were arranged by opening date and split into quartiles. The study objective was to test the same number of stations from each quartile while also testing stations with varying characteristics. It is important to note that the age distribution of stations is not uniform.

Test Device

The test device referred to in this report was developed in partnership with the US Department of Energy (DOE), H2FIRST, and Sandia National Laboratories (SNL), and has been operated in California by CARB staff since 2016. The primary purpose of the test device is to speed up and streamline the station commissioning process to meet customer demand. It is designed to be used by a validation/certification agency to measure the performance of hydrogen dispensers with respect to the required fueling protocol standard. Specifically, the device has been designed to carry out the tests defined in HGV 4.3 to confirm adherence to SAE J2601. These include vehicle-to-dispenser communication testing, fault detection tests, and complete fills to 70 MPa. The test device includes 3 Type IV 70 MPa tanks (the same type used on FCEVs) capable of storing a total of 9.3 kg (228 L) of hydrogen. The tanks and receptacles are instrumented with digital pressure and temperature sensors. The device has IrDA communications integrated with a data acquisition, analysis, and control system. The test equipment is enclosed in a utility trailer-based platform (Figure 1).

Figure 1: HyStEP test device (exterior and interior view)

Test Method

Stations were tested using an adaptation of the HGV 4.3:22 test method (APPENDIX B). Testing was generally performed in the order shown; however, test order varied at times to efficiently utilize the remaining tank capacity of the test device and to continue testing while recently defueled tanks warmed to ambient temperature. Table 1 below provides an overview of the tests categories conducted, including a brief description of the purpose.

Table 1: Overview of the testing category matrix

Testing Order	Testing Category	Purpose
1	Emergency and Customer Stop Tests	Safety
2	General Fault Tests *(Series of tests)*	Tests are intended to determine if dispensers will react properly to exceeding fault limits defined in Clause 5 of HGV 4.3:22.
3	Communications Testing *(Series of tests)*	Tests intended to confirm the communication system, IrDA properly operates within the boundary limits defined in SAE J2799.
4	Fueling Protocol Evaluation Testing	Tests are intended to evaluate dispenser's ability to properly fuel a vehicle within the SAE J2601 boundary limits. Test conducted for these tank categories: - Category A Complete Fill - Category B Complete Fill - Category C Complete Fill

Although some stations are programmed with older versions of SAE J2601, the HGV 4.3:22 test procedures were followed to keep testing uniform. Stations tested in this study use the following protocol versions:

- J2601- 2014 Table-based fueling protocol.
- J2601-2016 Table-based fueling protocol.
- SAE J2601 2016 MC Formula-based fueling protocol.
- SAE J2601 2020 MC Formula-based fueling protocol.

Station operators were usually given less than one week of notice of each station test to minimize station maintenance in preparation for station testing. The test matrix was optimized to take less than eight hours to reduce disruptions to operations and to test multiple stations per trip. One dispenser was selected by CARB staff for testing on the day of testing. The full HGV 4.3 test matrix of general fault tests, communications testing, and protocol evaluation testing was performed on the selected dispenser. One complete communication fill was attempted for each light-duty CHSS capacity category that the station is programmed to fuel. No retests were performed unless there was an issue recording data, or the cause of a failed test was outside the scope of the testing protocol and unrelated to the safety and performance capabilities of the station.

Test results were evaluated using a combination of field notes and dispenser data. For tests that require analyzing logged data (e.g., fills) to evaluate pass/fail criteria, the test device data log and the dispenser data log were used to graph and evaluate the fueling tests. However, dispenser data logs were not supplied by some stations. When the test pass/fail criteria could not be evaluated due to missing dispenser data, the test was marked as 'undetermined'. Similarly, if a technician was not equipped to run certain tests, those tests were marked 'undetermined'.

For general fault and communications testing, a failed test means that the station did not respond correctly to a fault condition or communication error. Common responses to a fault condition or communication error include the termination of fueling or continuation of fueling in non-communication mode. For fueling protocol evaluation tests, a failed test means the fill terminated without reaching the target SOC, or the fill ended because a measured parameter (i.e. pressure or temperature) was outside the allowed boundary.

Results for each station test were recorded in a database and a summary report was prepared for each station. These reports include a general station description, dispenser fueling protocol programming, unique operating characteristics, a summary of fault and communication test results, and graphs and analyses of the complete-fill tests. These test reports are being provided directly to the station operators. For stations that utilize the MC Formula fueling protocol and can provide the necessary dispenser data, Wenger Engineering MC Formula Validation Calculator V. 3.9 was used to evaluate protocol calculation, process, and end of fill checks. For stations that utilize the Table-Based fueling protocol, the HDTADA program, developed by the National Renewable Energy Laboratory, was used to evaluate fueling performance. When stations were not able to provide dispenser data, CARB staff used data from the test device, such as the state of charge (SOC) and field observations to assess the performance of the station.

Results & Analysis

Overall Results

None of the 22 stations tested in this study passed all the tests in HGV 4.3:22 (Figure 2). Test results are detailed by test category in the following sections: general fault and communication tests and fueling performance in communication and non-communication tests.

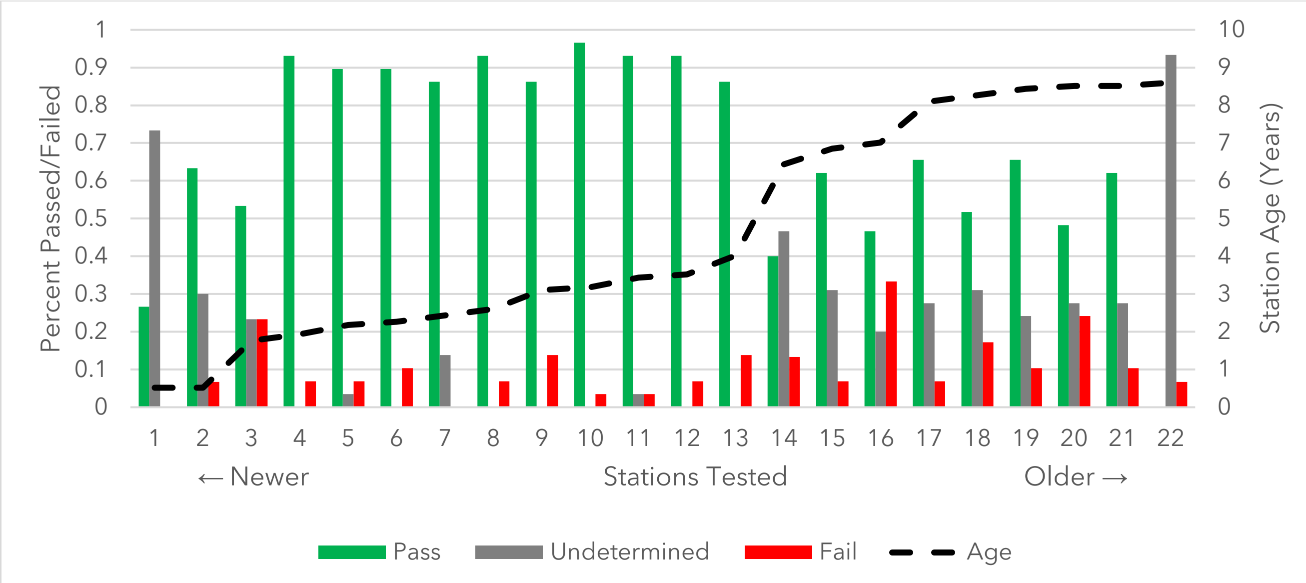

Figure 2: Overall test results.

