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Demonstration of Advanced Fueling Method for Achieving Full Fills in Natural Gas Vehicles

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division manages the Natural Gas Research and Development program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater natural gas reliability, lowers costs, and increases safety for Californians and focuses in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Demonstration of Advanced Fueling Method for Achieving Full Fills is the final report for the Advanced Fueling Method to Achieve Full Fill for Natural Gas Vehicles project (PIR-14-013) conducted by Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The natural gas vehicle industry struggles with safely and accurately achieving a full fill in a natural gas vehicle when using compressed natural gas dispensers. The technical challenges involved when filling an onboard storage tank with compressed natural gas can result in underfilling, or the inability to use 100 percent of the maximum tank capacity. Major fleets and industry experts cite underfilling of about 20 to 25 percent using current dispenser technology. Underfilling directly affects the operational cost and range of natural gas vehicles. Consistently achieving full fills also improves safety with compressed natural gas fueling by reducing the chances for overfilling and lowers costs by reducing the volume of storage needed onboard the vehicle. The causes preventing current natural gas vehicles from receiving a full fill include 1) inaccuracies in determining when a vehicle has reached a full fill condition, 2) uncertainty about the gas composition, and 3) heat generated when the gas is compressed.

This California Energy Commission project led by the Gas Technology Institute addresses these issues by developing an advanced full-fill algorithm and investigating various gas precooling technologies. The algorithm leverages communication between the vehicle and dispenser to measure the real-time temperature and pressure on the vehicle and then uses that information while considering variations in gas composition to deliver a full fill safely and accurately. The investigation of precooling technologies provides insight into viable methods for removing energy from the compressed natural gas before fueling to counteract heat of compression, and guarantee a full fill at higher ambient temperatures. Recommended precooling technologies include chillers and the development of a suitable expander design for enabling full fills.

Keywords: Full fill, compressed natural gas, CNG, natural gas vehicle, NGV, dispenser, temperature compensation, pre-cooling, dispenser communication, expander

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EXECUTIVE SUMMARY

Introduction

For more than 30 years, California has been committed to policies to reduce greenhouse gas emissions and other air pollutants associated with the production and use of energy. In 2006, the state enacted the California Global Warming Solutions Act (Assembly Bill 32, Núñez, Chapter 488, Statues of 2006) to reduce statewide greenhouse gas emissions to 1990 levels by 2020. Ten years later, Senate Bill 32 (Pavley, Chapter 249, Statutes of 2016) established a statewide goal to reduce greenhouse gas emissions 40 percent below 1990 levels by 2030. In 2018, Governor Edmund G. Brown, Jr. issued Executive Order B-55-18 to set a statewide goal to achieve carbon neutrality by 2045 and negative greenhouse gas emissions afterward.

Transportation is the largest source of greenhouse gas emissions in California, accounting for about 40 percent of statewide emissions in 2016. One strategy to reduce emissions in the transportation sector is using natural gas as a transportation fuel, which has demonstrated benefits to California ratepayers that include greenhouse gas and air pollutant emission reductions. When combined with renewable natural gas, natural gas vehicles (NGVs) provide a cost-effective pathway for immediately displacing petroleum, cutting greenhouse gas emissions, and reducing air pollution caused by the heavy-duty transportation sector. While the economics of NGVs are already favorable for applications such as buses, concrete mixers, and waste fleets, technical barriers such as vehicle range and cost of ownership are preventing broader adoption.

A major technical challenge that the natural gas vehicle industry continues to struggle with when using a "fast-fill" dispenser is safely and accurately achieving a “full fill” in an NGV. The NGV industry defines a full fill as a vehicle filled with natural gas at 3,600 pounds per square inch of pressure and 70° Fahrenheit. As medium- and heavy-duty NGVs become more commonplace for regional and long-haul applications, the NGV industry must make improvements in accurately achieving complete and safe full fills with large vehicle on-board storage volumes.

This project directly addresses vehicle range and the incremental cost of the high-pressure cylinders used to store compressed natural gas (CNG) onboard NGVs. These high-pressure cylinders are the most expensive components, directly contributing to the increased incremental capital cost of NGVs compared to diesel vehicles. To compensate for difficulties with fully using the actual volume of their fuel systems, NGVs typically have oversized fuel systems at additional cost and weight penalties to meet operating range requirements. Fully using the high-pressure storage of an NGV by consistently achieving full fills will result in weight and cost reductions or range improvements.

The research explored technical barriers that prevent full fills, as well as some short-term and long-term solutions. The barriers include uncertainty about the temperature and gas compositions of the vehicle, and the heat generated when compressing the gas during fueling that causes the vehicle cylinder to reach the pressure limit before it is full. Short-term solutions with low incremental cost compared to the current state-of-the-art include the use of vehicle-to-dispenser communications and an improved filling algorithm to maximize the fuel transferred to the vehicle using existing CNG station equipment. The long-term solutions that may require additional technology advancement include development of cost-effective gas cooling equipment that can overcome heat of compression, enabling full fills regardless of ambient temperature.

Project Purpose

While the actual amount an NGV is underfilled depends on a variety of factors, 20-25 percent is frequently cited as the deficit by major fleets and industry experts. This figure is further supported by the fact that commercial fuel systems are designed to be 30 percent larger than the estimated usable fuel capacity quoted by the manufacturer, which includes 20-25 percent caused by underfilling and 5-10 percent stranded gas, which is the remaining low-pressure gas in the tank that cannot be used by the engine. On many heavy-duty CNG vehicles, adding 30 percent extra storage can easily result in the difference between needing three or four storage cylinders to reach the required range of the vehicle. If underfilling can be eliminated, manufacturers can eliminate the need for a fourth cylinder to reduce the weight and cost of the fuel storage system by 25 percent.

While underfilling and low-pressure stranded gas reduce the usable fuel system capacity, manufacturers are already developing solutions for using the stranded gas that include novel regulators and engine controls. The regulators reduce the full flow pressure drop from vehicle storage to the engine, and the controls reduce the engine power to allow a truck to make it to the next fueling station when running on fuel. However, preventing underfilling has seen little improvement because the solution requires changes to vehicles and dispensers, as well as cost-effective precooling at the CNG station. This project explored these barriers, seeking to develop and demonstrate short-term solutions where possible or make recommendations about long-term solutions to achieve consistent full fills.

The research team presents these project results to a broad audience of stakeholders interested in learning about and solving the issue of underfilling. By making the information widely available, the team hopes that some of the recommended changes can be adopted by the NGV industry, leading to improved performance and lower costs for these vehicles. Adoption of some or all of the technologies and solutions presented in this report should help increase the adoption of NGVs in California, resulting in lower costs and reduced emissions from heavy-duty vehicles, directly benefiting ratepayers who are affected by the use of heavy-duty diesel trucks.

Project Approach

Gas Technology Institute (GTI) worked and consulted with industry stakeholders that included commercial CNG station and fuel system manufacturers to ensure an accurate assessment of the barriers preventing full fills, as well as the viability of proposed solutions. The project started with an assessment of existing CNG stations and vehicles to validate the extent of underfilling with current technology and determine the variables that prevented existing NGVs from getting a full fill. GTI used its existing CNG station and dispensers from two manufacturers to conduct the underfilling validation. Both dispensers consistently underfilled the target cylinder from various starting conditions, demonstrating that full fills are indeed an issue faced by the NGV industry.

After evaluating the fuel-filling barriers facing the NGV industry, GTI developed a dynamic simulation tool using real gas properties to evaluate the performance of CNG stations and dispenser algorithms across the full range of operating conditions and evaluate the effect of various improvements made to the station. GTI identified the CNG dispenser algorithm that determines when a vehicle is full as a fundamental barrier preventing full fills. There may be little to no improvement seen with other solutions if the dispenser cannot accurately determine how full the vehicle is at any time. Therefore, a major component of the project involved using the dynamic simulation to evaluate, compare, and improve various dispenser algorithms.

GTI validated the dynamic simulation by testing real-world fills using GTI's CNG station. GTI conducted tests on a range of CNG cylinder types and sizes, including a commercial fuel system used for heavy-duty natural gas trucks.

The technical advisory committee (TAC) consisted of industry experts and stakeholders from ANGI Energy Systems, Agility Fuel Solutions, and Southern California Gas Company (SoCalGas). The TAC advised the project about CNG full-fill barriers and provided recommendations about the feasibility of proposed solutions. The TAC supported economic analysis of various solutions, which was validated using quotes from manufacturers.

Project Results

GTI developed and evaluated a number of filling algorithms using a simulation of a fast-fill CNG station. None of the algorithms could perfectly achieve full fills because of limitations described in detail in the report, but this work resulted in the development and verification of a preferred algorithm that represents a significant improvement over the state of the art. The preferred algorithm uses pressure and temperature targets to define a full fill, and makes adjustments based on measured temperature onboard the vehicle. The preferred algorithm can fill an NGV to within a few percentage points of full capacity across a wide range of filling conditions and gas compositions. In addition, the preferred algorithm can eliminate the possibility of overfilling, which occurred with every other test algorithm. The preferred algorithm is expected to be relatively easy to implement in new and existing CNG stations; it requires only a minor code modification in the dispenser, properly located temperature sensors on the vehicle, and the addition of a low-cost wireless transmitter in the dispenser and on the vehicle. The total material cost for the retrofit is expected to be well under $100 per dispenser and vehicle. These changes would provide immediate benefits to NGV users.

While the preferred algorithm provides greater success in achieving full fills compared to the state of the art, it does not completely solve the issue of underfilling. Precooling is required to counteract heat of compression and guarantee a full fill, especially at higher ambient temperatures. GTI evaluated various precooling technologies for the associated ability to provide sufficient cooling to achieve a full fill at reasonable costs. Of the various technologies, chillers are the best near-term solutions because of the associated commercial availability and active use for compressed hydrogen stations. However, the development of a highly efficient expander may provide a more attractive long-term solution because of the high potential cooling effectiveness and low operating costs.

Technology and Knowledge Transfer

Sharing Of Knowledge

The first step in disseminating the knowledge gained from this project includes publishing the findings with the California Energy Commission (CEC) in publicly accessible reports. These reports will detail the technologies that were studied, as well as the test results.

Utilities are a critical stakeholder group for natural gas vehicles, so there is an emphasis on transferring information to them. As a member of the TAC and cofunder of this project, SoCalGas staff participated in project discussions and stayed informed on key findings. SoCalGas is a leader in sponsoring natural gas vehicle research and development. Furthermore, the gas utility excels at the outreach and marketing of new technologies to its customers and its broader connections to end-user natural gas vehicle fleets. GTI is sharing technology details with SoCalGas to leverage its capabilities in disseminating knowledge across the NGV industry.

