Retail Hydrogen Station Reliability Status and Advances

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Abstract

One of the most important emerging commercial markets for hydrogen is fuel cell-powered mobility including cars, trucks, and buses. These vehicles are refueled via a network of hydrogen fueling stations, with the highest number of U.S. stations being in California. The numbers of both fuel cell electric vehicles (FCEVs) and hydrogen stations have increased in the last two years, with anecdotal information from FCEV drivers indicating that station reliability is hurting the consumer acceptability of FCEV technologies. Therefore, this study benchmarks the current state of hydrogen station reliability in practice and presents on-going research that is investigating the failures that are contribute to hydrogen station reliability issues. This is accomplished with an analysis of operation, safety, and maintenance data from hydrogen stations and fuel cell electric vehicles to benchmark the maintenance and failure of hydrogen stations and their components. This analysis, of over 5,000 station maintenance events, presents the leading maintenance categories and failure rates, and is a prerequisite to the development of data-driven reliability improvement plans. We present a reliability growth analysis and on-going research into the root causes of failure for dispensers, a particularly failure-prone subsystem.

Keywords: hydrogen, infrastructure, station, reliability, operation

1 Introduction

Hydrogen can be a key enabler for U.S. energy goals such as affordability, reliability, sustainability, and security as described in the U.S. Department of Energy's (DOE) Hydrogen at Scale (H2@Scale) research [1]. Embedded in the H2@Scale system of systems is the infrastructure to enable robust connections between the generation and consumption of hydrogen. Hydrogen infrastructure is presently used to support many applications such as fuel cell transportation (like forklifts, cars, buses, and trucks), stationary power (e.g., baseload distributed heat and power, peak shaving, and backup power), and industrial processes (e.g., ammonia, petroleum refining, and paper processing). To meet these needs, the United States produces approximately 10 million metric tons of hydrogen a year [2]. For the purpose of this paper, the focus is on a key and growing subset of the H2@Scale vision hydrogen stations for light-duty passenger fuel cell electric vehicles (FCEVs).

An FCEV has many of the same consumer-preference attributes (fast fueling time, range, mass, and size) as today's conventionally fueled vehicles. The infrastructure necessary to supply hydrogen to the FCEV provides production and delivery to the station (or production at the station), storage, compression, and dispensing. These systems are collectively referred to as a hydrogen station for the purposes of this paper. Hydrogen stations must have many of the same consumer-preference attributes as conventional (gasoline) fueling stations (e.g., location, 24/7 operation, and accessibility). Technically, the goal of a station is to safely transfer hydrogen fuel into a vehicle's storage system while meeting time, pressure, and temperature requirements. These activities must be performed with high reliability, while minimizing maintenance costs.

The numbers of hydrogen stations are growing as their importance in supporting public FCEV fleets increases. There are currently 35 retail hydrogen stations operational in California, the region with the highest U.S. deployment of hydrogen stations and FCEVs [3]. More than 6,000 FCEVs, which have been bought or leased through automobile dealers, are on US roads. Hyundai, Toyota, and Honda all offer FCEVs for purchase and/or lease [4]. In their early demonstration stages (prior to 2015) most hydrogen stations were private stations, not for retail, and had restrictions on users, training, and hours of operation. There were fewer than 10 U.S. retail hydrogen stations prior to 2016 [5], and in less than 2 years the number of retail hydrogen stations has climbed to more than 40[1]. The majority of stations have hydrogen delivered to the station, and fewer than 5 have on-site hydrogen production. In California alone, the number of hydrogen stations is expected to exceed 60 within 2 years [6]. The California Fuel Cell Partnership released a vision for 1,000 hydrogen stations supporting 1,000,000 FCEVs in California by 2030 [7]. This vision addresses near-term deployment strategies that are focused on coverage and high-density urban areas, then moving towards a self-sustained market for hydrogen stations and FCEVs. In a report reviewing deployment options for the Northeast US [8], 50 hydrogen stations are projected to be operational in the region by 2022. Another future deployment study considered two scenarios for hydrogen station deployment [9]. One scenario with only limited FCEV adoption in populated urban areas and the second scenario with widespread FCEV adoption across the U.S. The urban area analysis, used to understand requirements and not to project FCEV deployment, suggests a need for 105 stations in 2020 and over 700 stations in 2030 dispensing approximately 300 kg/day and 550 kg/day respectively.

In order to safely dispense hydrogen to a FCEV, a hydrogen station typically has those major subsystems identified in Figure 1 [10]. The hydrogen source identifies where the hydrogen comes from for the station. For example, delivered hydrogen (either gas or liquid) is produced away from the station and brought to the station via truck or pipeline. The source, along with how the hydrogen will be dispensed and estimated capacity, determines the size and type of station storage. Dispensed hydrogen gas is compressed by the compression subsystem to either 35 MPa or 70 MPa, depending on the vehicle type. Hydrogen station dispensing pressure was increased to 70 MPa from 35 MPa for light-duty vehicles around 2009 [11], and fueling protocols [12] for this higher pressure were developed at that time. The 70 MPa fueling protocol require a hydrogen dispensing temperature of -40 ^{o}C to enable safe and fast fueling without overheat the on-board vehicle storage tank(s). The chiller subsystem performs fuel cooling immediately before dispensing to the vehicle. The user interface, and station-to-vehicle interface are typically contained within the dispenser subsystem. An overall management subsystem and safety subsystem interface with all aspects of the station equipment and control.

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[1] Refer to the Alternative Fuels Data Center (afdc.energy.org) for the latest station count (and planned stations) as the number of stations changes frequently