Generally, the older stations passed fewer tests than the newer stations. Multiple factors contributed to this difference, including but not limited to:

- More undetermined tests due to insufficient data logging capabilities to evaluate pass/fail criteria.
- More undetermined tests due to station design not allowing for simulated fault tests that require altering station sensor readings during fueling.
- More failed tests caused by known station issues first demonstrated during commissioning testing that have not been resolved.
- Some older stations did not go through an official validation process using a proper and capable test device when first brought online and therefore failed to comply with certain fault and performance requirements.

While station age undoubtedly can play a role in test results, there are confounding factors that prevent drawing a clear conclusion on how long stations can go between validation testing based on age alone. The older stations are not simply older, they represent first-generation retail hydrogen fueling technology. Newer stations have revised/improved technology based upon the experience of operating the first-generation stations. Additionally, it cannot be concluded that all newer stations will perform better than older stations because the in-use study test results also vary by station operator and technology provider (this report does not distinguish results by operator or technology provider for confidentiality).

Stations were most successful in passing communications testing, followed by general fault, protocol fault, and finally fueling evaluation (performance tests). The pass rate was low for all test categories (Figure 3).

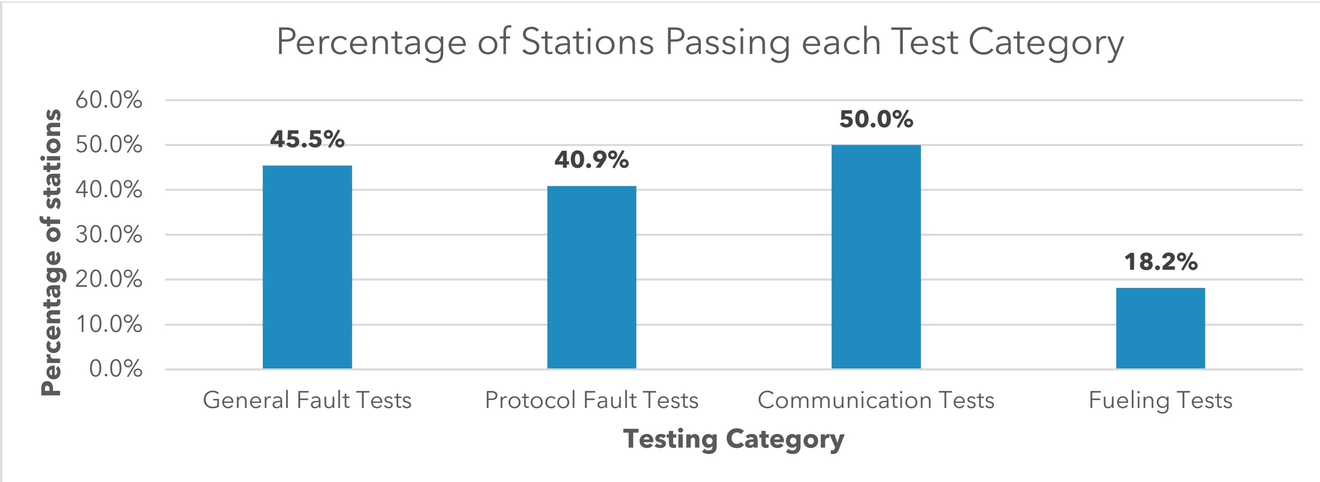

Figure 3: Percentage of passing results breakdown by testing category.

Most stations are programmed for MC formula-based fueling (Figure 4). Many older stations have been upgraded to use the MC formula-based protocol since being commissioned.

As shown in (Figure 4), of the 22 stations that were tested in the study, 6 stations were commissioned with table-based fueling protocols and later were updated to MC formula-based fueling protocols, 10 stations were commissioned and remain programmed for MC formula-based fueling, and 6 stations were commissioned and remain programmed for table-based fueling. Furthermore, the actual number of stations that have been updated from the table-based fueling protocol to the MC formula-based fueling protocol are roughly 45% of all operational light-duty stations in California.

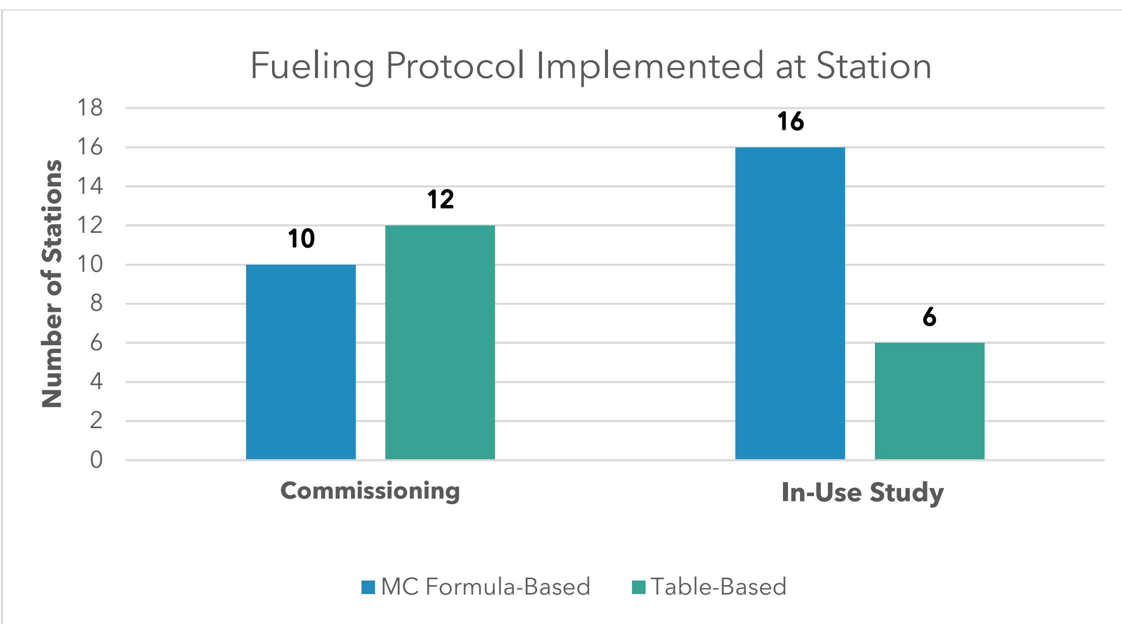

Figure 4: Number of stations operating under each fueling protocol at time of commissioning and in-use testing.

General Fault and Communication Tests

The results of all general fault and communication (fault) tests have been combined in this section to present a summary of the test results. These tests are designed to prevent FCEV tanks from overheating or over-pressurizing. The HGV 4.3 test method does not distinguish between performance and fault tests for conformance with SAE J2601. A station that passes all fault tests but fails to reliably deliver complete fills is still operating safely, albeit unsatisfactorily.

Of 22 stations tested for this study, 5 passed all fault and communications tests (Figure 5). Five additional stations may have passed all fault tests if the full in-use study test matrix was completed without any "undetermined" results. Overall, newer stations tended to perform better on fault tests, as demonstrated by the lower failure rate of the newer stations (Figure 5). First-generation stations failed some tests consistently and a large fraction of tests were undetermined. Some of the first-generation stations did not go through initial validations using a test device, but rather utilizing Original Equipment Manufacturers (OEM) vehicles. The following sections detail the general fault and communication test results by category.