GTI worked closely with many industry suppliers and equipment providers throughout the project duration to ensure the commercial viability of—and interest in—the developed technology. While no commercial agreements are in place, stakeholders have continued to express interest in further developing the technology and continuing to demonstrate the benefits across a range of operating conditions.

Another important avenue for disseminating the knowledge learned during this project is through presentations to industry at conferences, workshops, and forums. The Natural Gas Vehicle Technology Forum and the Alternative Clean Transportation Expo is an example of the type of event used to share this information with interested stakeholders. GTI has already presented some of the recommendations and results to industry members at these types of events in past years and plans to continue providing updates in the future.

Lastly, GTI is working with the Canadian Standards Association (CSA) Group to develop codes and standards for areas such as vehicle and dispenser communications and the filling algorithm. A task force approved by CSA Group is taking a closer look at the required standards and ways the solutions developed in this project might fit into the existing landscape.

Intended Uses

Suppliers of dispensing equipment and vehicle fuel systems will need to be involved in the commercialization of the communications and sensing hardware, as well as the improved algorithm for achieving full fills. At this time, the preferred approach is to make the design standardized for use across the industry. To accomplish this goal, GTI is working with CSA Group to develop standards and language describing the use and application of the technology to improve full fills across all vehicle segments.

Published Documents

To date, there have been no published journal of periodical articles that were based on project research. The project team will notify the CEC when articles are published. The team will also provide copies of any such documents, fact sheets, journal articles, press releases, and other documents prepared for public dissemination, when they become available.

Policy Development/Public Requests

GTI has presented a high-level overview of the work done in this project to CSA Group to consider development of standards surrounding communications methods between vehicles and dispensers, as well as possibly standardizing the algorithm to be used with communications. CSA Group hired GTI to write a guiding document discussing challenges with temperature compensation and full fills. This guiding document will be the start of a new standard that will cover safe full fills and dispensing algorithms, and may lead to additional standards for communications. The project team will notify the CEC if standards related to this project are published.

Benefits to California

This project has the potential to improve CNG fueling, vehicle cost, and system efficiency dramatically for fleets that are most critical to the rapid adoption of NGVs. Providing consistent, full-capacity fueling of NGVs will improve the satisfaction of fleet users and could help increase adoption for fleets that are sensitive to range. The regional and long-haul trucking industries are particularly challenging markets to serve because they have demanding range specifications, more than 600 miles a day. Some fleets have experienced disappointing trials with CNG trucks due to the poor fueling performance of current dispensing systems.

This project has significant potential benefits, even with a conservative estimate that full-fill improvements could result in an additional 1 percent of the regional and long-haul market transitioning to CNG from diesel. One percent adoption in California would displace about 27 million gallons of diesel and reduce annual greenhouse gas emissions by 120,000 tons of carbon dioxide equivalent. This level of adoption is possible considering full fills can reduce the incremental cost of heavy-duty NGVs by as much as 25 percent. The reduced cost and weight of the CNG fuel system significantly reduces the financial risk and payback period of NGVs, increasing the likelihood that more fleets will adopt natural gas over diesel.

CHAPTER 1:
Vehicle Characterization

Natural gas is attractive as a vehicle fuel because it produces less carbon dioxide and fewer criteria pollutants such as nitrogen oxides than gasoline or diesel vehicles. In addition, compressed natural gas has relatively low adoption and fuel costs, making it attractive to medium- and heavy-duty vehicles and fleets interested in minimizing vehicle and fuel costs while maintaining the ability to haul large loads over long distances. However, natural gas at standard conditions has a low energy density, so it must be compressed to pressures as high as 3,600 pounds per square inch gauge (psig)[1], and stored in high-pressure cylinders onboard vehicles. Natural gas is compressed and stored at CNG fueling stations which control and measure the transfer of CNG to the vehicle using a dispenser. The following section describes the operation and challenges facing modern dispensers.

Current State of the Art

CNG dispensers are designed to look and operate similarly to traditional gasoline or diesel fuel dispensers. They process payment information, control the dispensing of fuel from multiple storage banks, accurately measure the amount of fuel dispensed, and ensure that the vehicle is filled as full as possible without exceeding the pressure or volume limits of the tanks. Dispensers control the fueling process and serve as the primary customer interface with a CNG station, making them a critical variable in the customer satisfaction with that station and with using CNG as an alternative fuel. However, one common customer complaint is under-filling, or having less than 3,600 psig at 70°F. This affects the range, cost, and customer experience when using CNG.

Accurately filling a vehicle using a gaseous fuel is considerably more challenging than when using a liquid fuel. Liquid fuel dispensers have sensors and meters that accurately quantify the fuel dispensed, with a relatively simple mechanical switch in the nozzle to determine when a full fill is achieved. When the liquid level in the tank is high, it covers a hole or slot at the end of the liquid fuel nozzle, causing a mechanical switch to shut off the flow of fuel. This mechanical trigger allows any size fuel container to be filled to 100 percent using the same dispensing nozzle because the vehicle is always full when the sensing port becomes submerged.

On the other hand, a CNG full fill, according to NGV 4.1 [7], is defined as a pressure (3,600 psig) at a specific temperature (70°F). There are several challenges with this approach. First, the vehicle cylinder is never at a steady 70°F due to variations in vehicle operating conditions and ambient temperature. It might be close if it is 70°F

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1 Psig is a pressure measurement relative to the atmospheric pressure of the Earth.

outside, but a cylinder on a truck sitting in the sun can easily be hotter than the surrounding air, and a cylinder on a truck getting off the highway can easily be colder since the pressure is steadily dropping in the tank as fuel is consumed. Therefore, predicting the starting temperature of the tank without direct measurement can result in significant error. Second, adding gas to a cylinder will cause the temperature of the tank to change throughout the filling process due to a combination of Joule-Thomson cooling, heat of compression, and transfer of heat to the tank wall. Accounting for this change in temperature, referred to as temperature compensation, affects the target fill pressure required to get a full fill. The changes in temperature and pressure are governed by the real gas law shown in Equation 1.

$$PV=ZnRT \qquad \text{(Equation 1)}$$

P is the pressure in the CNG tank. V is the actual volume of the CNG tank. Z is the compressibility factor of the actual gas composition in the tank (Z=1 for ideal gases). n is the number of moles in the tank. R is the gas constant. T is the absolute temperature of the gas in the tank. Using the real gas law, it is apparent that at a target pressure (3,600 psig) and temperature (70°F), there is a fixed number of moles that equal a full fill. As the temperature in the tank changes, the target pressure that defines a full fill also changes.

This highlights one of the most fundamental limitations of existing dispensers: the inability to measure the temperature of the CNG cylinder. Modern dispensers do not actually measure any of the variables in Equation 1 except for an indirect measurement of pressure, which is measured at the dispenser, upstream of multiple fittings and check valves. The measurements that most dispensers make are ambient temperature, gas pressure in the dispenser, mass flow rate of the gas flowing through the dispenser, and occasionally the temperature of the gas in the dispenser. Using this data, modern CNG dispensers must estimate when the vehicle is full based on indirect measurements of gas conditions within the cylinder, which results in high uncertainty, unlike the accuracy of the liquid level switch used in gasoline and diesel.

To address the challenge of filling a gaseous fuel vehicle, the CNG industry has used multiple approaches over the years. One of the early approaches used mechanical temperature compensation in the form of dome load regulators that used a reference gas to adjust the regulator set point depending on the ambient temperature. Dome load regulators faced challenges such as leaks in the reference gas chamber and the inability to compensate for heat of compression, which varies depending on how full the vehicle is at the start of a fill.

Today, most dispensers use electronic control systems that adjust the stopping pressure based on proprietary algorithms developed by commercial dispenser manufacturers. The simplest control algorithm is similar to a dome load regulator in that it compensates for the ambient temperature only, and does not account for gas composition or heat of compression. These systems are frequently used in time fill applications where many vehicles are simultaneously filled from a single compressor over a long period of time. More advanced versions of these algorithms compensate for the ambient temperature, but will then adjust for heat of compression using an additional multiplier. This empirically derived multiplier is highly proprietary, making it difficult to determine the precise accuracy, or safety, of a dispensing system. The accuracy of the multiplier also changes with variations in natural gas composition.

The last known method predicts the volume of the vehicle's tank using a series of short, controlled fills, and then fills the tank to a predefined mass density using the estimated volume and mass measured by a mass flow meter.

None of the above techniques can fully define all the variables necessary, making it impossible to guarantee a 100 percent full fill without ever exceeding the pressure and volume limits of the storage tank. This leads to conservative filling, or under filling, which is apparent from the test data of actual dispensers from reputable manufacturers shown in Table 1. GTI conducted five fill tests using various starting conditions to verify and quantify the extent of under-filling experienced with current technology. The initial conditions measured included the pressure vessel's starting pressure and temperature in two locations, as well as the ambient temperature. GTI filled the vessels with the dispensers until the filling stopped. The test vessel used was a 10 gasoline gallon equivalent (GGE) type 2 cylinder, and the tests were conducted when the station's cascade system was full to eliminate gas supply as a variable.

The end-of-fill measurements were recorded shortly after the fill was completed, and included the tank pressure and two temperature measurements. After the fill, the tank was moved to a location where the temperature and pressure could settle, and measured again when the internal temperature reached ~ 70°F. Lastly, the fill percentage was quantified using the measured gas composition (used to determine Z) and Equation 1 to determine the settled mass density and compared to the mass density of that gas composition at 3,600 psig and 70°F.

The resulting under filling ranged from 7.5 percent to 15.7 percent. These results show better fill performance than empirical industry data that indicates 20 to 25 percent under filling. However, every fill ended below the dispenser's pressure limit of about 4,250 psig, indicating that there is room for improvement since additional gas could have been added.

Table 1: Dispenser Full Fill Testing

Date	IC Tamb	IC TE 1	IC TE 2	IC P	SC Tamb	SC TE 1	SC TE 2	SC P	GGE Disp.	End of Fill TE 1	End of Fill TE 2	End of Fill P	% Full Rated D	% Full Set-tled D	% Full
10/14/15	62	78.6	80.3	423	55.5	64.3	63.7	2797	7.568	125.1	122.2	3510	13.015	10.969	84.3
10/15/15	56.5	56.3	56.1	1158	57	66.6	68.6	2913	5.281	108.1	205.3	3520	13.015	11.221	86.2
10/16015	50.9	62.3	63.4	2210	79.6	85.3	83.8	3434.4	2.429	101	103.8	3740	13.015	12.04	92.5
10/20/15	67.5	69.7	69.8	180.3	62.7	68	67.2	2955.5	8.176	124	121	3750	13.015	11.338	87.1
10/21/15	64.9	63.8	63.2	2133	68	68.9	69.8	3051	2.31	101	98.7	3530	13.015	11.547	88.7

Source: Gas Technology Institute

Critical Vessel Specifications and Characterization

The real gas law defined in Equation 1 is the equation of state that defines the relationship between state variables, or fully defines the gas density under a set of measured conditions. In other words, every variable in the equation must be known to guarantee a full fill 100 percent of the time. These variables and current characterization techniques are described in detail below.