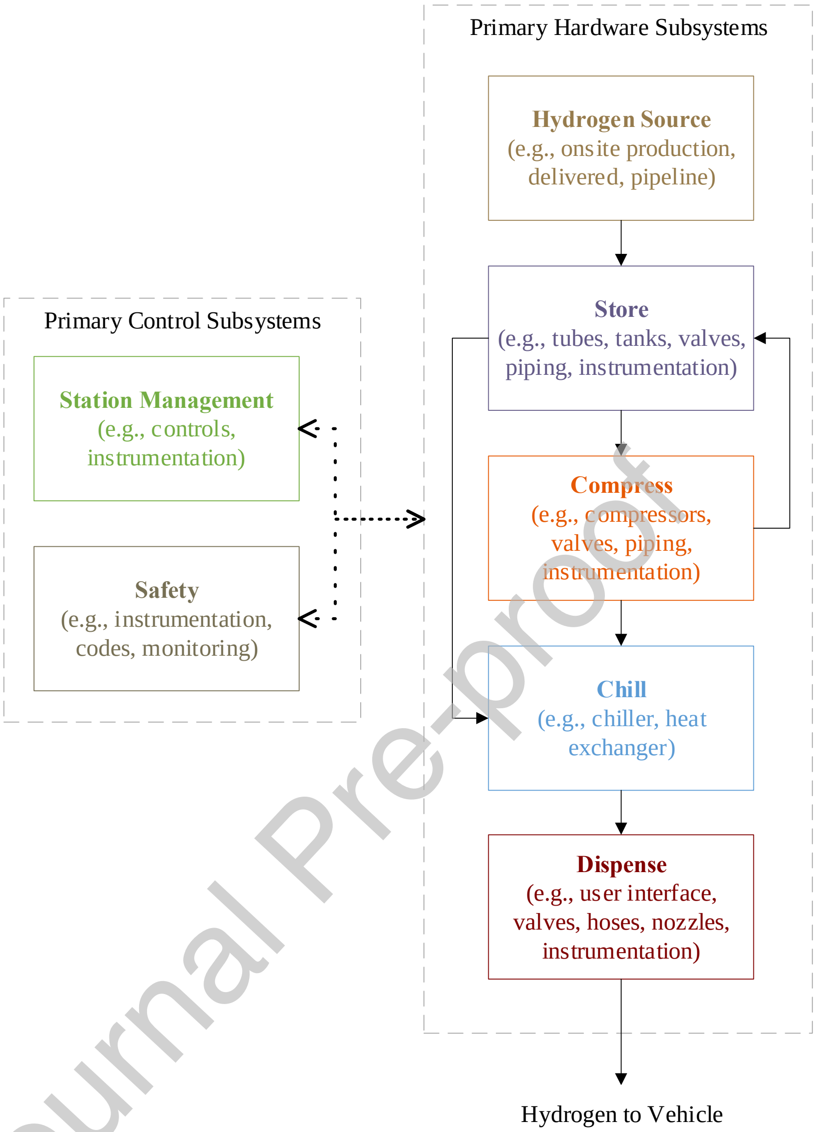


Figure 1. Generic hydrogen station block diagram (color code corresponds to subsystems in Figure 2)

With over 6,000 FCEVs on the road, the demand for hydrogen is high enough that some current stations have a high utilization percentage [13]. Projections [6], [14], [15], [16], [17] indicate that the number of FCEVs is expected to continue to increase with more and bigger hydrogen stations needed to fuel the FCEVs as well as trucks and buses [18], [19]. One anecdotal concern for FCEV drivers, as detailed in a consumer survey [20], is hydrogen station availability, which is directly connected with station reliability. Therefore, this work aims to answer three research questions.

- Is hydrogen station reliability an issue?
- What are the leading causes of hydrogen station failures?
- How can hydrogen station reliability be improved, if needed?

In order to answer these questions, we perform an analysis of hydrogen station maintenance data, and a reliability growth analysis using field data from hydrogen stations and an understanding of the hydrogen fueling market.

This paper is organized as follows. The overview of the data and reliability analysis methods is covered in Section 2. The reliability of current hydrogen stations is provided in Section 3. Section 4 reviews on-going research into the failures of hydrogen dispenser components that can improve hydrogen station reliability with conclusions covered in Section 5. This work is novel in that it uses a consistent reliability analysis method to provide a status of hydrogen station reliability as a benchmark to track progress and needed improvements. This research originates from a unique dataset of multiple hydrogen stations operating under real-world conditions. This work also connects the current reliability status, where dispensers are the leading subsystem requiring maintenance, with dispenser component failure research that is expected to improve station reliability.

2 Datasets and Analysis Methods

2.1 NFCTEC Datasets and Methods

Researchers at NREL’s National Fuel Cell Technology Evaluation Center (NFCTEC), supported by DOE’s Fuel Cell Technologies Office, have studied the operation, maintenance, and safety of hydrogen stations and FCEVs for nearly 15 years [5], [11], [21]. In order to understand the current status and gaps for hydrogen station reliability, this study mines the NFCTEC datasets that are communicated from the hydrogen stations and their operators. The NFCTEC collects hydrogen infrastructure data from more than 10 project partners to a centralized site. Project partners report operation, performance, maintenance, station cost, and safety data for fuel cell system(s) and infrastructure. This data is received at least quarterly and is then processed, stored, analyzed, and aggregated. An internal analysis of all available data is completed quarterly and a set of technical composite data products (CDPs) is published every 6–12 months.

To inform stakeholders, data-driven results are uploaded to NREL’s technology validation website [21] and presented at industry-relevant conferences. The CDPs present aggregated analysis results across multiple systems, sites, and teams in order to protect proprietary data and summarize the performance of hundreds of fuel cell systems and thousands of data records. A review cycle is completed with the data partners before the CDPs are published. This review cycle includes providing detailed data products of individual system- and site-performance results to the specific data provider. Detailed data products also identify the individual contribution to the CDPs. Analyses are created for general performance studies as well as for application- or technology-specific studies. By working closely with the data providers, the quality and validity of the dataset can be continuously assessed and improved.

The hydrogen station operators report to NFCTEC using data templates (the maintenance data template is shown in Table 1). All of the NFCTEC maintenance and reliaiblity analyses use data from the maintenance template, which includes one row entry for each maintenance event. The date, component, subsystem, action, cause, effect, downtime, category, labor time, and costs are recorded and reported. For this study, we use both the NFCTEC maintenance log from each station, and the NFCTEC log of hydrogen filling events data that includes fill date/time and fill amount. Both of these data sources are available for every station. The data is analyzed and aggregated to benchmark station performance and maintenance events and to inform research needs to improve the reliability of hydrogen station subsystems and components.

Table 1. Sample NFCTEC maintenance data template

Maintenance Template	*Example Entry*
Site	Station A
Date of Repair/Replacement	10/5/16
Component Name	Dispenser Nozzle
Subsystem	Dispenser
Component	Nozzle
Action	Replace
Cause	Material Fatigue
Effect	Functionality Lost
Station Unavailable (hours)	8
If still available, station performance affected (hours)	0

The NFCTEC maintenance data is then parsed into categories of maintenance data and reliability data. The maintenance data focus on maintenance categories and aggregated statistics, such as percentage of maintenance events that were unscheduled. Tracking of hydrogen leaks is included in the maintenance dataset because it has proven relevant to investigations into hydrogen leak frequency and quantitative risk assessment tools such as the Hydrogen Risk Assessment Model [22]. The reliability data focuses on characterizing maintenance and failure events as a function time, including metrics such as mean fills between failures. The fill event data includes over 183,000 fills from 29 stations with over 4,600 maintenance events from 2015 to 2017.