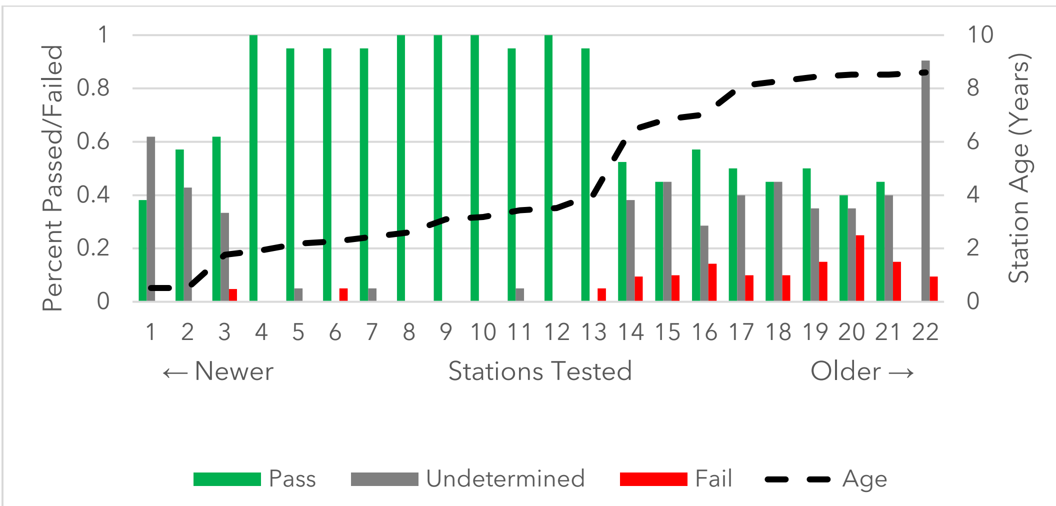

Figure 5: General fault and communication test results for each station.

Fault Tests

Protocol Fault Tests

Although there were no failed tests for protocol fault testing, many of the tests could not be performed due to station limitations (Figure 6, Table 2). Protocol fault testing is dependent on the ability of the station operator to provide fueling data and to alter station parameters during fueling. Older stations were generally less able to perform these tests due to technological limitations with simulating fault conditions. Newer stations that could not perform protocol fault testing were due to operators lacking the necessary on-site expertise and/or failing to provide fueling data.

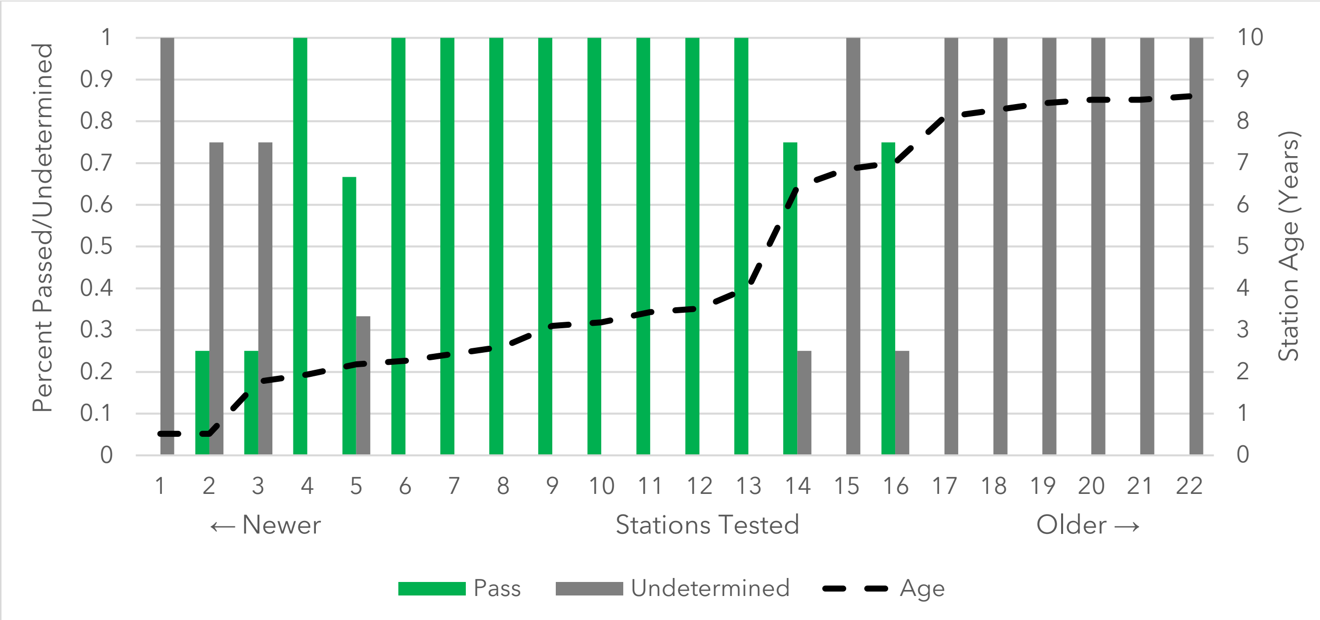

Figure 6: Protocol fault test results for each station.

When station technicians were unable to simulate or alter station parameters, the following protocol fault tests could not be performed:

- Upper and lower pressure tolerance (unless the station caused these faults during other tests)
- Fuel delivery temperature at cool-down (table-based protocol only)
- Fuel delivery temperature tolerance (table-based protocol only)
- MAT 30 above maximum allowed temperature (MC formula-based protocol only)

Table 2: Individual Protocol Fault Test Results

Protocol Fault Tests[3]	Percent of Stations Passed	Number of Stations Passed	Number of Stations Failed	Number of Stations Undetermined
Fuel Delivery Temperature at Cool-Down (table-based only)	33%	2	0	4
Fuel Delivery Temperature Tolerance (table-based only)	33%	2	0	4
Upper Pressure Tolerance	45%	10	0	12
Lower Pressure Tolerance	64%	14	0	8
MAT30 Above Maximum Allowed Temperature (MC formula-based only)	56%	9	0	7

[3] A total of 6 table-based stations and 16 MC formula-based stations were tested.

General Fault Tests

Many newer stations passed all or most of the general fault tests (Figure 7, Table 3). The oldest stations had the most failed tests. Multiple older stations, and a few of the newest stations, had many undetermined test results as detailed below

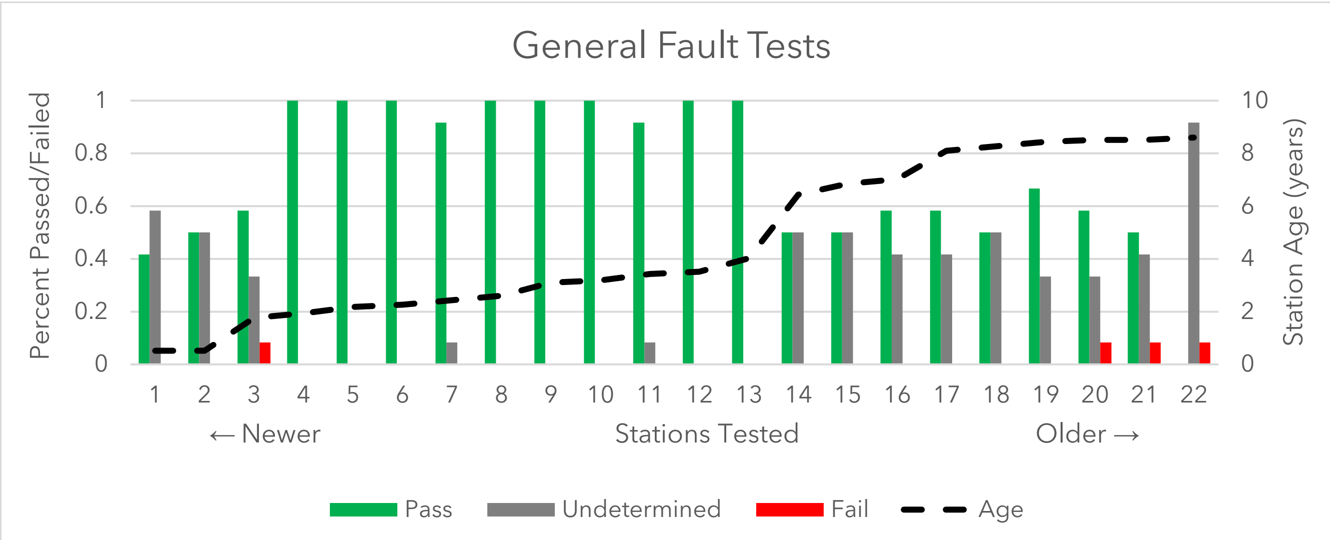

Figure 7: General fault test results.