- Pressure: A pressure transducer measures the static and flowing gas pressure within the dispenser, which is then used to estimate the vehicle's actual tank pressure. The accuracy of the pressure transducer, length and size of the refueling hose, resistance of the inline check valves, and design of the vehicle refueling system all affect the pressure measurement. Pressure is frequently measured directly onboard the vehicle for estimating remaining vehicle range, but this information is rarely communicated to a station dispenser.
- Volume: The actual volume of a vehicle's storage system, including tanks, tubing, and fittings, is needed to accurately determine whether a vehicle is full. The volume is a relatively fixed value, but it can change if cylinder valves are closed or if a cylinder is removed or replaced. The volume is not used in most modern filling algorithms, with the notable exception of mass based algorithms that target a specific mass density to determine the total amount of mass that should be dispensed. Most dispensers cannot measure the volume directly, making it necessary for complex filling procedures to be used to estimate the volume of a tank. These filling procedures usually involve a series of small fills, or "huff-steps", that are followed by a measurement of the new tank pressure. A complex polynomial is then used to predict the volume based on the starting pressure, temperature, and predicted rise of each as gas is added. The main problem with this technique is uncertainty about the starting temperature and composition of the gas onboard the vehicle.
- Compressibility: Compressibility is the temperature, pressure, and composition dependent ratio of real gas to ideal gas state points (a measure of the deviation from ideal behavior). The compressibility of a gas cannot be directly measured, making it difficult to guarantee a full fill without knowing the temperature, pressure, and composition of the gas in the vehicle's cylinder.
- Moles: This is the number of moles of gas in the vehicle's tank. The number of moles cannot be directly measured, but can be calculated using the mass and molecular weight of the gas. Mass is currently measured using a Coriolis mass flow meter located in the dispenser. Molecular weight is not currently measured, but new sensors are currently being developed that can measure molecular weight using a proprietary measurement technique.
- Ideal Gas Constant: 8.3144598 J/(mol-K)

- Temperature: This is the temperature of the gas in the vehicle's tank. State of the art dispensers measure the ambient temperature, but do not have any way of directly measuring the vehicle's tank temperature. The tank temperature is generally assumed to be near ambient; however, this value could have significant error depending on location and driving conditions prior to filling. Cars parked in a heated garage during a winter day would have a warm cylinder, which would result in an overestimate of the amount of gas in the vehicle at the start of a fill. Alternatively, a vehicle driving down the highway could have a cylinder significantly colder than ambient due to isentropic cooling as the pressure in the cylinder drops due to fuel consumption. In that case, the dispenser would underestimate the amount of gas in the cylinder, potentially leading to overfilling. Like pressure, temperature sensors are often installed on vehicles to help estimate the remaining range; however, this measurement is rarely communicated to a station. Some recent exceptions to this are fleets using the temperature and pressure to estimate fuel consumption of each vehicle.

The information above shows the challenge of accurately filling a vehicle that runs on a high pressure gaseous fuel, particularly one that does not have a predictable composition such as natural gas.

Additional Factors Impacting Full Fills

In addition to the variables described above that directly impact the measurement and quantification of a full fill in a vehicle's cylinder, many additional factors can limit the ability for a vehicle to achieve a full fill. These factors include instrumentation accuracy, station construction, and the thermodynamic limitations of the filling process.

Instrumentation error can affect the performance of a station, as well as the fullness of a fill. For example, error in a temperature sensor or pressure transducer will directly impact the fill that is received because the error will impact the filling algorithm directly. High quality instrumentation, regular calibration, and redundancy can help control instrumentation error. Limitations of the measurement accuracy of various components can also lead to errors. For example, mass flow meters must accurately measure the total fuel dispensed within the limitations of National Institute of Standards and Technology (NIST), Handbook 40, Examination Procedure Outline No. 28 [8], which specifies a measured dispenser accuracy within 1.5 percent of the actual fuel dispensed. Coriolis meters can maintain a high accuracy over a wide range of flow conditions; however, 4 pounds/minute (109 kilograms/hour) is listed as the minimum flow required to maintain 0.5 percent batch accuracy of a fill on a commonly used flow meter. Below this limit, the dispenser should shut off, or risk inaccurate measurement. This flow rate is determined by the pressure differential and flow coefficient of the station and vehicle's gas tubing. Depending on the design, there could be several hundred psi of pressure drop between the station storage vessels and the vehicle's storage tank. This pressure drop and flow limit can reduce the amount of fuel the station can physically dispense onto the vehicle before the minimum flow limit is reached.

Flow limitation touches on some of the limits imposed by equipment, but station design can also have a large effect on full fills. A large pressure drop in the station or vehicle plumbing can greatly reduce the amount of fuel that can be dispensed to the vehicle. The solution to this problem is proper design of the fueling station, dispenser, and vehicle to minimize total pressure drop. Some station and dispenser manufacturers have recognized this limitation, and are now opting to install larger diameter tubing for a given station size to minimize the effect of flow restrictions on the quality of the fill. In addition to the pressure drop, station compressors are generally designed to turn on once the station storage has been depleted below a certain level. The fullness of the station storage, determined by the compressor controls and station traffic, can also substantially influence the quality of a full fill, and is compounded by the pressure drop in the station tubing. Lastly, dispensers are required to have pressure relief valves that release at 1.25 times the rated delivery pressure, or at 4,500 psig on a 3,600 psig dispensing system. This requirement is a safety feature designed to protect the vehicle's fuel system from an accidental overpressure event should a dispenser fail. While this is an excellent design practice, it reduces the pressure that can be delivered by the dispenser to about 4,250 psig. This reduced pressure is used to reduce the risk of the relief valve opening since the set point can drift over time. This limit, like the others discussed, reduces the maximum delivered pressure to the vehicle and the chance the vehicle can get a full fill.

In addition to station hardware and instrumentation, the fill process can also be limited by the thermodynamics of a fill. During filling, the gas in the vehicle typically heats up to the point where it is much warmer than the ambient air. This increase in temperature increases the pressure required to reach a gas density that will settle to 3,600 psig at 70°F. This effect can significantly impact the fullness of a fill as the dispenser's pressure limit is reached before the tank is actually full. The impact of this heating is shown in Table 2 below for two different gas mixtures. The pressure of each gas mixture is shown at various settled temperatures assuming each has a fixed density that would result in a full fill (3,600 psig at 70°F). If the density is kept constant and the tank is heated or cooled, then the measured pressure will rise or fall accordingly. Table 2 shows that the dispenser pressure limit of 4250 psi is reached or exceeded at 110°F. The GTI test data shown in Table 1 indicates that the tank temperature can exceed 110°F during a fill, even on a relatively cool day where the ambient temperature is about 60°F. The only solution to this issue is some sort of pre-cooling to ensure the tank temperature stays cold enough to achieve a full fill before the station pressure or flow limits are reached.

Table 2: Pressure Rise with Temperature of a Fixed Density Gas

Methane Temperature (F)	Methane Pressure (psia)	Methane Density (G/cc)	Ekofisk Temperature (F)	Ekofisk Pressure (psia)	Ekofisk Density (G/cc)
130	4549.16	0.1914	130	4739.24	0.2383
120	4391.46	0.1914	120	4549.74	0.2383
110	4233.55	0.1914	110	4360.05	0.2383
100	4075.44	0.1914	100	4170.21	0.2383
90	3917.14	0.1914	90	3980.23	0.2383
80	3758.65	0.1914	80	3790.15	0.2383
70	3600.00	0.1914	70	3600.00	0.2383
60	3441.19	0.1914	60	3409.83	0.2383
50	3282.25	0.1914	50	3219.70	0.2383
40	3123.19	0.1914	40	3029.66	0.2383
30	2964.04	0.1914	30	2839.78	0.2383
20	2804.83	0.1914	20	2650.14	0.2383
10	2645.58	0.1914	10	2460.84	0.2383
0	2486.58	0.1914	0	2271.99	0.2383
-10	2327.17	0.1914	-10	2083.74	0.2383
-20	2168.10	0.1914	-20	1896.25	0.2383
-30	2009.19	0.1914	-30	1709.74	0.2383
-40	1850.53	0.1914	-40	1524.52	0.2383

Left: Methane from REFPROP, Right: Ekofisk from REFPROP

Source: Gas Technology Institute

The second major takeaway from Table 2 is the significant difference in pressure rise and fall with temperature of the two mixtures. The two mixtures both have a relatively high methane content, but impurities can extensively affect the way the gas mixture behaves at various temperatures and pressures. Impurities can also cause potential over-pressurization if pressure and temperature targets are used for filling without knowledge of gas composition. For example, a dispenser that might use methane temperature compensation values to fill on a cold day could actually have something similar to Ekofisk (Table 3) delivered in the supply. If the dispenser filled the cylinder up to 2,486 psi at 0°F, then drove into a 70°F garage, the cylinder would be over-pressurized. Pressure might not rise above the 4,500 psi limit for the vessel, but it would certainly be higher than 3,600 psi. This example is an extreme case, but highlights the risk of filling to a target pressure without knowing the exact temperature in the vehicle's tank, or the composition of the gas.

Table 3: Ekofisk Composition

Ekofisk Components	Mole Fraction
Methane	0.85906
Nitrogen	0.010068
Carbon Dioxide	0.014954
Ethane	0.084919
Propane	0.023015
Isobutane	.003486
Butane	.003506
Isopentane	.000509
Pentane	.00048

Source: NIST Standard Reference Database 23, Version 9.1

Overall, many station design considerations need to be made to maximize vehicle fills. Using cheaper tubing and measurement equipment may seem attractive during station construction, but could have a significant impact on the cost of vehicles that will require larger fuel storage systems to compensate for the lack of full fills. The industry does seem to recognize these issues, and is starting to design stations using better construction practices to maximize fills; however, additional work needs to be done to solve problems related to gas conditioning and dispensing algorithms.

Recommendations

Developing a way to guarantee a full fill for natural gas vehicles could substantially improve a driver's experience, while also reducing the required volume and weight of fuel systems used on heavy-duty vehicles. This reduction would reduce the cost and payback of the vehicle, while increasing the net payload capacity, which is often the most valuable metric for the fleet. However, guaranteeing a full fill is extremely challenging, requiring good station and vehicle design in addition to improvements to the dispenser algorithm to get a full fill most of the time. Even then, a full fill on hot days requires some sort of gas conditioning to guarantee the maximum mass allowed by the code is delivered to the vehicle.