2.2 Reliability Analysis Methods

This study presents a reliability analysis based first on an analysis and categorization of the types of failure modes and maintenance events that were recorded in the NFCTEC datasets. Each type of failure and maintenance event is allocated to a subsystem, cause, effect, operation mode, and more. These analysis results are presented to communicate the types of failures that these hydrogen stations encounter, their frequencies and subsystems that are particularly failure prone.

The second set of results use the Crow-AMSAA reliability growth model [23], [24], [25] to more quantitatively understand the dynamics of hydrogen station system failure. Although other methods of analysis were considered (e.g., Weibull [26], [27], [28], [29], failure modes and effects [30], physics of failure, and fault tree analyses), for a few reasons, the fundamental Crow-AMSAA model was found to be most effective and applicable for analysis of the NFCTEC dataset. First, the NFCTEC data can be characterized as dirty data in that it is not specifically controlled for reliability analysis and it may be incomplete with mixed failure modes. Second, this analysis considers each hydrogen station to be a repairable/maintainable system [31], so that the Crow-AMSAA modeling can be used to track reliability growth and predict failure modes and forecasting of future failures. Finally, the Crow-AMSAA model can also be used to evaluate the success of a reliability improvement plan by studying the rate of failures before and after improvements.

The instantaneous failure rate Crow-AMSAA equation is:

$$\rho(t) \tag{1}$$

where $\rho(t)$ is the rate of occurrence, λ is the scale parameter, β is the shape parameter, and t is the aging parameter (often time but it may be fills or dispensed hydrogen amount for candidate hydrogen station reliability models). A shape parameter that is greater than one indicates an increasing failure rate and less than one indicates a decreasing failure rate. This instantaneous failure rate is the first derivative of cumulative events:

$$n(t) \tag{2}$$

where $n(t)$ is the cumulative failure events. The reciprocal of the instantaneous failure rate is the mean time between failure (MTBF):

$$\frac{}{\rho(t)} \tag{3}$$

This type of Crow-AMSAA model is applied to each station, subsystem, and key components for all available NFCTEC datasets.

3 Current Status of Hydrogen Station Reliability

Results of the categorization of each of the failures and maintenance events in the NFCTEC dataset is presented in this section. No differentiation among the stations is made for these results.

3.1 Analysis of Hydrogen Station Maintenance Data

Each of the hydrogen station maintenance events are allocated to categories (allocation to systems, subsystems, etc.), and maintenance types (scheduled or unscheduled). The analyzed maintenance data through 2017 included 4,663 maintenance events, 69% of which were unscheduled. Maintenance events for the major station subsystem and component categories (dispenser, compressor, and chiller) account for 78% of the events (Figure 2). A miscellaneous category captures 14% of the maintenance events and includes subsystems such as feedwater, electrolyzer, thermal management, storage, safety, gas management, air, electrical, and other. The events are categorized based on the station operator-supplied categories and are aggregated among all the stations providing data.

The results of this categorization are shown in Figure 2. The largest fraction (46%) of maintenance events (planned and unplanned) and maintenance hours are associated with the dispenser subsystem. This subsystem includes various components that have relatively high rates of failure including the flexible hoses, dispensing valves, and user interfaces. On the other hand, unclassified station events make up a disproportionate fraction of the maintenance hours, and therefore maintenance costs. Several failures (~930) were recorded as allocated to the station as a whole identified as “Station System”, which are primarily scheduled maintenance events like preventative maintenance, and upgrades. The “Station System” or “Entire” category is for any feature or detail that station operators and technicians categorize as encompassing multiple subsystems such as overall station controls and interfaces. There is also large number of maintenance hours allocated to this system’s repair in the “Station Other Subsystems” category. This is representative of maintenance events that may require more time to identify and fix. The “station other” category represents general station electrical, gas management, storage, on-site production, and thermal management systems which can be high hour maintenance events. This breakdown of events and maintenance hours provides a benchmark to inform hydrogen station stakeholders of the leading maintenance categories.

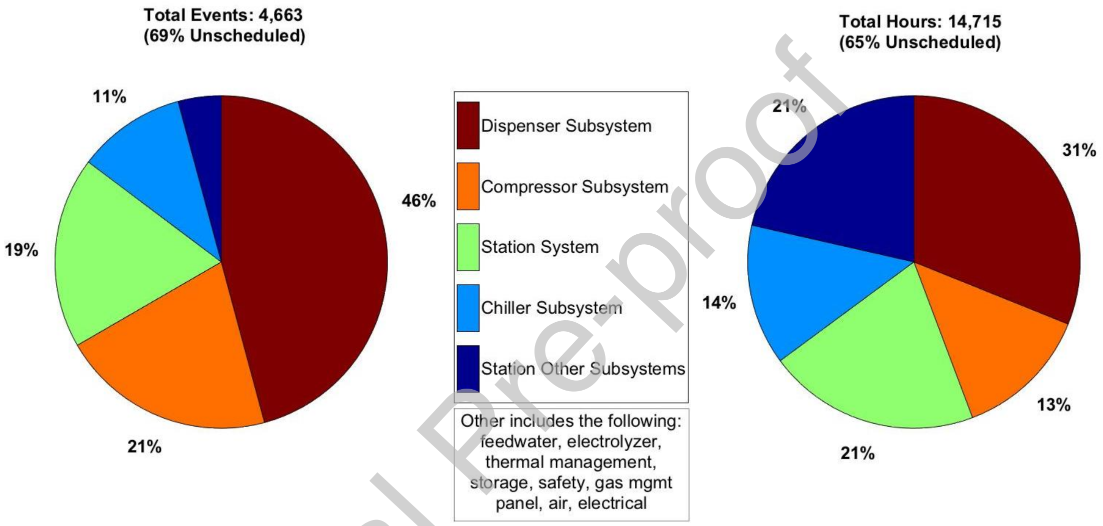


Figure 2. Maintenance events and maintenance hours by equipment type for NFCTEC retail stations

Expanding on the results of this benchmark, we studied unscheduled maintenance events associated with particular failure modes, as shown in Figure 3. In the case of the dispenser subsystem, the failure modes can be categorized as either communication-related, undetermined, miscellaneous, or scheduled. Of the recorded dispenser maintenance events, 18% are scheduled maintenance and more than 75% are the undetermined/miscellaneous failure mode, indicating that many of the failure modes are failures, leading to unplanned maintenance. As comparison, the compressor subsystem has significantly less frequent maintenance events than the dispenser category does, but it has a high fraction of undetermined or miscellaneous (i.e. unplanned) maintenance events.