The main cause of undetermined test results was the inability of the station operator to simulate fault conditions on the station side during fueling. This prevents the following general fault tests from being performed:

- Ambient temperature limits
- Minimum fuel delivery temperature
- Maximum CHSS pressure test without communication

The second cause of undetermined test results was the inability of the station operator to provide the necessary fueling data for test pass/fail criteria, which prevents the evaluation of the following general fault tests:

- Maximum flow rate
- Maximum startup mass
- Minimum startup time

Failed tests mean that the station did not respond correctly to a fault condition (by terminating the fill). The specific tests with at least one fail are:

- Minimum initial CHSS pressure
- Maximum initial CHSS pressure
- Maximum state of charge
- Maximum flow rate

Table 3: Individual General Fault Test Results

General Fault Tests	Percent of Stations Passed	Number of Stations Passed	Number of Stations Failed	Number of Stations Undetermined
CHSS Capacity Range	95%	21	0	1
Ambient Temperature Limits	45%	10	0	12
Minimum Fuel Delivery Temperature	45%	10	0	12
Maximum CHSS Gas Temperature	95%	21	0	1
Minimum Initial CHSS Pressure	86%	19	1	2
Maximum Initial CHSS Pressure	91%	20	1	1
Maximum CHSS Pressure Test with Comm	91%	21	0	1
Maximum CHSS Pressure Test without Comm	59%	13	0	9
Maximum State of Charge	86%	19	1	2
Maximum Flow Rate	55%	12	1	9
Maximum Startup Mass	59%	13	0	9
Minimum Startup Time	45%	10	0	12

Communication Tests

Communications testing does not rely on the station operator altering dispenser parameters or providing fueling data logs. As a result, fewer of the communication test results were undetermined. Many newer stations passed all communications tests (Figure 8). Most failed tests occurred in the older stations. The primary cause of undetermined results were operational issues during testing that prevented fueling, which could not be readily fixed.

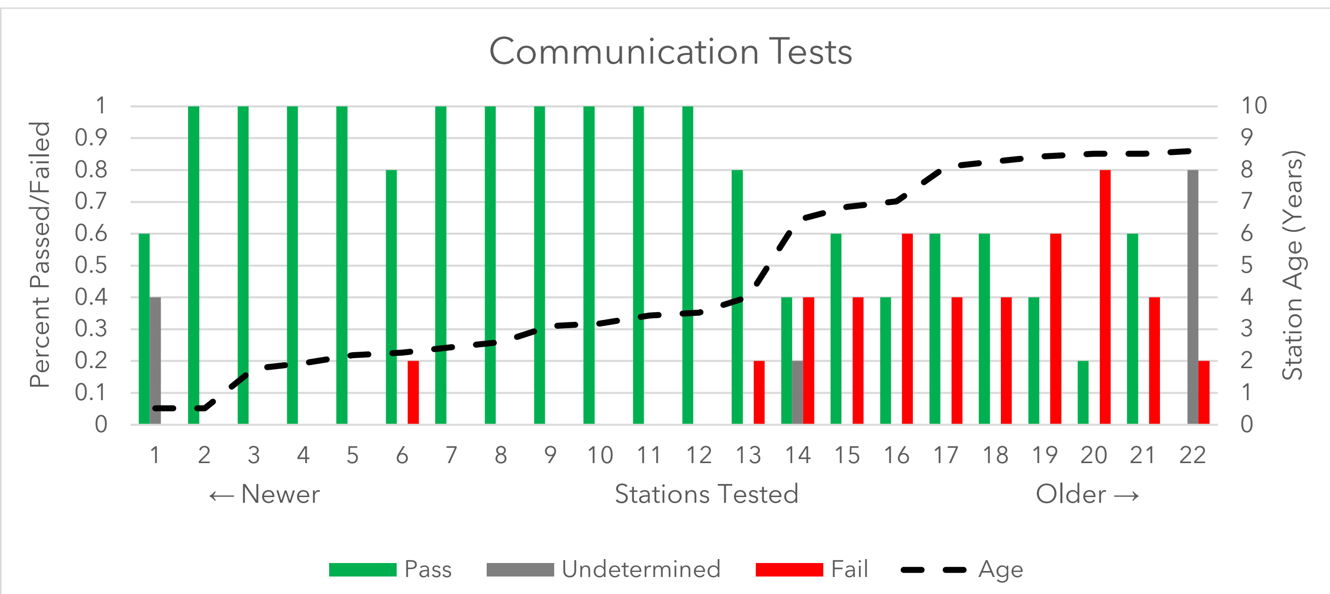

Figure 8: Communication test results for each station.

A failed test means that the station did not respond correctly to communicated vehicle (test device) data by terminating fueling or by switching to non-communication fueling (options depend on the specific test). Each specific communications testing category failed at least once during the in-use study (Table 4).

Table 4: Individual Communications Testing Results

Communications Testing	Percent of Stations Passed	Number of Stations Passed	Number of Stations Failed	Number of Stations Undetermined
Abort Signal Test	86%	19	2	1
Halt Signal Test	91%	20	1	1
Data Loss Test and Resumed Fueling Test	68%	15	4	3
Invalid CRC Communication Test	59%	13	8	1
Invalid Defined Data Value Test	59%	13	8	1

Fueling Evaluation (Performance) Tests

Fueling evaluation (performance) testing consisted of three complete communication fills, one in each light-duty CHSS capacity category: A (2-4 kg), B (4-7kg), and C (7-10kg). Each fill was evaluated for pass/fail on the following metrics:

- Process limits not exceeded.
- Final SOC between 95-100%.
- Fuel delivery temperature within designated range.

With 3 CHSS capacity categories and 3 pass/fail criteria for each fill, every station had a total of 9 individual metrics that were evaluated for fueling performance. Of 22 stations, 4 passed all 9 metrics with most stations having 1 or 2 failed metrics (see appendix A for full matrix). Unlike the general fault and communication tests, there is no clear trend of older stations performing worse in fueling performance testing (Figure 9, Table 5). The 4 passing stations were some of the oldest. Multiple factors during fueling can cause performance issues. All light-duty mass market FCEVs to date have CHSS capacities in the Category B (4-7kg) range. Therefore, many stations have been optimized for filling Category B and do not perform as well in Category A or Category C test fills.