The physical design of stations, dispensers, and vehicle storage systems has constantly been improving, enabling fuller fills as the pressure drop from station to vehicle is reduced. These improvements generally involve using larger diameter components to reduce the pressure drop through the system, and should be relatively inexpensive when compared to the total cost of the vehicle or station. However, these improvements are not a complete solution, and will not correct under filling caused by inaccurate dispensers or high ambient temperatures.

Accurate dispensing of fuel is necessary for achieving safe, full-fills, regardless of other influencing factors. As discussed above, the indirect measurement of pressure and ambient temperature used by state of the art dispensers is not sufficient to guarantee a full-fill. Additional information about the vehicle's storage cylinder and gas composition are required to safely fill the vehicle 100 percent of the time. This will likely require the addition of some form of vehicle-to-dispenser communication enabling the dispenser to more accurately calculate how much fuel can be delivered. Several fleets already incorporate communication protocols in the form of telematics that can report the vehicle pressure and temperature every time it arrives or leaves the fleet's property. The pressure and temperature are being used to estimate the fuel consumption of each truck, but could also be adapted to communicate pressure, temperature, and storage volume to the station dispenser. Knowing information about the state of the gas onboard the NGV should greatly improve the accuracy of fills, but would still be subject to variability related to gas composition. Measuring gas composition on the vehicle would be very challenging, though it may be possible to measure it at the station to help improve the accuracy of the fill. With this information, it should be possible to maximize a fill every time a vehicle connects to a dispenser, reducing the variability and error of some modern dispensers.

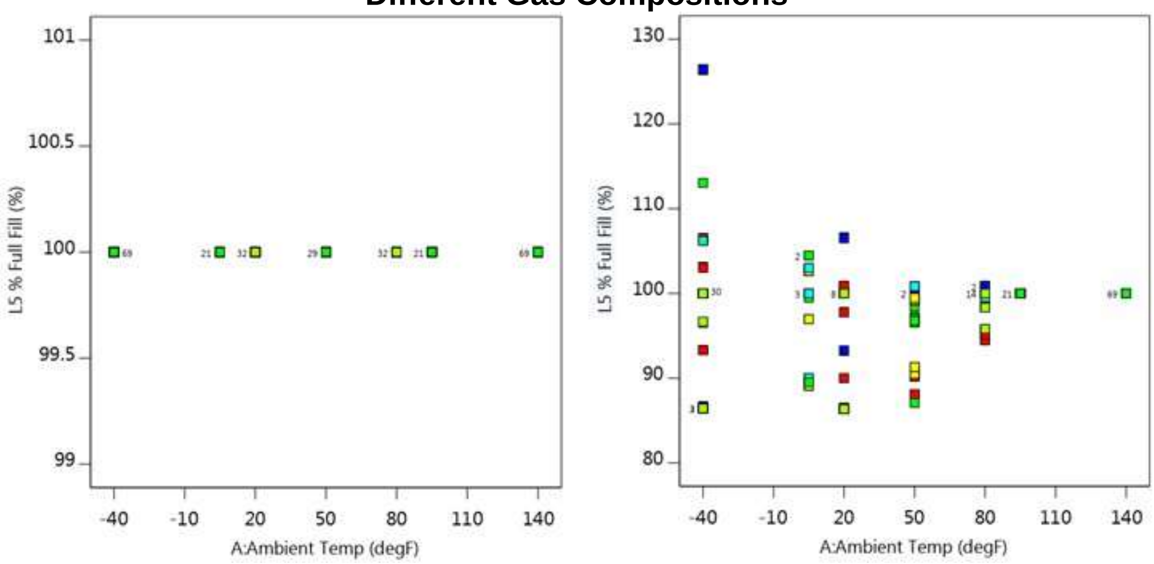
The final limitation that would have to be addressed to guarantee a full-fill is the thermodynamics of a fill on a hot day. If the vehicle's tank reaches the pressure limit before it is full, the only way to add additional gas is to cool down the gas in the tank. This is not practical on board the vehicle, so it must be done at the station. By conditioning the gas before adding it to the vehicle, the ambient temperature has less impact on the overall filling process. It could still affect the temperature of the vehicle's tank, but if the tank is mostly empty, this should have little impact on the overall fill. Predictive models show that the gas temperature needs to be about 20-30°F to guarantee a full fill from empty.

To address some of the fundamental issues preventing full fills, GTI worked to develop a more accurate filling algorithm, and spent some time investigating gas cooling technologies that could be used to counteract the heat of compression. Chapter 2 discusses the detailed analysis of this work.

CHAPTER 2: Fueling Simulation Tool

To aid in the design and analysis of an improved CNG fueling algorithm, GTI developed a fueling simulation tool that represents the transient thermodynamics of the station and vehicle during a typical fast fill. The simulated fast fill includes pressure equalization from a stationary storage cascade (usually three high-pressure storage tanks at a CNG station) and a compressor top off that flows into a simulated vehicle cylinder. In other words, a vehicle would be filled from low, medium, and high banks of a typical storage array, and then the vehicle would be topped off using the compressor until the simulated vehicle cylinder reaches 5,000 psi or 34.5 megapascals (MPa). In parallel to the simulated fill process, multiple programmed dispenser algorithms use select information (for example, temperature, pressure, volume, mass, and so on) from the station and vehicle systems to estimate a full fill. When a particular algorithm calculates that the vehicle cylinder is full, it triggers a logic gate that records the actual percent full in a data sheet for post analysis. A perfect algorithm would achieve 100 percent for every filling case, while anything over 100 percent is an over-fill and under 100 percent is an under-fill. Figure 1 shows an example of the results format.

Figure 1: Distribution of Full Fill Results using the Same Algorithm and Two Different Gas Compositions



The left image is a perfect algorithm (L5) capable of achieving 100 percent full fills across every filling scenario. The right image is the same algorithm with a different gas composition, and shows a wide range of fills that both under-fill and over-fill the cylinder.

Source: Gas Technology Institute

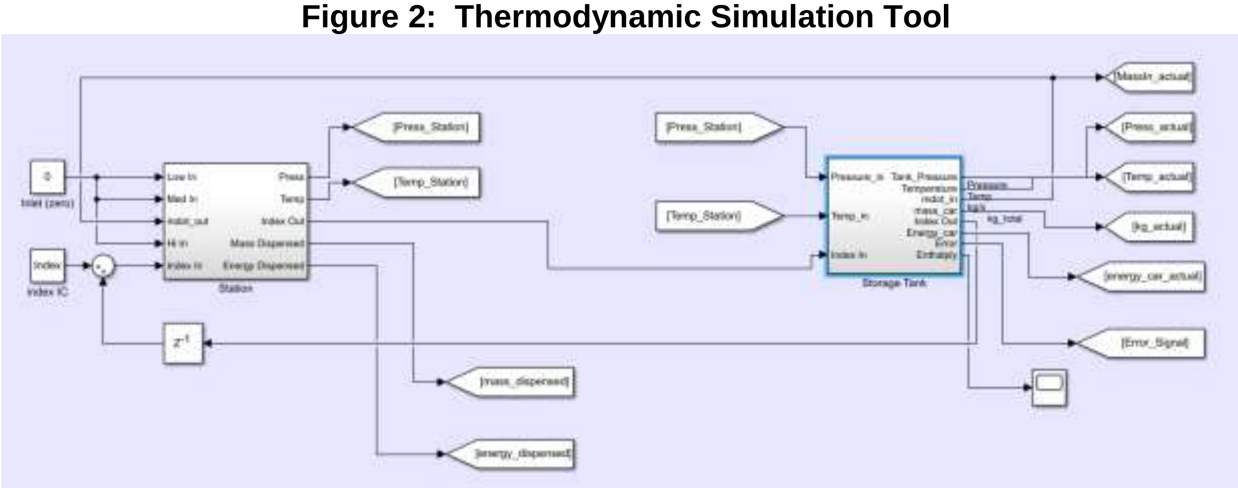
The simulation was designed to run hundreds of fill scenarios that varied the vehicle and station conditions. Those fills were then evaluated against nine different filling algorithms based on existing designs, past GTI designs, and newly developed algorithm designs. The results could then be entered into an analysis tool that compared the filling accuracy of every algorithm at every starting condition. This greatly simplified the analysis required to determine how well a filling algorithm worked, and what variables might be causing the algorithm to under or overestimate a fill.

Overall, the simulation proved useful in identifying underlying issues with many filling algorithms; however, the simulation approach ran into issues using certain gas compositions. These issues were mostly related to available gas composition data at temperatures and pressures that caused heavy hydrocarbons in the gas to drop out, resulting in a two-phase fluid. The gas property data from NIST Refprop could not solve these data points, resulting in the simulation crashing. To overcome these issues, GTI settled on two primary gas compositions that were based on extreme gas mixtures from a GTI gas composition survey: pure methane, and an 80:20 methane-to-ethane mixture.

Simulation Design

The dynamic simulation was built in Matlab/Simulink software using real gas properties from NIST Refprop to calculate incremental gas state points over time as a vehicle was filled. The simulation was designed with a three bank storage cascade and a compressor top off; however, the simulation could be easily reconfigured to evaluate a fill directly from a compressor. In addition, any station or vehicle design variable that might impact a fill (for example, station storage volume, vehicle tank size, heat transfer, and so on) could be adjusted to simulate its effect on full fill performance.

Figure 2: Thermodynamic Simulation Tool



The station components are represented on the left, and the vehicle storage tank is on the right.

Source: Gas Technology Institute

The broad capabilities of the simulation required GTI to put restrictions on which variables were considered the most relevant to a full fill, and fix all other variables at design points that were considered reasonable for most CNG stations. The variables altered during the analysis phase included ambient temperature of the environment surrounding the station (-40°F to 140°F), the deviation of the car's temperature from ambient (-30°F to +30°F from ambient), the vehicle starting pressure (0 psig to 3,000 psig), and the vehicle's tank volume (1 to 300 GGE). Using these variables, a design matrix (Figure 3) was created with 273 runs that tested every possible combination of the variables listed above, including points between the extremes. In addition, gas composition was varied by changing the gas property reference tables and re-running all 273 cases with the new composition. The performance using various gas compositions could then be compared across the full range of filling conditions to ensure the algorithm was still accurate.