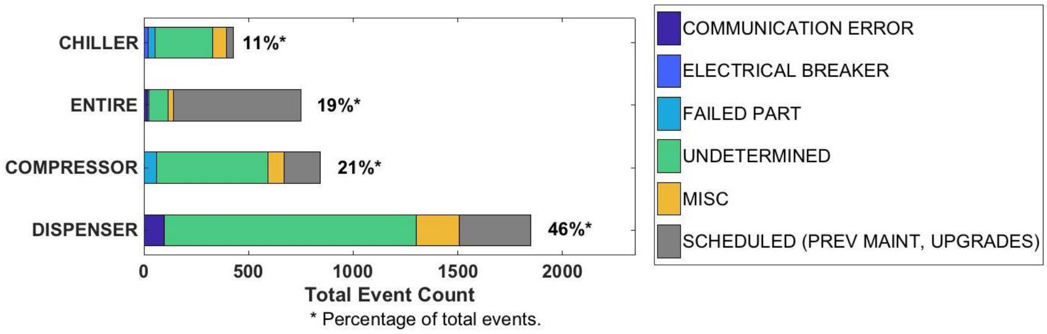


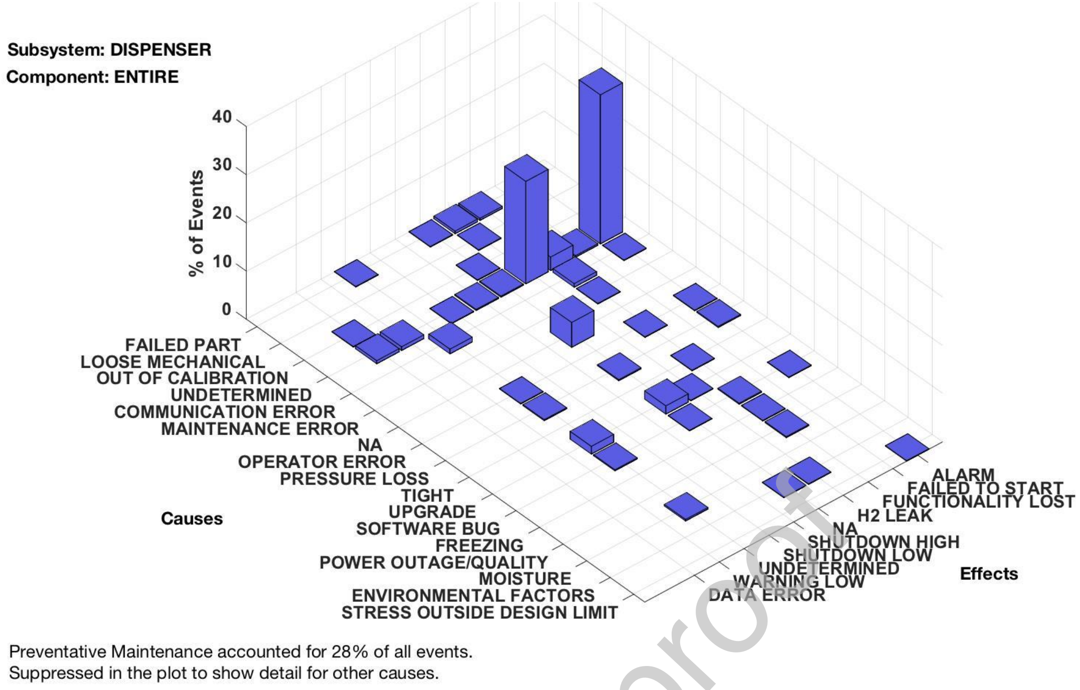
Figure 3. Failure modes for four key maintenance categories

As a final means to gain insight into the maintenance of hydrogen stations, we studied correlations among maintenance cause and effects. For this example, we consider the hydrogen dispenser subsystem and dispenser nozzle. For each maintenance event, the station operator, or maintenance technician, completes the data template and the data is categorized, aggregated, and reported through NFCTEC. The NFCTEC researchers interpret the narrative that is input to the database to categorize the types of causes and effects, and to allocate them to components and subsystems.

Figure 4, presents the data subset where maintenance was performed on the dispenser subsystem and the failed component is classified as “entire”, which means that either a dispenser component was not identified and entered, or the maintenance events were for the entire dispenser subsystem. As illustrated in Figure 4, the majority of causes were categorized as “undetermined”, and the majority of effects were categorized as either “undetermined”, “hydrogen leaks”, and “alarms”. This example illustrates that when considering maintenance logs for complicated components (such as the entire dispenser subsystem), the probability of having failures for which the root component cause is not known can be high.

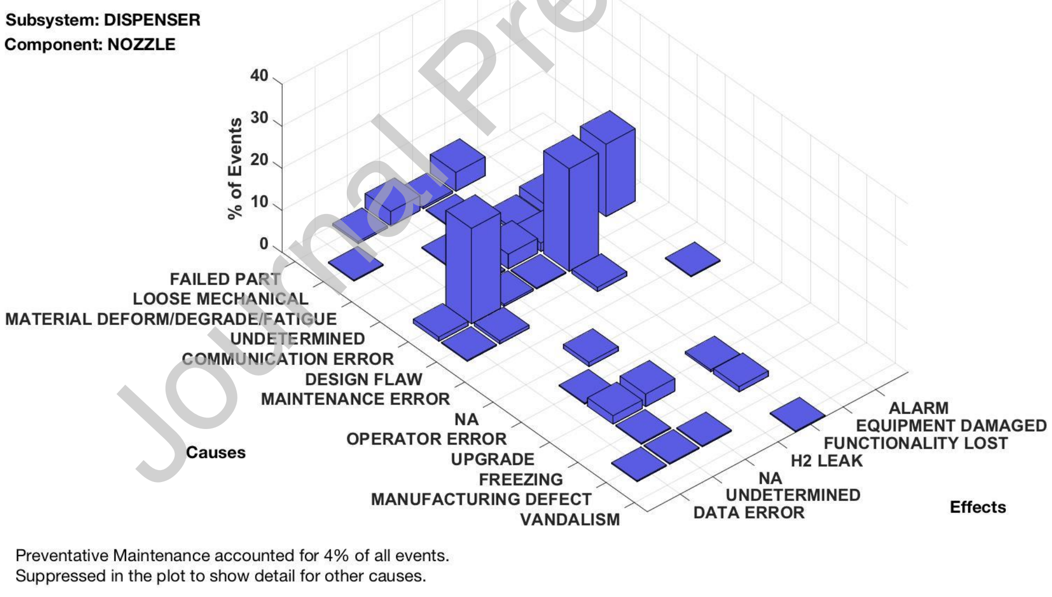
In Figure 5, we consider the dispenser nozzle (a subset of the dispenser subsystem) as the subsystem. As illustrated in Figure 5, although undetermined failure effects due to undetermined failure causes was still a large fraction of the maintenance events, this system is small or simple enough that the technician is more easily able to determine and record failure causes and effects. For dispenser nozzles, failures that are root caused by part failures, communication errors, and design flaws are significant sources of unplanned maintenance events.