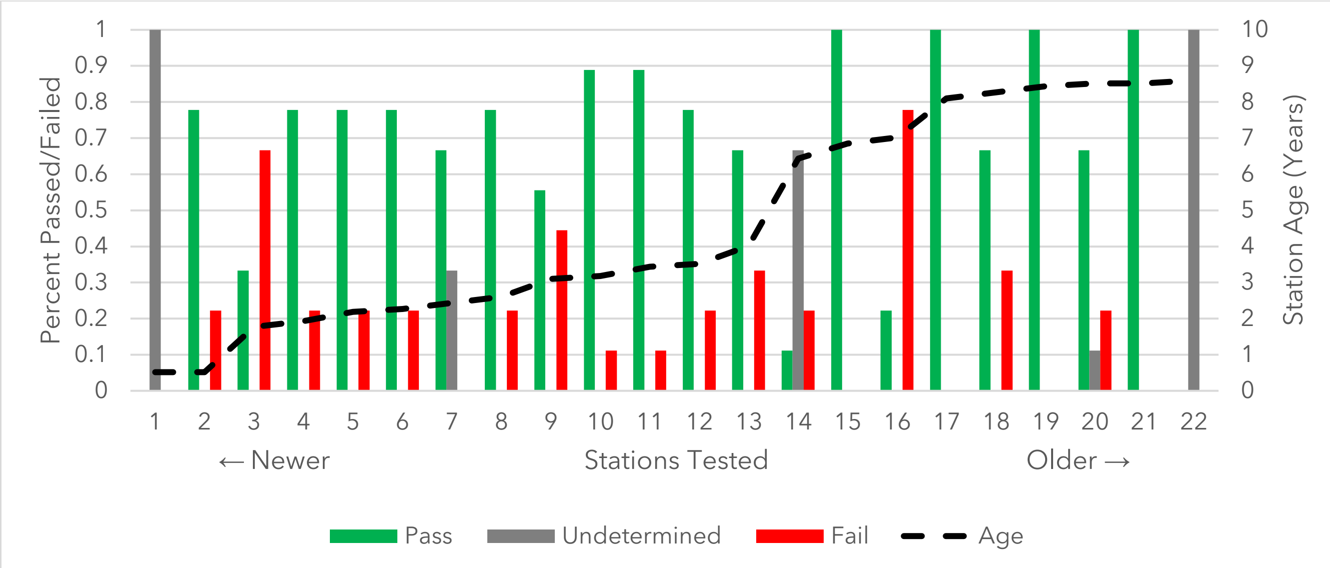

Figure 9: Fueling performance test results for each station.

Table 5: Individual Fueling Performance Tests Results

Fueling Performance Tests	Percent of Stations Passed	Number of Stations Passed	Number of Stations Failed	Number of Stations Undetermined
CHSS Category A Fueling	64%	14	5	3
CHSS Category B Fueling	59%	13	7	2
CHSS Category C Fueling	36%	8	11	3
Original Temperature Category (T40) Met	9%	2	18	2

Test results differ among the three pass/fail criteria and between CHSS categories (Figure 10, Figure 11). Overall, stations were most successful in meeting their selected temperature category (i.e., T30), followed by meeting the 95% SOC threshold, and finally staying within the process limits. CHSS Category B fills show the highest success rate in achieving 95% SOC and staying within the selected temperature category. CHSS Category C fills were the least successful, particularly at staying within the process limits.

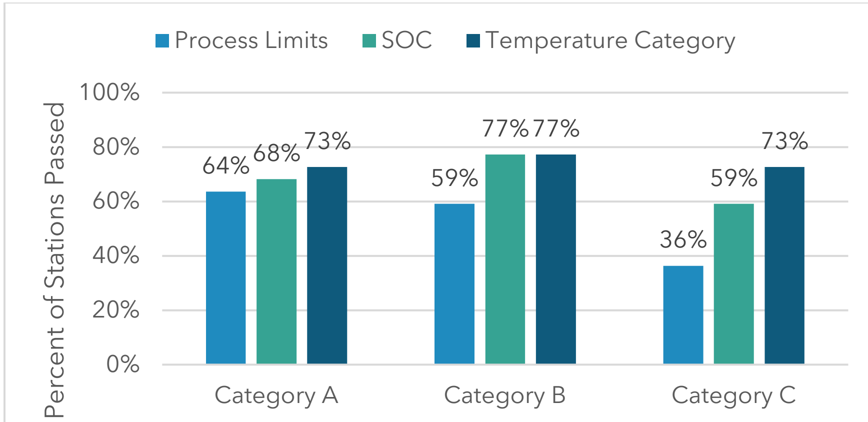

Figure 10: Individual test results by CHSS category.

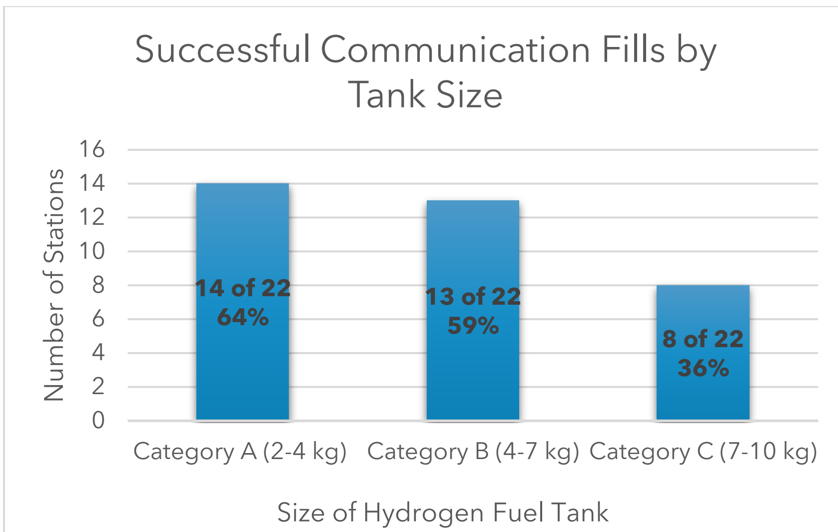

Figure 11: Communication fill results by CHSS category.

Some stations are tuned such that dispenser pressure drops below the lower pressure corridor tolerance at the final part of fueling, causing the fill to end with a lower pressure corridor limit fault (when the black line falls below the dotted blue line) (Figure 12). These fills end at or above 95% SOC (light blue line) and meet their temperature category rating but exceed the process limits prior to meeting the dispenser's SOC target. The dispenser is still attempting to fill the CHSS, but the station pressure is not sufficient to continue fueling. Although fueling performance as perceived by an FCEV driver is likely unaffected, these fills do not pass the test requirements as defined in HGV 4.3: 22, section 10.7.1.3. This situation occurred on 4 of 22 Category B fills.

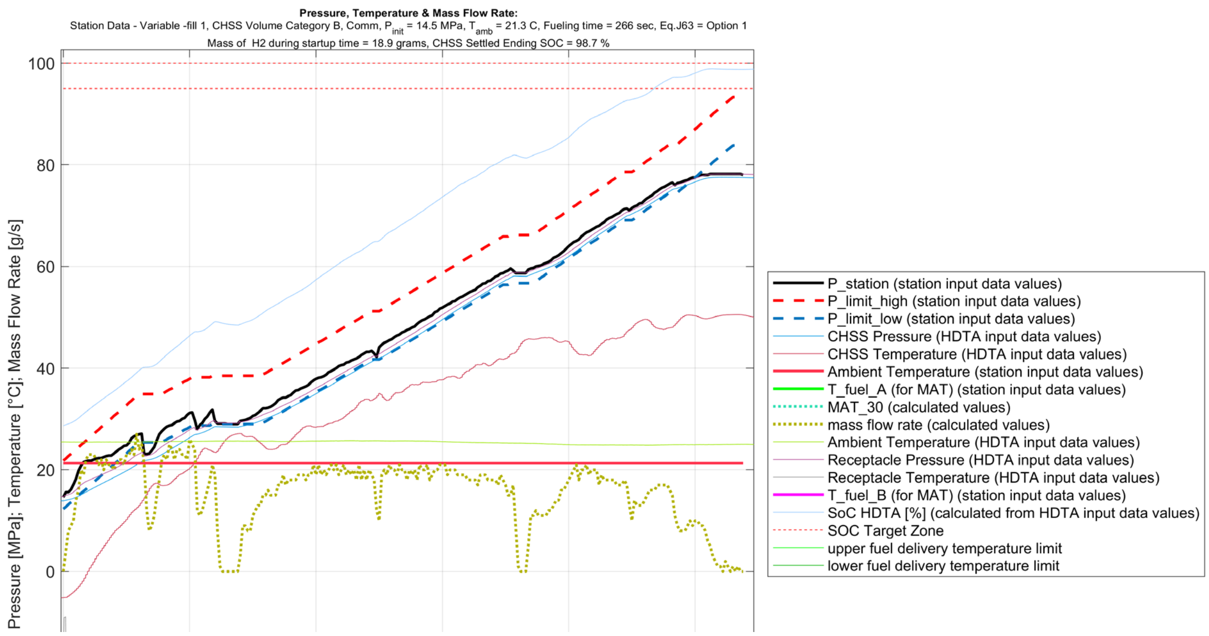

Figure 12: Example of fill ending with lower pressure corridor tolerance fault above 95% SOC.