Figure 3: Design Matrix

Study Type	Response Surface		**Runs**	273		
Design Type	User Defined		**Blocks**	No Blocks		
Design Model	Cubic		**Build Time (ms**	32.00		
Factor	**Name**	**Units**	**Type**	**Subtype**	**Minimum**	**Maximum**
A	Ambient Temp	degF	Numeric	Continuous	-40	140
B	Vehicle Tank Temp	degF	Numeric	Continuous	-30	30
C	Vehicle Tank Pressure	psig	Numeric	Continuous	0	3000
D	Vehicle Tank Volume	GGE	Numeric	Continuous	1	300

Source: Gas Technology Institute

For simplicity, other station attributes that were deemed less critical to the algorithm development were fixed for every run. For every scenario, the vehicle was filled from a three-bank 300 GGE storage cascade (100 GGE per bank) with CNG that started at 4,500 psig and ambient temperature. The station compressor was fixed at a 5,000 psi discharge at ambient conditions to ensure the tank could be filled to at least the 4,250 psig dispenser limit. Flow into the vehicle was calculated using compressible flow equations through a fixed orifice. Although this approach oversimplifies the flow through a real CNG station, it allowed the station to simulate choked flow at high differential pressures between the station and vehicle, and reduce the flow over time as the station and vehicle pressure delta lowered. This approach also varied the fill time between vehicles, which impacted heat gain or loss by the vehicle which was calculated using a simple thermal resistance and the temperature delta between the tank and ambient temperature.

The simulation simplifies the real world behavior of a fill, but it includes the basic thermodynamics of the gas leaving the station and entering the vehicle as well as heat gained and lost during this process. The simulation provides the basis for a fair comparison of performance between algorithms under ideal conditions. Any issue calculating a full fill within the simulation is a result of a shortcoming of the algorithm itself as opposed to measurement error or other external variables that can impact physical testing. Preferred algorithms that could perform well under ideal conditions were evaluated separately for impacts caused by real world measurement accuracy. Some of this real world analysis is discussed in Chapter 3.

Key algorithms tested using the simulation include the state of the art algorithm used in some dispensers today, mass and energy based filling algorithms, and a simple pressure-temperature algorithm. Results for each algorithm are displayed using the same graph as the results displayed in Figure 1. These graphs provided a basic visual comparison of the simulation results, but also allowed the project team to review individual outlying cases to determine why the algorithm under-filled or over-filled for that case. Algorithms that avoid over-filling and have results closer to 100 percent across the full range of cases and gas compositions are considered more accurate.

An idealized version of each algorithm was tested in the simulation to evaluate the dispenser performance. The simulated algorithm was ideal because it was able to measure the exact vehicle starting pressure, mass, temperature, etc. as opposed to real world dispensers that have some measurement error or are measuring vehicle pressure through the dispenser hose and nozzle/receptacle check valves. A full fill was evaluated based on the actual density of the gas being used to fill the tank at 3,600 psi at 70°F, for example methane was compared to methane, and high-ethane was compared to high-ethane. This way the algorithm could determine if the vehicle was under- or over-filled using various gas compositions. However, scenarios that resulted in a hot tank that was impossible to fill to 100 percent were evaluated based on the algorithm's ability to recognize this situation and fill the cylinder to the dispenser pressure limit of about 4,250 psi, maximizing the fill. If an algorithm let a vehicle fill to 4,250 psi, it received a 100 percent even if the vehicle was not actually full based on mass. If it was possible to fill the vehicle to 100 percent of the target density, then the algorithm was scored based on how full the vehicle actually got using that gas composition.

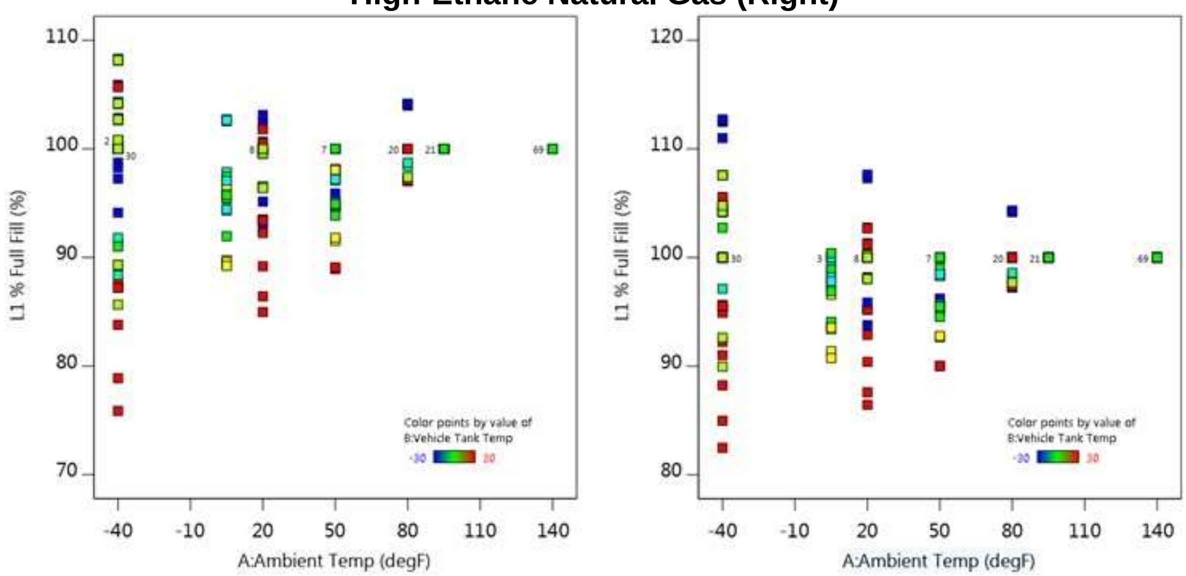
In other words, fills were compared to a perfect dispenser that knows everything about the gas composition, temperature, pressure, and so on. The perfect dispenser would fill to 100 percent under any condition, regardless of gas compositions, or fill to 4,250 psi while trying to get to 100 percent. This perfect dispenser was the measuring stick used to judge all other algorithms.

State of the Art Algorithm

Many, if not all, of the commercial dispensing codes are proprietary to the individual dispenser manufacturer, with many claiming improved fills over their competition. GTI's goal in accessing these filling strategies was to identify the single best option that could reliably and safely fill a CNG vehicle across a wide variety of filling conditions as described in the previous section. To establish a baseline, GTI worked with commercial dispenser manufacturers to evaluate the performance of a state of the art filling algorithm. The selected algorithm used the starting vehicle pressure measured through the hose, and the ambient temperature to calculate a full fill. A simple formula used these values to compensate for the ambient temperature and estimate the heat of compression to determine a stopping pressure. The dispenser calculates the stopping pressure at the start of the fill and simply stops fueling once the vehicle reaches that pressure.

The graphical results of the simulation are displayed in Figure 4. The left hand graph represents the simulated fill results of the vehicle using pure methane, while the right hand results represent the simulated fill results using a high ethane blend based on an extreme gas composition seen in a natural gas survey conducted by GTI. These two compositions are considered extremes, but should stress the performance of the algorithm being tested to help highlight any issues with the algorithm design. The results are displayed with ambient temperature on the x-axis and percent full, measured as described above, on the y-axis. A perfect algorithm would simply be a flat line of dots at 100 percent. In addition, the dots are colored based on the vehicle's temperature deviation from ambient at the start of the fill with dark blue being 30˚F below ambient and red being 30˚F above ambient. These cases represent the highway and parking lot cases that can cause temperature in the tank to deviate from ambient.

Figure 4: Commercial Fill Algorithm Full Fill Results using Methane (Left) and High-Ethane Natural Gas (Right)



Source: Gas Technology Institute

The algorithm appears to struggle when the tank temperature is higher or lower than ambient. This is indicated by the red and blue colored dots bordering the fill results. This is not surprising considering modern dispensers have no way of measuring the vehicle's actual gas temperature. GTI was unable to verify vehicle temperatures during an actual driving cycle, but tested a highway case that drained the fuel tanks over a few hours to simulate a vehicle constantly consuming fuel while driving on a highway. The tests, discussed in more detail in Chapter 3, verified that the cylinder acts as an insulator and the internal temperature can deviate from ambient conditions significantly. It is also noteworthy that some cases overfilled a vehicle by more than 10 percent. These are not cause for alarm as they mostly occur at extremely cold temperatures (-40°F), but do highlight that an algorithm using limited information will struggle to maintain accuracy across a range of vehicle filling scenarios.

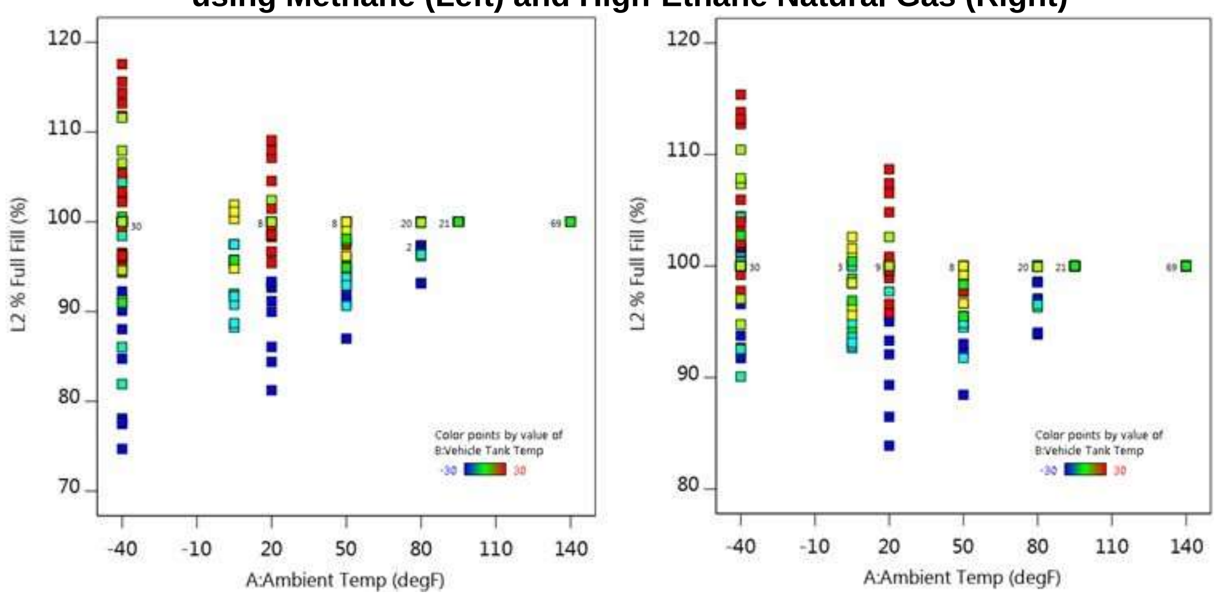
Modern algorithms do a good job of filling vehicles despite not reaching 100 percent full in every case. This good performance is not surprising, as the industry has had years to refine filling methods; however, the following section will compare GTI's attempts to improve on the state of the art algorithms and compare those results.

State of the Art Algorithm with Communication

To improve on the state of the art algorithm, GTI revised the formula for calculating the stopping pressure to use the actual tank temperature rather than the ambient temperature. This represents a significant hardware and software change for real world dispensers that cannot measure tank temperature, and only measure tank pressure through the hose.