These examples illustrate that additional data, analysis, and experiments are often needed at subsystem and component level because the undetermined or miscellaneous failure mode is so common when failures are described at system level. In the case when many of the maintenance events are categorized as undetermined, further investigation is needed to evaluate why undetermined was selected. If the cause of failure is unknown and of high priority, root cause analysis should be completed.



Preventative Maintenance accounted for 28% of all events.
Suppressed in the plot to show detail for other causes.

Figure 4. Dispenser maintenance cause and effects—entire



Preventative Maintenance accounted for 4% of all events.
Suppressed in the plot to show detail for other causes.

Figure 5. Dispenser maintenance cause and effect—nozzle

3.2 Hydrogen Station Reliability

The unscheduled maintenance event data can be used to quantify station reliability. This section presents the failure rates and reliability growth by fills and by station for 29 stations. For this analysis, the aging variable, *t*, is fill count. Fill count was chosen instead of time or kilograms because fill count represents the operating conditions (i.e., cycle count, pressure change, and temperature change) for a station. A time-based aging equation may be more characteristic of station age in a phase with higher demand and station technology maturity.

Using fill count as the aging parameter for station reliability, the reliability results as a function of fills are presented in Figure 6. Figure 6 shows the mean fills between failure (MFBF) for the 29 stations by station cumulative fill count. All stations except for one have an MFBF of approximately 500 or less. To provide context with calendar time, the average monthly fill count was just under 600 fills at the end of 2017. Figure 6 also provides insight into the distribution of total fill counts relative to the stations; there are a few high-fill-count stations, but most are grouped on the first half of the x-axis. (Note the x-axis tick numbers were intentionally left off this graph.) An unscheduled maintenance visit every month is not adequate to meet retail customers' expectations, as an unscheduled maintenance event may indicate the station is unavailable for fueling. This implies that station reliability is a major problem for current hydrogen stations, yet it does not provide insight into whether failure rates are changing over time.

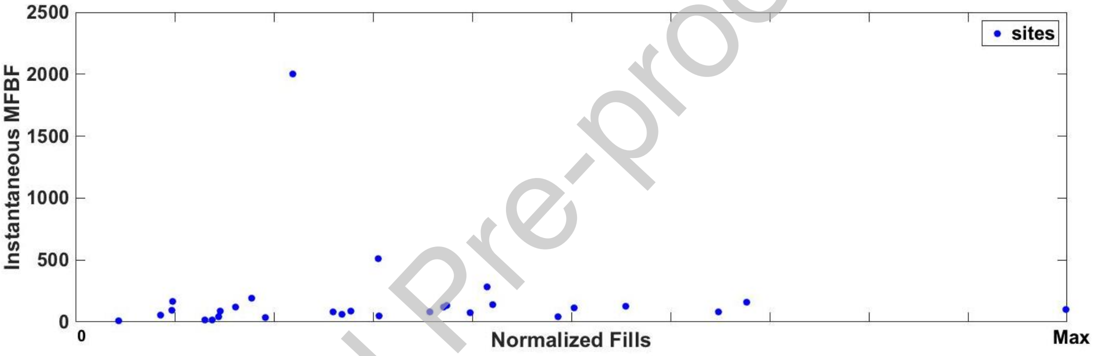


Figure 6. Station mean fills between failure by cumulative fills

Figure 7 illustrates the instantaneous station failure rate at various stages of station life. The station on the far left is the station with the lowest fill count and the station on the far right is the station with the highest fill count. (This sorting may not directly correlate with how long a station has been operational.) Three metrics are shown for each station: the shape parameter for the early failure event history, entire failure event history, and latest 20% of failure events. The shape parameter (which describes whether the failure rate is increasing, decreasing, or steady) for all failure data per station is shown in the blue bar. Out of 29 stations, 24 stations have seen a decrease in failure rate, meaning that the number of fills between failures is increasing as the station operates. The early history shape parameter is shown by the red star markers, 15 stations had a shape parameter of greater than 1 meaning that their failure rate was increasing early in their operation lifetime. The early history and last 20% of events (yellow) bar are specified in the figure because reliability growth and the instantaneous failure rate (Equation 1) can vary significantly over the aging parameter. For instance, station #7 has a shape parameter value of approximately half its initial value. The instantaneous failure rate improved for 20 stations in the last 20% of failures per station, while the four stations with the highest total fill count (stations #26–29) saw an increase in failure rate.