Most stations are now set to operate in the T30 (-33 °C ≤ Tfuel ≤ -26 °C) fuel delivery temperature category (Figure 13), although they were originally set to T40 (-40 °C ≤ Tfuel ≤ -33 °C) per contract requirements of the CEC grant funding opportunities and stipulated by the FCEV automakers. Fueling in the T30 temperature range results in a slower fill when compared to a T40 fill. However, stations that use the MC formula-based protocol, which adapts fueling rates to the specific fuel delivery temperature being achieved, will typically fuel faster at T30 rather than a station using the table-based fueling protocol and filling at T40. Station operators that have switched from T40 to T30 fueling prefer T30 for lower energy costs and reducing station equipment failure rates.

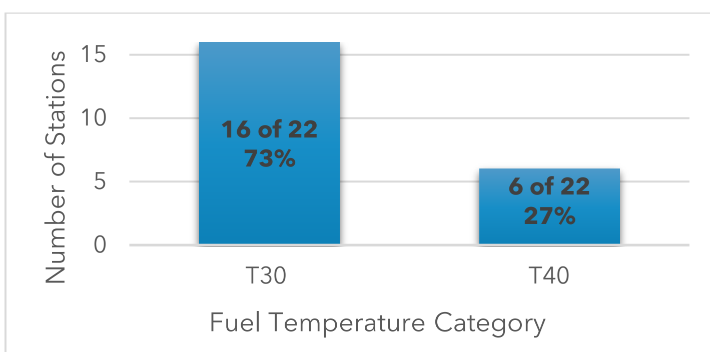

Figure 13: Number of stations using each temperature category.

Comparing Commissioning to In-Use Study Test Results

Of the 22 stations tested in this study, 16 were tested with the test device prior to the station opening to the public. The commissioning testing process differs from the in-use study testing process in that the commissioning process follows the full HGV 4.3 test method, which includes more complete fills. Additionally, problems with the station are often discovered and fixed during commissioning testing, whereas during this study, tests were attempted once, and problems resulted in failed or undetermined test results. Finally, during commissioning testing, station operators were more willing and/or able to provide fueling data needed for evaluating test results than during this study.

A reduction in pass percentage between commissioning and in-use study testing for older stations would indicate that stations fall out of compliance with J2601 over time, which does not appear to be the case (Figure 14). Eight stations tested passed more tests during commissioning, two stations had equal results, and six stations passed more tests during the study.

Only three stations in the study group passed all tests during commissioning. The remaining stations either had undetermined tests or failed at least one complete fill performance test. Not achieving full compliance could be allowed if there were no safety issues present, and if FCEV manufacturers agreed that fueling performance was adequate during commissioning. Additionally, station operators were required to correct any deficiencies identified during testing.

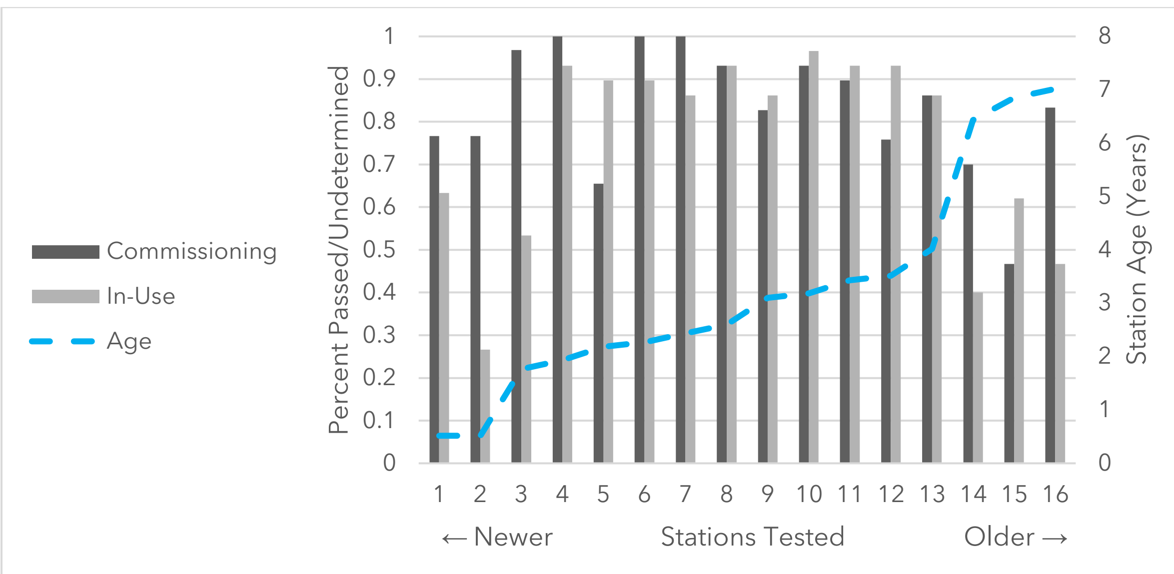

Figure 14: Station passing rate during commissioning and in-use testing by station age.

Station Operational Problems Encountered

Prior to beginning the study, a list of anticipated testing problem categories was created. During testing, any problem that inhibited staff from performing an individual test was noted and categorized. The results show that fueling performance, such as completing fills with ≥95% SOC, was the most common issue (Figure 15). Hydrogen supply problems were not encountered during testing though regional supply problems did occur that prevented us from testing certain stations during the study period.

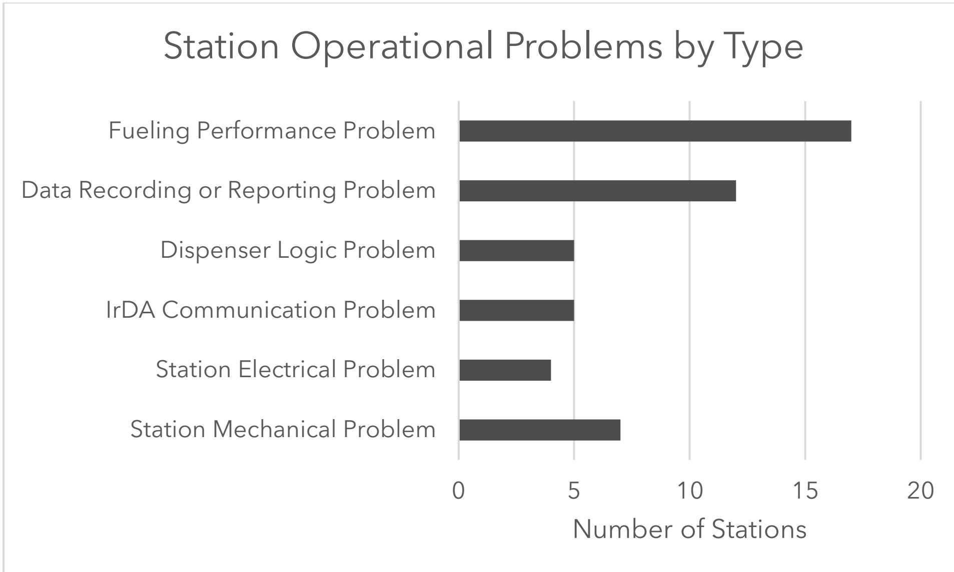

Figure 15: Number of stations with each type of operational problem.