Results of the analysis are shown in Figure 5 using the pure methane and high-ethane gases described above. The results show a wider distribution than the results without communication, but they also show a more distinct separation of hot and cold starting tank temperatures. This was likely caused by the algorithm adjusting for the starting vehicle temperature, but not the temperature of the gas entering the tank from the station.

Figure 5: State of the Art Fill Algorithm with Communication Full Fill Results using Methane (Left) and High-Ethane Natural Gas (Right)



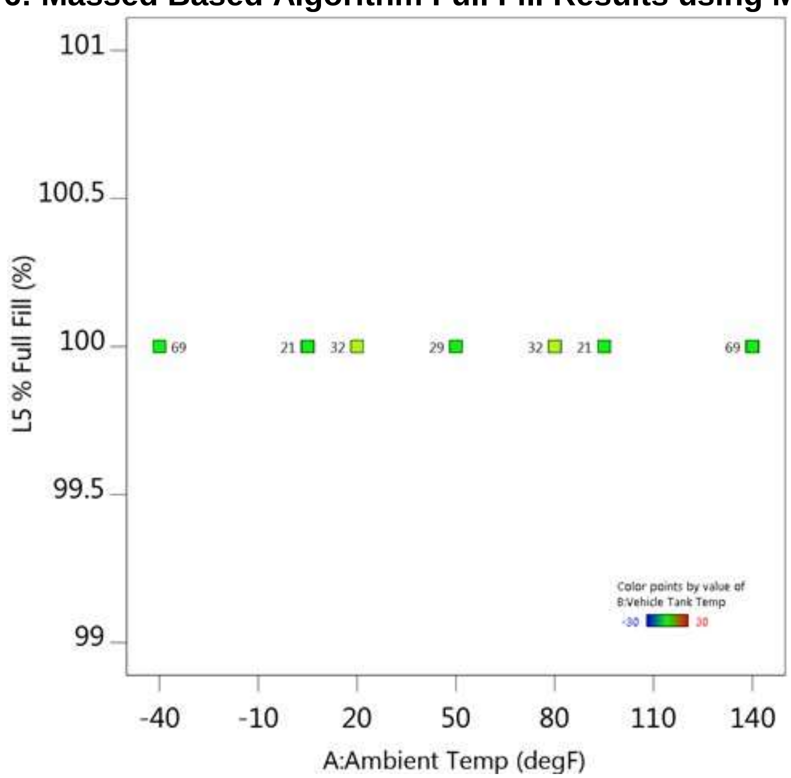
Source: Gas Technology Institute

Mass Based Algorithm

GTI developed a mass based filling algorithm that was roughly based on prior work done by GTI during the development of the Accufill algorithm. The original Accufill algorithm used gas "huff steps" to estimate the vehicle cylinder's volume. Using this estimated volume, the ambient temperature, and starting pressure, Accufill would estimate the mass of CNG in the tank at the start of the fill. It would then calculate the mass of gas that needed to be added assuming an average gas composition in the tank and at the station. When the measured mass had been added to the tank, or the 4,250 psi limit was reached, the fill was completed.

In an attempt to modernize and improve Accufill, GTI assumed communication between the vehicle and dispenser that would allow the exact vehicle volume, starting temperature, and pressure to be used when calculating the initial mass and target full fill mass. Figure 6 shows the results of this simulation using methane to fill the vehicle and a reference gas that is also methane. The resulting algorithm can perfectly achieve a full fill under every filling scenario, or fill to 4,250 psi when a true full fill is not possible. These results are made possible because the filling algorithm knows the starting tank pressure, temperature, volume, and the exact gas composition. This allows for a perfect calculation of the starting mass in the tank. The algorithm then simply needs to measure the additional mass required to fill the known tank volume to the full fill density of the known gas.

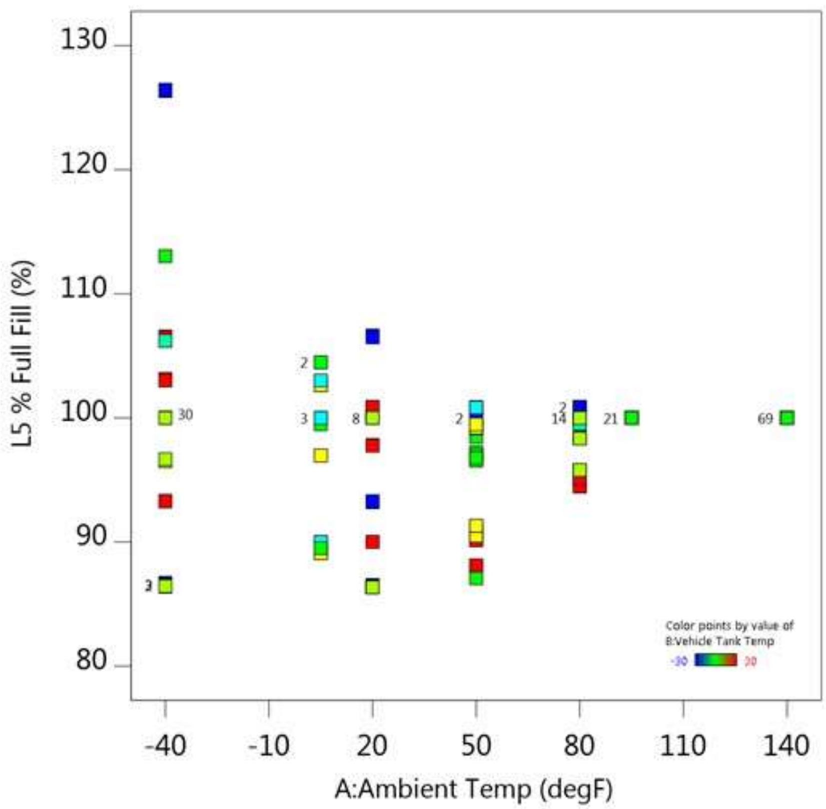
Figure 6: Massed Based Algorithm Full Fill Results using Methane



Source: Gas Technology Institute

However, issues appear with this approach when considering unknown gas compositions. Figure 7 shows the results of the same algorithm using the same pure methane reference gas, except the actual gas filling the tank is a high-ethane mixture similar to the high-ethane natural gas seen in GTI's gas survey. It is immediately apparent that the algorithm's performance is not as ideal as when the reference gas matches the actual gas entering the tank. While it is extreme to fill a tank with high ethane gas using a pure methane reference gas, it helps to highlight the issues associated with this filling algorithm, including the fact that neither the starting tank gas compositions nor the station gas composition may match the reference gas used in the algorithm. A gas chromatograph or other gas-analyzing device can determine the station gas composition; however, it cannot detect the gas composition onboard the vehicle. This uncertainty could result in significant under-filling or over-filling of the CNG tank.

Figure 7: Mass Based Algorithm using High Ethane Natural Gas and a Methane Reference Gas

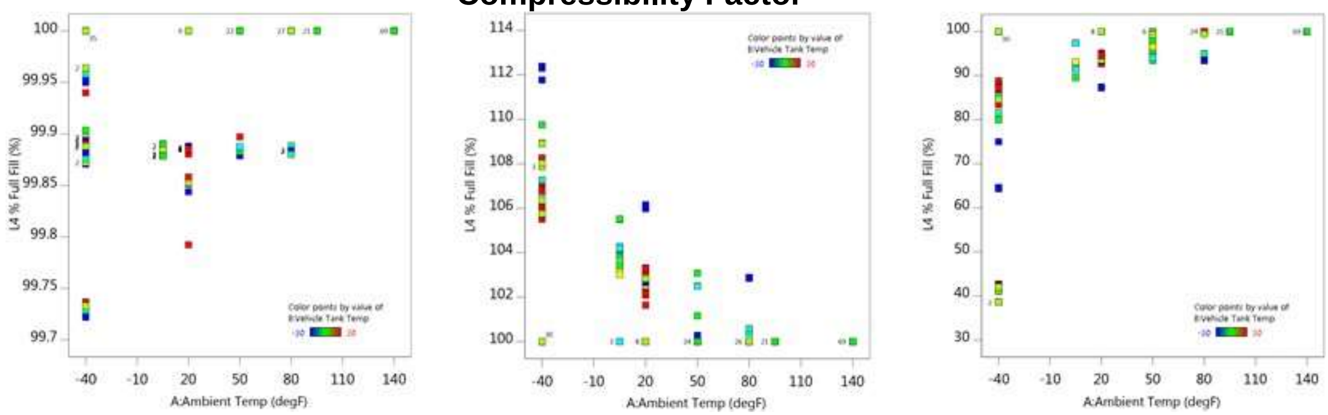


Source: Gas Technology Institute

Real Gas Equation

Another variation on the filling algorithm was the use of the real gas law, described in Chapter 1, to fill to a molar density. The only issue with this approach is the uncertainty in gas composition that results in uncertainty of the compressibility factor. GTI used two approaches to overcome this limitation: (1) use the compressibility of a reference gas to estimate the compressibility at a given pressure and temperature, (2) use a molecular weight sensor and response surface equation to estimate compressibility. Figure 8 shows the results of the reference gas algorithm. Methane filling a vehicle with a methane reference is shown on the left with a tight distribution around 100 percent for all conditions. The center shows results for ethane filling using a methane reference, and the results on the right are methane using an ethane reference. The center and right results have issues, particularly as the temperature drops. This is related to the fact that the compressibility of various natural gas compositions are similar at high temperatures and pressures, but start to deviate as the pressure and temperature drops.

Figure 8: Real Gas Law Algorithm using a Reference Gas to Estimate the Compressibility Factor

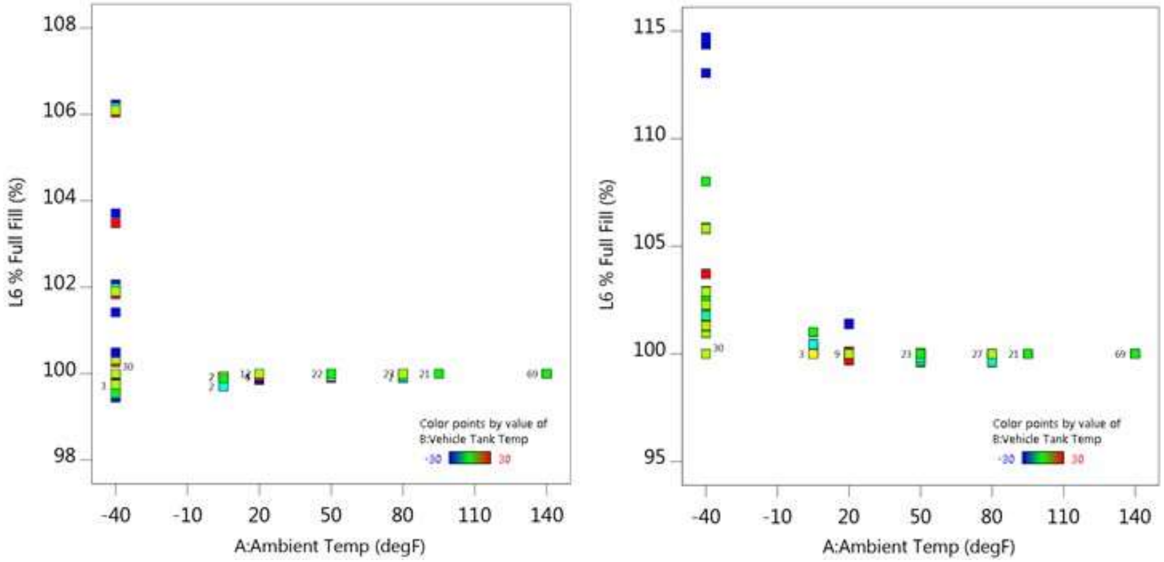


Left: methane using methane as the reference gas. Middle: high ethane natural gas using methane as the reference gas. Right: methane using high ethane natural gas as the reference gas.