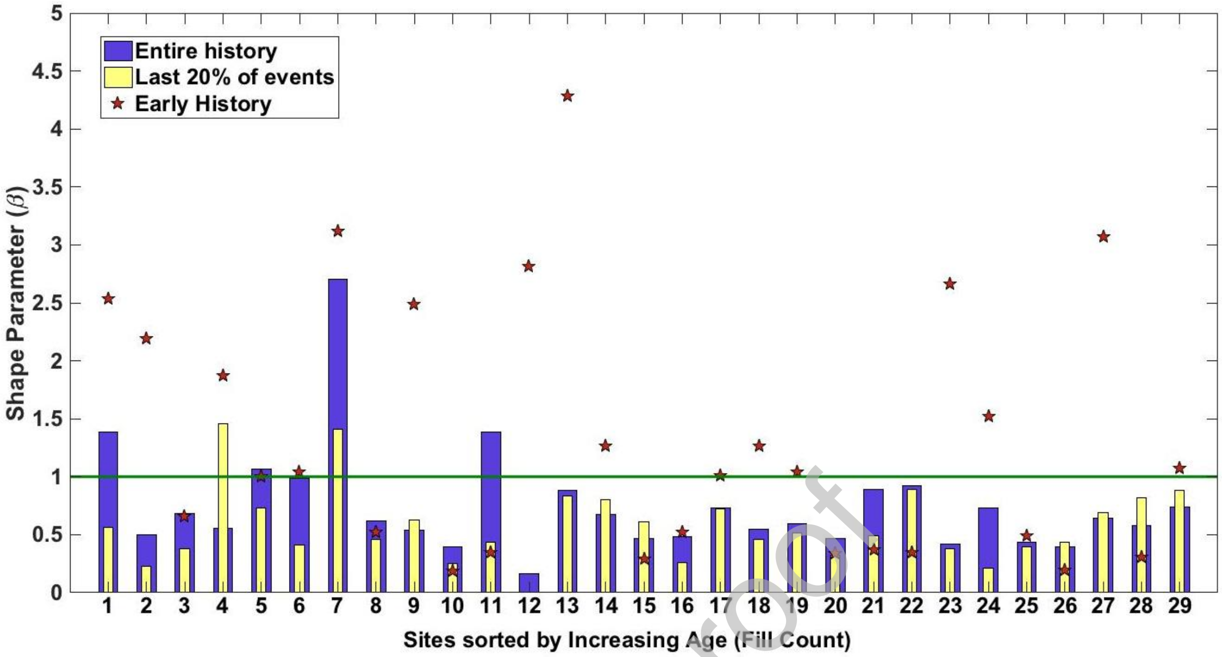


Figure 7. Retail station reliability growth

Comparing station failure rates can be a challenge because the stations are at different operation phases (such as a newly commissioned station), utilization, technology generations, and dispensing capabilities. All station and historical failure rate data were plotted to study how the data fits the trend of a reliability bathtub curve (Figure 8). Individual station operation data like fill count and early (identified by the star) and current failure (identified by the yellow bar) history are shown with various features in Figure 8. Each failure event and accompanying fill count is plotted for all the stations, shown in the blue dot. The x- and y-axes have been limited because only a small percentage of the data exceeds a failure rate of 0.4 and fill count greater than 10. The green line represents a least-squares fit of the scatter data, with a similarity to the left side of the bathtub curve, with the following equation:

$$\rho(t) = 1.3 * 0.62 * Fill^{0.62-1} \tag{4}$$

The heel of the curve is approximately around 1,000 fills, where the MFBF is 17 (the inverse of $\rho(t)$). This is an indication that failures seen today are likely either early or random failures. Fatigue or gaining failures are not in evidence in this dataset yet. One significant caveat is that this is for all stations and all failures.

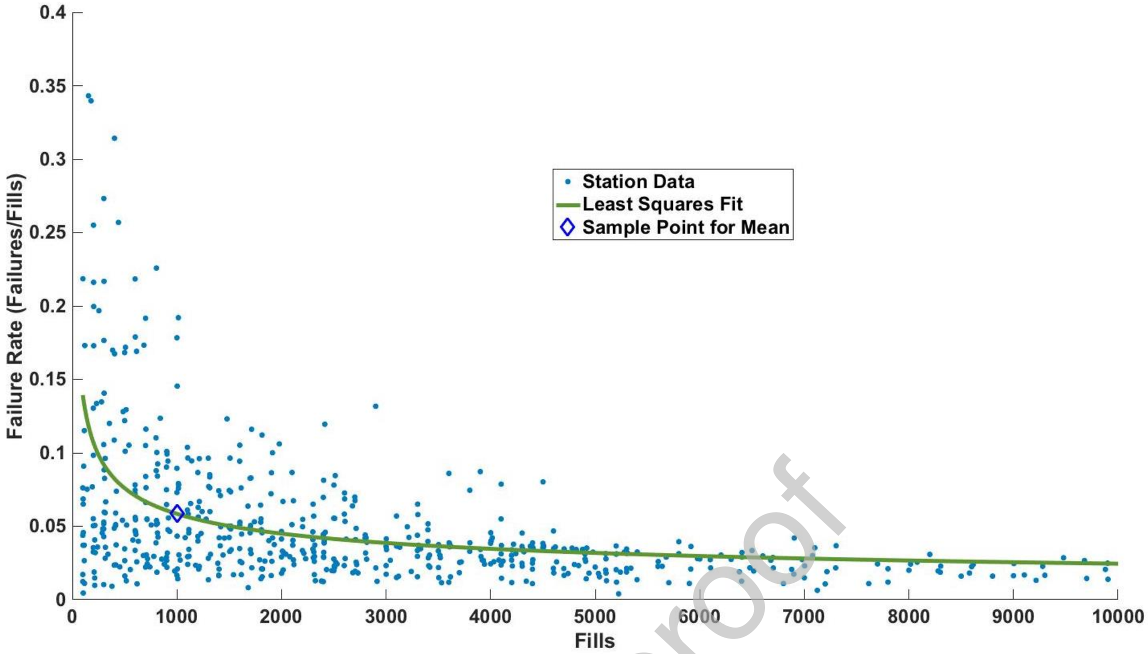


Figure 8. Historical failure rate by fills for retail hydrogen stations

The hydrogen station reliability growth analysis shows that:

- Failure rates are decreasing: most stations have a decreasing rate of failure, which demonstrates positive progress by station operators and equipment suppliers.
- Reliability of most stations has improved compared to their early operation history: about 30% of stations had frequent failures early in the operating period yet approximately 65% of the stations (including all of the stations with an increasing failure rate in the early history) have decreased the rate of failure compared to the early history.
- High fill count may lead to potential failures: the oldest four stations have an increasing failure rate for the last 20% of events, which may indicate failures due to a higher cycle count.
- Failure rates are still too high to achieve mass market acceptance: even with most stations having a decreasing failure rate.

One assumption made in this hydrogen station reliability study is that the reliability has to be as good as a traditional gasoline station. Anecdotally there is a gasoline station available when a driver stops to fill but there is limited public information on gasoline station reliability. One study of 41 gas stations and 577 dispensers aimed to decreased frequency of corrective maintenance by optimizing preventative maintenance activities [32]. In this study, three categories were created for high, medium, and low failure stations. The medium failure station category (17 stations and 248 dispensers) had a failure rate of 0.001935 failure/hour/dispenser, which is a mean time between corrective maintenance (MTBCM) activities of 516 hours or 21.5 days. The low failure station category (17 stations and 196 dispensers) had a MTBCM activities of 820 hours or 34 days.