There is no clear trend of newer stations having fewer problems than older stations (Figure 16). Only two stations had no problems during this study.

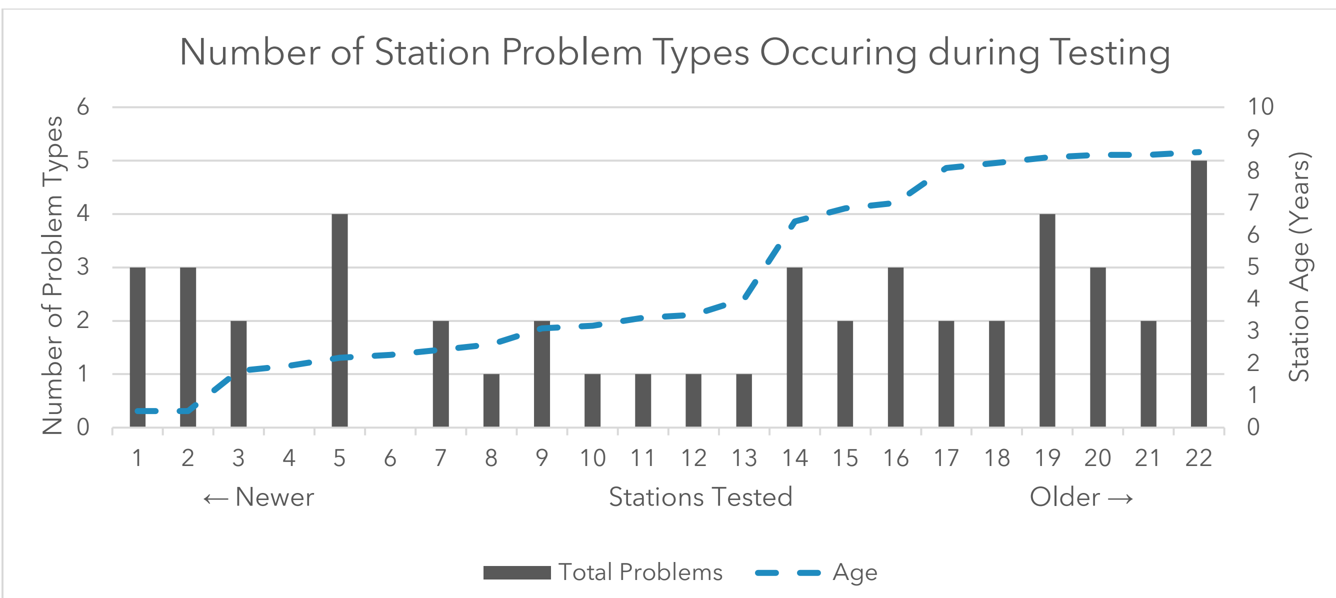

Figure 16: Number of problem types encountered per station by station age.

Protocol Implementation Differences

Fueling protocol implementation is sometimes done more conservatively than prescribed by J2601. The fueling protocol logic for some stations that use the table-based fueling protocol differs from what is prescribed in J2601 in the following conservative ways:

- H70 fills without communication terminate at 43 MPa (approximately half-full) instead of fueling to the non-communication target pressure in J2601 look-up tables.
- Minimum initial CHSS pressure is set at 2 MPa instead of 0.5 MPa.
- Dispensers do not use the required top-off fueling protocol, which is prescribed when initial CHSS pressure is below 5 MPa.
- Dispensers use the most conservative Average Pressure Ramp Rate (APRR) instead of the prescribed APRR for the specified CHSS capacity, including communication fills.

Conclusions

The in-use study tested 22 existing hydrogen stations to assess station adherence to SAE J2601 and to identify changes from the time of station commissioning to the time of the in-use study. Some stations made programming changes after commissioning. These changes are not prohibited, but oversight including validation is necessary to ensure the public receives safe, fast, and consistent fueling that maintains compliance with applicable standards and specifications. The in-use study resulted in the following findings:

- All stations fell short of fully adhering to SAE J2601 and no station passed all communication, fault, and performance tests.
- Stations that were not originally validated with the testing device during commissioning failed some fault and communication tests during the in-use testing.
- The majority of stations are fueling in the T30 fuel delivery temperature category despite originally being commissioned as T40 stations.
- Many stations made changes to their fueling protocols, fuel delivery temperature, allowable CHSS categories, and dispenser programming from the time of commissioning to the time of the in-use testing.
- Some stations are not equipped to record and/or adhere to the dispenser data requirement in HGV 4.3, which affects the ability to simulate certain fault conditions and assess station compliance.

Recommendations

There are two main recommendations based on the findings of the in-use study.

Hydrogen station periodic testing should be considered to ensure safer and more reliable hydrogen fueling experience.

Station operators currently have autonomy to make any changes to the station programming, operations, and fueling protocols once validation/commissioning is complete. Changes to station programming, fueling protocols, and fuel delivery temperatures were noted at many stations during the in-use study. The changes include changing from table-based fueling protocols to MC formula-based protocols, enabling fueling of CHSS Category D, altering fuel delivery temperature, and adjusting minimum initial CHSS pressure limit. There are currently no requirements to document and/or re-validate any changes or notify interested parties of the changes, and there is no existing procedure to ensure stations continue to fuel vehicles with the same level of success as when first commissioned. Additionally, many stations were never validated with the test device and these stations failed multiple tests during the in-use study. Therefore, periodic testing should be considered to level the playing field and promote access to safe and reliable hydrogen fueling infrastructure into the future.

A test device is needed to test CHSS Capacity Category D fueling.

The current test device is only able to perform tests for CHSS capacity category A, B, and C. Several tested stations in the in-use study had category D fueling enabled, despite being originally commissioned only for categories A, B, and C. SAE J2601 2020 allows stations to choose which CHSS capacity categories to implement. Category D is used for medium and heavy-duty FCEV and there is currently no test device able to fully test CHSS Category D. As more medium-duty and heavy-duty hydrogen vehicles enter the market, a new test device will be needed to support safe and efficient category D fueling. A test device for category D fueling will take time to design and build so these efforts need to become a priority for the industry.

1. Appendix A

Results for this study were tabulated in an Excel workbook. Each individual test is shown here, along with the results of an example station.

Test Type	Station Info							
Header Description	Station	Station Quantile	Operator	Test Date	Test Type	Fueling Protocol & Version	Temperature Category when Tested	Original Temperature Category Designation
HGV 4.3 2022 Test Clause	-			-				
	Station Name	1	Operator	9/13/2023	Study	MC Formula 2016	T30	T40

General Fault Tests											
CHSS Capacity Range	Ambient Temperature Limits	Minimum Fuel Delivery Temperature	Maximum CHSS Gas Temperature	Minimum Initial CHSS Pressure	Maximum Initial CHSS Pressure	Maximum CHSS Pressure Test with Comm	Maximum CHSS Pressure Test without Comm	Maximum State of Charge	Maximum Flow Rate	Maximum Startup Mass	Minimum Startup Time
3	8.4	8.5	8.6	8.7	8.8	8.9	8.10	8.11	8.12	Monitored during all tests	Monitored during all tests
Pass	Undetermined	Undetermined	Pass	Pass	Pass	Pass	Undetermined	Fail	Pass	Pass	Undetermined