Source: Gas Technology Institute

Around the time this algorithm was being developed, GTI was evaluating a prototype sensor that claimed to measure molecular weight, so this capability was added to the dispenser algorithm to determine if it improved the performance. GTI developed a correlation between pressure, temperature, molecular weight, and compressibility for a number of natural gas compositions and created a response surface equation based on the results of that analysis. The response surface equation was used to estimate the compressibility at a measured pressure, temperature, and molecular weight. That compressibility was then plugged into the real gas law to determine when the CNG tank was full. Results from that analysis are displayed in Figure 9.

Figure 9: Real Gas Law Algorithm using Molecular Weight to Estimate the Compressibility Factor. Pure Methane (Left) and High Ethane Natural Gas (Right)



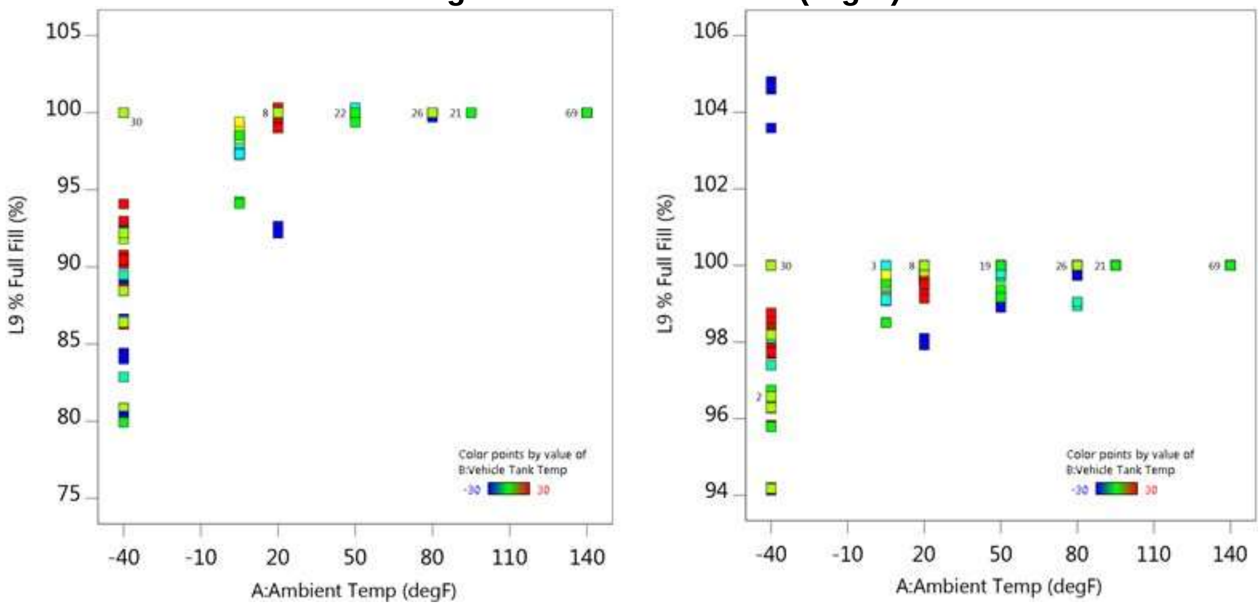
Source: Gas Technology Institute

Figure 9 shows a vast improvement in the real gas law algorithm compared to the simple reference gas results displayed in Figure 8. The algorithm can also adjust for the two significantly different gas compositions while keeping most of the results near 100 percent. The algorithm struggles at very cold temperatures, but this is likely an issue with the response surface that is being used to estimate compressibility rather than with the algorithm itself. The response surface likely needs to be extended to better cover the cold temperatures. GTI did not fully explore these issues as the sensor needed to estimate molecular weight is not yet commercially available. The difference in gas composition between the station and the vehicle would further complicate the need for sensor placement. To resolve this issue, sensors would be required at both the station and the vehicle, or communications must be in place to transmit gas composition at the station to the vehicle. Overall, this algorithm approach appears to be very promising, but it cannot be implemented until a reliable molecular weight sensor is developed, verified, and made commercially available.

Pressure-Temperature Targets

The final algorithm worth discussing is the use of conservative pressure and temperature targets to define a full fill. A given gas composition has a specific full fill density at 3,600 psig and 70°F. As the temperature changes, the pressure also changes, creating a line that defines a full fill for that composition. The challenge is selecting an appropriate pressure and temperature line to represent a full fill because the target pressure at a given temperature changes for every gas composition. Table 3 demonstrates how significantly these targets can change with various natural gas compositions. If conservative gas compositions are selected, such as methane and high-ethane, then separate full fill lines can be created above and below 70°F to prevent overfilling. The results for this algorithm are shown in Figure 10.

Figure 10: Pressure-Temperature Algorithm Full Fill Results using Methane (Left) and High Ethane Natural Gas (Right).



Source: Gas Technology Institute

The results for methane are displayed on the left, while high-ethane results are on the right. Above -10°F, the algorithm can consistently estimate full fills for both compositions, with most results well within 3 percent of full. However, as the temperature gets colder, the algorithm can significantly under-fill using pure methane. This is caused by the algorithm using a low methane content gas composition for temperatures below 70°F, so the error increases as the temperature drops. Most gas compositions will fall somewhere between the two extremes displayed above, so they should perform slightly better than pure methane at those low temperatures. It is also worth pointing out the four data points above 100 percent on the ethane results. These are most likely caused by the response surface that was used to develop the algorithm not adequately including those low temperature data points so they don't result in over-filling.

Design of Experiment

GTI used standard design of experiment procedures to evaluate the full range of possible filling conditions that might occur during a fast fill. As described above, the primary variables were ambient temperature, vehicle tank temperature deviation from ambient, starting tank pressure, and vehicle tank volume. Gas composition was also varied by rerunning the filling scenarios after the gas composition lookup tables were changed in Matlab. The responses, or results, included the percent full of every algorithm being tested. Many of the graphical results from this analysis are displayed above; however, the results can also be evaluated using the statistical results in Table 4. Table 4 shows some of the statistics for each algorithm (L1-L9) using both methane and high-ethane gas.

Table 4: Summary of Algorithm Test Results

Algorithm	Min.	Max.	Mean	Std. Dev.	Ratio	Comment
Methane L1% Full Fill	79	108	98	4.39	1.43	State of the art
Methane L2% Full Fill	75	118	98	5.21	1.57	State of the art w/communications
Methane L3% Full Fill	55	102	98	9.41	1.87	Rejected, passive communication
Methane L4% Full Fill	100	100	100	0.06	1.00	Real gas law w/ref gas
Methane L5% Full Fill	100	100	100	0.00	1.00	Mass target
Methane L6% Full Fill	99	106	106	0.85	1.07	Real gas law w/molecular weight
Methane L7% Full Fill	99	106	106	1.39	1.07	Rejected, passive communication
Methane L8% Full Fill	100	100	100	0.06	1.00	Combined mass target and real gas law
Methane L9% Full Fill	80	100	98	4.85	1.26	Pressure-temperature
High-ethane L1% Full Fill	82	108	99	3.51	1.30	State of the art
High-ethane L2% Full Fill	84	115	99	3.72	1.38	State of the art w/communications
High-ethane L3% Full Fill	100	115	103	4.48	1.15	Rejected, passive communication
High-ethane L4% Full Fill	100	110	102	2.68	1.10	Real gas law w/ref gas
High-ethane L5% Full Fill	86	113	98	5.31	1.31	Mass target
High-ethane L6% Full Fill	100	108	100	1.08	1.08	Real gas law w/molecular weight
High-ethane L7% Full Fill	95	108	100	1.33	1.14	Rejected, passive communication
High-ethane L8% Full Fill	86	110	98	5.27	1.27	Combined mass target and real gas law
High-ethane L9% Full Fill	94	100	99	1.17	1.06	Pressure-temperature

Source: Gas Technology Institute

GTI did not consider L3 and L7 because they used communication only during the start of the fill, which was determined to be impractical in the real world compared to continuous communication. GTI also rejected L6 because it required a measurement of molecular weight, which is not commercially available. L4, L5 and L8 performed very well with methane, but they all had the potential to overfill using high-ethane gas with a large distribution of results. L9 performed significantly better than the state of the art algorithms L1 and L2 in terms of successfully estimating full fills with a narrow distribution of results. L9 was also the only algorithm to eliminate the possibility of overfilling after removing outliers at extremely low temperatures.