In order to correlate this gasoline MTBCM data with the hydrogen station data, it is necessary to look at the frequency of fills against calendar time. The latest data shows an average of approximately 1,000 fills per month for the studied stations [13]. Station MFBF, shown in Figure 6, shows that the majority of hydrogen stations in this dataset have a MFBF of less than 500, which can be translated to approximately 15 days. This is less than the MTBCM of the medium failure gasoline station category, however this is not to say that this comparison is done with similar data or method so future study could be completed to benchmark hydrogen station reliability against gasoline station or another alternative fueling infrastructure. One additional challenge to meeting the same reliability as a gasoline station is there are significantly fewer hydrogen dispensers than gasoline dispensers. When one hydrogen dispenser is unavailable, it is more likely that there would be a significant impact on the FCEV drivers who may have to drive to another station for hydrogen than for gasoline vehicle drivers. This can be especially problematic as the demand for hydrogen stations increases.

The amount of hydrogen dispensed in 2017 was 4 times what was dispensed in 2016, and at the end of 2017, two stations had a utilization of greater than 80% (based on a daily capacity). These two details indicate that hydrogen demand is changing rapidly, and this has an impact on station maintenance and reliability. For instance, maintenance cost per kilogram is decreasing (Figure 9). This decreasing trend is primarily due to an increase in the amount of hydrogen dispensed. The demand for hydrogen is expected to increase, along with demand for additional hydrogen stations [33]. There are few other inferences from maintenance cost data in that some maintenance is becoming routine and doesn't require in-depth failure investigation or advanced training. The cost of some replacement parts may also be decreasing with more online stations and bulk purchases [34].

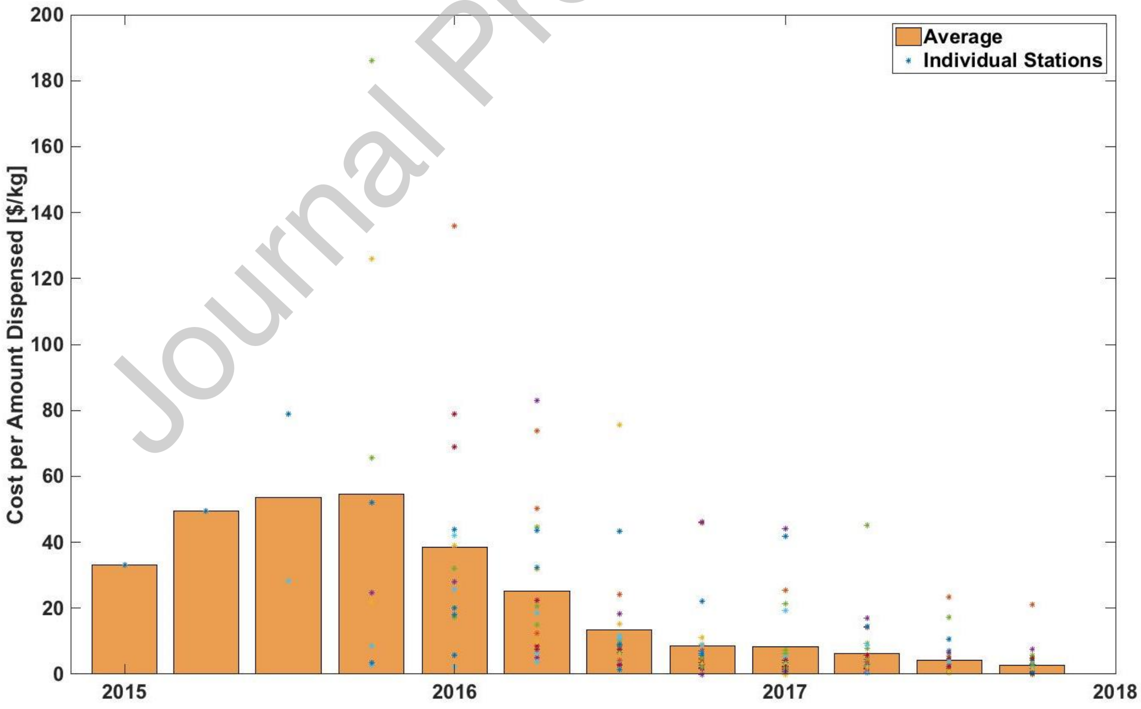


Figure 9. Maintenance cost per kg dispensed over time

4 Using Maintenance Data to Improve Hydrogen Station Reliability

Much of the reliability growth analysis presented here has been focused on commonalities and straightforward reviews of station maintenance, which includes both preventative maintenance and unscheduled maintenance due to failures and alarms. One gap in the data for this analysis is that the condition of components at failure is not known, nor is the reason for failure. Condition and cause of failure identification is needed for corrective action that will improve station reliability. This section covers on-going research for dispensers, a subsystem with the highest count of unscheduled maintenance events (46%) of all stations analyzed.

This in-progress research aims to supply data component condition at failure from laboratory-controlled experiments. Controlled failure condition data like this will help researchers and operators answer questions about how differently a component fails based on the field operating conditions. These additional scientific findings combined with the maintenance and reliability benchmarking completed so far provide researchers and operators valuable information about early failures that are due to new stations coming on line, how experience gathered during station operation and maintenance can improve reliability, and how station failures change as a station ages in both cumulative fill counts and time.

4.1 Failure Condition Data Experiments

Recurring failures, especially those which are experienced at high utilization, are ideal failures to focus on for additional research. In the past, the compressor system was the leading maintenance category, but compressor research and development has contributed to an improved compressor system MFBF. For example, NREL researchers studied compressor reliability and provided data on physics of failure of compressor seals. This research identified metal fragments as a major contributor to seal failure. Also, lubricants used on elastomer seals were found downstream of compressor systems, which identified a need to use hydrogen-compatible lubricants [35]. In addition, the project showed that seal failures are the main driver for compressor downtime, that typical failures take more than 2 hours to repair with multiple people, and that downtime can be avoided with real-time monitoring of the compressor leak detection circuit [36].