Table Based & MC Formula Fault Tests					Table Based & MC Formula Communications Tests				
Fuel Delivery Temperature at Cool-Down (Table Based only)	Fuel Delivery Temperature Tolerance (Table Based only)	Upper Pressure Tolerance	Lower Pressure Tolerance	MAT30 Above Maximum Allowed Temperature (MC Formula only)	Abort Signal Test	Halt Signal Test	Data Loss Test and Resumed Fueling Test	Invalid CRC Communication Test	Invalid Defined Data Value Test
9.9.6	9.9.7	9.9.8 or 10.9.6	9.9.9 or 10.9.7	10.9.8	9.10.2	9.10.3	9.10.4	9.10.5	9.10.6
Not Applicable	Not Applicable	Undetermined	Undetermined	Undetermined	Pass	Fail	Fail	Fail	Fail

CHSS Category A Complete Fill				CHSS Category B Complete Fill				CHSS Category C Complete Fill			
Process Limits Not Exceeded	Final SOC Between 95% - 100%, or met Ptarget	Temperature Category when Tested Met	Original Temperature Category Met	Process Limits Not Exceeded	Final SOC Between 95% - 100%	Temperature Category when Tested Met	Original Temperature Category Met	Process Limits Not Exceeded	Final SOC Between 95% - 100%	Temperature Category when Tested Met	Original Temperature Category Met
5.1 & 9.7 or 10.7	9.13.2.5	9.7.1.3.1 or 10.7.4.1		5.1 & 9.7 or 10.7	9.13.2.5	9.7.1.3.1 or 10.7.4.1		5.1 & 9.7 or 10.7	9.13.2.5	9.7.1.3.1 or 10.7.4.1	
Fail	Fail	Undetermined	Fail	Pass	Pass	Pass	Fail	Pass	Pass	Pass	Fail

Problems Encountered						
Station Mechanical Problem	Station Electrical Problem	IrDA Communication Problem	Dispenser Logic Problem	Data Recording or Reporting Problem	Fueling Performance Problem	Hydrogen Supply Problem
No	No	No	Yes	Yes	Yes	No

2. Appendix B

Table 1B: In-use Study Testing Matrix

Test & *Section* #	Test Name	Comm Mode	Tank Capacity	Starting Pressure	End Pressure or IrDA Signal	Pass Criteria
1	E-Stop	N/A	N/A	N/A	N/A	Terminates
2a	NC Minimum Initial CHSS Pressure (8.7)	NC	Large	P_o<0.5 MPa	N/A	No main fueling
3	Customer Stop					Terminates
2b	C Minimum Initial CHSS Pressure (8.7)	C	Large	P_o<0.5 MPa	N/A	No main fueling
4a	CHSS Capacity Range Fault (8.3)	C	Medium or Small	P_o~5 MPa	TV=45L	No fueling
4b	CHSS Capacity Range Fault (8.3)	C	Medium or Small	P_o~5 MPa	TV=250L	No fueling
10	Maximum CHSS Gas Temperature (8.6)	C	Medium or Small	Low enough for 1 min of fueling	After 30s set MT= 360 K	Terminates 5s
14a	Abort Signal – at the beginning (9.10.2)	C	Medium or Small	P_o>10 MPa	FC= Abort before start	No startup fueling
14b	Abort Signal - after 30 sec of fueling	C	Medium or Small	P_o>10 MPa	PC= Abort after 30 sec	Terminates 5s
14c	Abort Signal - NC to C after 30 sec	NC to C	Medium or Small	P_o>10 MPa	FC = Abort sent when switched from NC to C	Terminates 5s
14d	Abort Signal C to NC to C	C to NC to C	Medium or Smal	P_o>10 MPa	Fuel 30 sec in C NC for 5 sec, C and send FC= Abor	Terminates at NC or terminates at FC = Abort
15	Halt signal test (9.10.3)	C	Medium or Small	P_o>10 MPa	FC= Halt after 30 sec	Terminates OR pauses: wait 15s, FC = Dyna, 30s, FC = Halt, stops after 60s
17a,b,c	Invalid CRC communication test (3 tests) (9.10.5)	C	Medium or Small	Low enough for 1 min fueling	CRC corrupt button after 30s	Terminate or switch to NC

Test & *Section* #	Test Name	Comm Mode	Tank Capacity	Starting Pressure	End Pressure or IrDA Signal	Pass Criteria
18a-g	Invalid defined data value test (7 tests) (9.10.6)	C	Medium or Small	>10 MPa	After 15s, corrupt button for ID, VN, TV, FC, MP, MT. For RT set at H35. Record corrupt values.	Terminate or switch to NC. Allow one NC to complete.
13	Maximum State of Charge (SOC) (8.11)	C	Medium	P_o >50 MPa	~60 MPa, after 30s set MT to 238K	Terminates 5s
12a	Maximum CHSS Pressure with Communication (8.9)	C	Medium or Small	Low enough for 1 min fueling	After 30s set MP=88 MPa	Terminates 5s
16	Data loss test and then resumed fueling test (9.10.4)	C to NC	Medium	35 MPa +/- 2MPa	Switch to NC after 30s If continues in NC, switch to C after 15s	Terminates or completes fill at NC Target P, SOC<95%
11a	NC Max Initial Pressure (8.8)	NC	Medium or Small	>70 MPa		No Main Fueling
11b	C Max Initial Pressure (8.8)	C	Medium or Small	>70 MPa	No signal changes made	No Main Fueling
	Category A Complete Fill	C	Small			
	Category B Complete Fill	C	Medium			
	Category C Complete Fill	C	Large			

The tests listed below in Table 2B were performed at the stations with the ability to simulate certain test conditions.

Table 2B: Testing Matrix for Protocol Function - Simulated Tests

Test & *Section* #	**Test Name**	**Comm Mode**	**Tank Capacity**	**Starting Pressure**	**End Pressure or IrDA Signal**	**Pass Criteria**
5	Ambient Temperature Limits (8.4)	C or NC	Medium or Small	Low enough for 1 min fueling	Station simulates **before start**: Tamb = -41.5C, 51.5C	No fueling
6	Minimum Fuel Delivery Temperature (8.5)	C or NC	Medium or Small	Low enough for 1 min fueling	Station simulates Tfuel = -42. Signal 10s after Tfuel< -33C	Terminates 5s
9 – Option 1	Maximum MAT30 Temperature USING WARM GAS OR FUEL T SIGNAL CHANGE (10.9.8)	C or NC	Medium or Small	Low enough for 2 min of fueling + no leak checks	Station opens bypass valve after 25s of main fueling time, MAT30 value should be > -17.5C when calculation begins	Terminates 5s or pause flow for 60s and continue fueling (J2601-2020 9.1.2.1)
9 – Option 2	Maximum MAT30 Temperature SIMULATED MAT30 VALUE (10.9.8)	C or NC	Medium or Small	Low enough for 2 min of fueling + no leak checks	Station simulates after 50s of main fueling time, station sets MAT30 value to > -17.5C	Terminates 5s or pause flow for 60s and continue fueling (J2601-2020 9.1.2.1)
8	Lower Pressure Corridor Limit (10.9.7)	C or NC	Medium or Small	Low enough for 1 min fueling	After 20s stop manually raising pressure.	Terminates within 15s of excursion
7a	Upper Pressure Corridor Limit (10.9.6)	C or NC	Medium or Small	Low enough for 1 min fueling	After 20s raise pressure above upper limit by less than 5 MPa	Continues for 5s, then terminates within 5s
7b	Upper Pressure Corridor Limit (10.9.6)	C or NC	Medium or Small	Low enough for 1 min fueling	After 20s raise pressure above upper limit by more than 5 MPa	Terminates 5s
12b	Maximum CHSS Pressure without Comm (8.10)	NC	Medium or Small	Below NWP and >30 sec of fueling	After 30 sec, station simulates dispenser pressure = 88 MPa	Terminates 5s