Based on the leading category for unscheduled maintenance frequency being dispensers, NREL has a set of active controlled experiments on dispenser subsystem reliability. During a fill, the dispenser system components experience a rapid change in both pressure (ambient to 70 MPa) and temperature (ambient to -40°C). These rapid pressure and temperature changes are thought to be a primary contributor to dispenser component failures. Benchmark data along with hardware experiments to improve dispenser reliability provide performance data back to manufacturers on how their components perform under controlled, retail-like conditions, with particular attention given to operating conditions that should generate valuable failure data. Extreme operating conditions and the external interfaces, which include both the driver and the vehicle, make for an interesting and challenging dispenser system and a top priority for reliable and safe operation.

Therefore, NREL's hydrogen dispenser reliability research is focused on critical dispenser components. The hose reliability project is an ongoing effort at NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF). The project utilizes a six-axis robot to mimic the mechanical bending and twisting of a person fueling their vehicle. The system performs a fill like what would be experienced in the field. Current results, from over 5,000 fill cycles, show that leaks tend to happen at the metal crimp-to-hose connection [37]. This project was initiated during a period of low station utilization and was first focused on completing a high fill count. With this data as a baseline for accelerated hose reliability, additional features are planned that include additional hose stresses such as varying interface angles and other thermal and mechanical conditions.

Benchmark data from the field lacks the design of experiments that are best able to identify failure conditions and causes. Another active NREL research project is the dispenser reliability project [38], which measures the mean fills and kilograms dispensed between failures of hydrogen components subjected to pressures, ramp rates, and flow rates similar to light-duty FCEV fueling. The project is exploring three different required cooling levels, at -40°C, -20°C, and 0°C, with -40°C being the current standard for light-duty vehicle fueling. The experiment (Figure 12) consists of flowing hydrogen through eight "dispenser like" systems simultaneously. The flow rates and ramp rates are in the range of a typical SAE J2601 fill. The components are ramped at ~17.5 MPa/min at a flow rate of ~0.5 kg/min through each component. The systems are packaged with two dispenser sets in series and four sets in parallel to complete the full system. The flow rate, ramp rate, and gas temperature are controlled on the front end with a research dispenser. The back end has a flow controller as well as a recycle loop to accelerate system recovery time at NREL's HITRF.

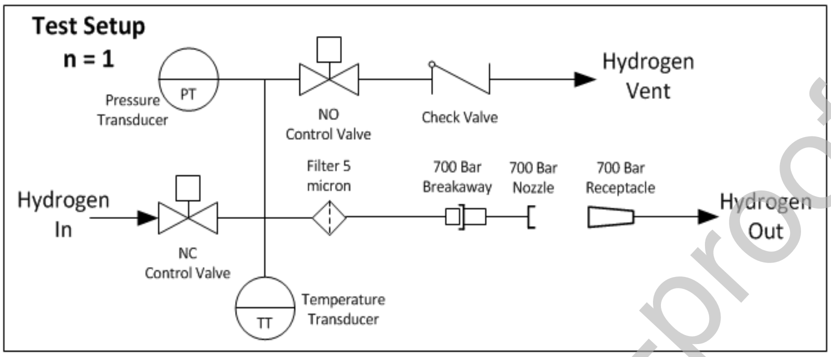


Figure 10. Overview of a dispenser reliability test setup

4.2 Data to Drive Failure Investigation and Reliability Improvement Efforts

Reliability improvement efforts are most effective when the improvements are informed by data, both from real-world operation and controlled reliability experiments. The retail hydrogen station maintenance data studied to date has many instances of undetermined failure modes. The combination of a lack of failure condition data with the maintenance benchmarking is guiding NREL's hardware research. More specifically, it is guiding what systems and operating conditions are studied. A basic objective of this research is to provide controlled data that can accurately and consistently identify failure conditions. Data from these experiments is expected to guide failure analysis only on the highest-priority components, which should generate meaningful feedback to equipment manufacturers for product improvements. This is a methodical process, driven by both field and lab data, to identify failures and improvements with more complicated and expensive diagnostic studies and instrumentation. For example, results from the dispenser reliability project will inform experimental setup and test plans based on the highest-frequency component failures and the accompanying conditions that generated failures. The future experiments will dissect the components to identify failure root cause with various mechanical, thermal, and humidity stresses and material investigations.

5 Conclusions

Hydrogen stations play a critical role in the supply of hydrogen to fuel cell technologies like cars, trucks, and buses. This specific reliability growth analysis sets out to answer three research questions.

The first question was whether hydrogen station reliability was sufficient to enable a commercial fueling market. An exponential increase in hydrogen demand in California has pushed stations to be able to reliably dispense hydrogen whenever the FCEV driver pulls up to the station. Yet the station reliability is lower than what the customers expect, as identified by the results presented here, and when compared with traditional gasoline station reliability. There are some concessions that can be made in this comparison because gasoline and hydrogen stations are at different commercialization phases and data processing may not have been similar between the gasoline and hydrogen station analyses. The maintenance benchmarking results presented here by category, frequency, labor time, and failure cause/effect create a trackable status of station maintenance and reliability. The benchmarking for station maintenance has identified the two leading maintenance categories as dispensers and compressors, which represent 67% of the retail station maintenance events. Crow-AMSAA was the analysis method of maintenance data from hydrogen stations, where the majority of hydrogen stations have a MFBF of less than 500 fills, which can roughly translate to every 15 days. This is lower than the MTBCM of 21.5 days for the medium failure gasoline station group.

The second research question was what are the leading causes for failures in the hydrogen station. This question is not as easily answered as the failure root cause investigations are on-going. On-going research specific to dispensers, a leading maintenance category, expects to show the impacts of cycle count and temperature on failure rates in a controlled lab environment, which will inform the next phase in the failure investigation.

Lastly, this work aimed to identify reliability improvement options. Results to date show improvements in MFBF and changes in the leading maintenance category as a function of time. There have been target component reliability improvements, for example with compressors, and lessons learned from the initial station deployments that make some failures only a one-time event. A couple of years ago, compressors were the leading maintenance category, but compressors have improved with updated technologies, preventative maintenance strategies, control strategies, new designs, and increased station utilization. A reliability improvement program is expected to also include changes in components and operation that is informed from laboratory findings to reduce failures.

Hydrogen station reliability has improved with time, yet it is still not meeting the same reliability for the incumbent, gasoline stations. This work has provided an independent and consistent study of the current hydrogen station reliability for multiple stations and operators, and it is informing root cause failure research needed to improve the station reliability. Future work is expected to answer the second and third research questions while continuing to study hydrogen station reliability from field data to monitor progress of reliability improvements and to discover future challenges.

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Graphical Abstract