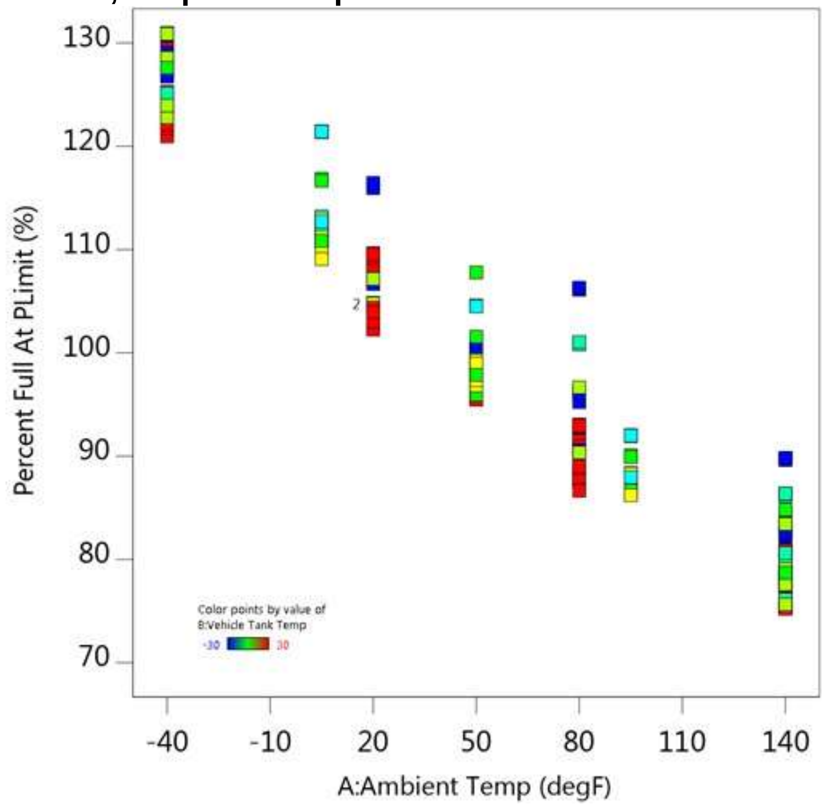
Simulation Results

The simulation was a useful tool for evaluating a number of different full fill algorithms; however, no single algorithm could achieve perfect full fill performance because of the variability in natural gas composition. Although the real gas law algorithm that used molecular weight to estimate compressibility performed better than L9, it requires gas sensing at the station and onboard the vehicle which may not be feasible in the real world. At this time, GTI's prefers the conservative pressure-temperature (P-T) algorithm because it achieved reasonable accuracy with relatively simple real world implementation. The only additional equipment required to utilize this algorithm are properly located temperature sensors onboard the vehicle (assuming pressure is already measured) and a means of communicating vehicle tank measurements to the dispenser. This equipment is expected to cost well under $100, so it should have very little impact on the price of the station or vehicle. By adopting a NGV filling approach that utilizes communication with the proper algorithm, it is clear that the NGV industry can significantly improve filling consistency and safety compared to the state of the art.

Pre-Cooling Technologies

An improved filling algorithm can make NGV fills more consistent and safer; however, it cannot deliver a full fill under all filling conditions since many fills are limited by the heat of compression. Many of the results described in the previous section show algorithms achieving full fills at hot temperatures, but the 100 percent result simply indicated that the algorithm maximized the fill for that scenario. Figure 11 shows how full the vehicle actually is at the dispenser's pressure limit of 4,250 psig. Any dot above 100 percent on the y-axis has the potential to get a true full fill of 3,600 psig at 70°F, and any dot below 100 percent is limited by heat of compression. As ambient temperatures get warmer, the gas being delivered to the vehicle from the station is also warmer, which reduces the volume of gas that can fit into the vehicle's cylinder before the pressure limit is reached. The results in Figure 11 indicate that a full fill is not guaranteed unless the gas supplied by the station is around 20°F. Above this temperature it is still possible to get a full fill under some conditions, but it cannot be guaranteed.

Figure 11: Actual Fill Percentage of Natural Gas Vehicle Filled to the Dispenser Pressure Limit of 4,250 pounds/square inch at Various Ambient Temperatures



Source: Gas Technology Institute

The only way to guarantee NGVs get a full fill is to combine the use of an accurate full fill algorithm with some form of gas conditioning capable of cooling the gas to around 20°F before it is delivered to the vehicle. This will enable NGV fuel systems to be properly sized for the required range, resulting in significant cost and weight savings.

Although the original project scope did not include pre-cooling technologies, GTI concluded that pre-cooling was a necessary component to achieving full fills. GTI conducted a high level analysis of several pre-cooling strategies including commercial chilling systems, vortex tubes, Joule-Thomson cooling, CNG refrigeration cycles, and isentropic expanders.

Chiller

Chillers are the best commercial option available for guaranteeing full fills. Chillers use a standard refrigeration cycle to cool an intermediary fluid such as glycol that is then used to cool the CNG. The hydrogen industry uses chillers at compressed hydrogen fueling stations. The virtual pipeline industry has also started using chillers to improve full fills on large CNG trailers used to transport natural gas to customers that do not have access to pipeline infrastructure. Chiller technology is mature, but it is still costly for CNG and hydrogen. GTI spoke with several manufactures of chillers, as well as virtual pipeline companies that had installed CNG chilling systems. A rough estimate of the cost to purchase and install one of these systems is about $100 per standard cubic foot per minute (SCFM) of CNG that must be chilled. For example, a station that delivers 2,000 SCFM would need a chiller at a cost of about $200,000. This is not insignificant compared to a CNG compressor that might cost between $500 and $1,000 per SCFM.

Joule-Thomson Cooling

A low cost alternative to chillers is Joule-Thomson (J-T) cooling. This pre-cooling approach cannot guarantee full fills, but it can improve stations that direct fill vehicles or virtual pipeline systems. Direct fill stations do not use a cascade storage system and fill vehicles or trailers directly from the compressor. When filling vehicles directly, the gas leaves the compressor at a pressure slightly higher than the vehicle, and about 20-30°F above ambient. This can cause significant under-filling because the gas entering the vehicle is essentially preheated, amplifying the heat of compression. J-T cooling uses a valve that forces the compressor to a higher discharge pressure, which causes the gas to drop in pressure and cool before entering the vehicle. J-T cooling can help a direct fill station improve fills, and ultimately achieve full fills close to fills seen at a normal cascade station, shown in Figure 11. The advantage of a J-T cooling system is that it is relatively inexpensive with an estimated cost of less than $5 per SCFM.

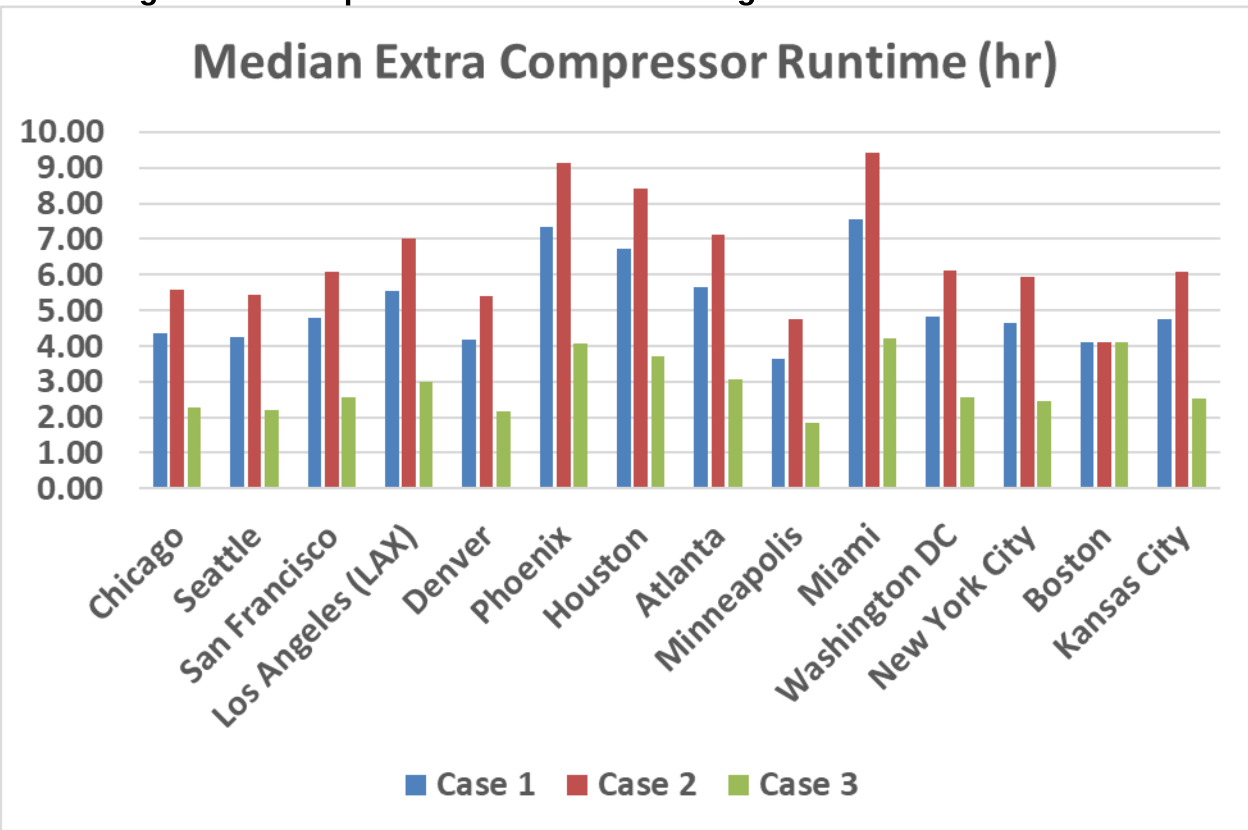
Vortex Tubes

Vortex tubes are used for cooling electrical cabinets with compressed air. The vortex tube is designed to take high-pressure gas and separate it into a hot and cold stream as the gas drops in pressure. The net cooling of the two streams when combined is equivalent to that of J-T cooling; however, GTI considered the possibility of removing some heat from the hot stream to achieve additional cooling of the CNG. However, the hot stream is still very cold for most of a vehicle fill, so this approach is impractical because it adds complexity to the J-T cooling approach with little benefit.

Compressed Natural Gas Refrigeration

CNG refrigeration uses the CNG compressor with a J-T cooling valve to generate cold CNG that could then be used to cool down a heat transfer fluid such as water or glycol. The compressor would run in cooling mode when the station was idle, and then use the heat transfer fluid to pre-cool the CNG entering a vehicle during a fill. The system would be less expensive than a commercial chiller because the CNG compressor is already available and idle at the station. However, the system costs more than the J-T cooling approach because it would still require tanks, pumps, valves, and heat exchangers for the heat transfer fluid. The additional run time on the compressor does not add significant concern because CNG compressors run more efficiently during continuous operation, rather than start-stop operation as seen in many CNG stations today. GTI evaluated this approach using a simple thermodynamic model that calculated the additional run time required for a CNG compressor to generate sufficient cooling to achieve full fills. The scenario assumed a station that filled vehicles over 6 hours at night, and then would recharge the thermal storage fluid during the day using the CNG refrigeration cycle. Figure 12 shows the median additional runtime required to generate enough cooling to achieve a full fill in various cities across the United States. The model also looked at three different cases. Case 1 assumed the gas leaving the compressor was 20°F above ambient, and needed to be cooled to 20°F before dropping in pressure across the J-T valve and flowing into the vehicle. Case 2 was the same as Case 1, but assumed the compressor discharge temperature was 30°F above ambient. Case 3 assumed the compressor discharge was 20°F above ambient, but the gas only needed to be cooled to 32°F instead of 20°F.

Figure 12: Compressed Natural Gas Refrigeration Median Run Time



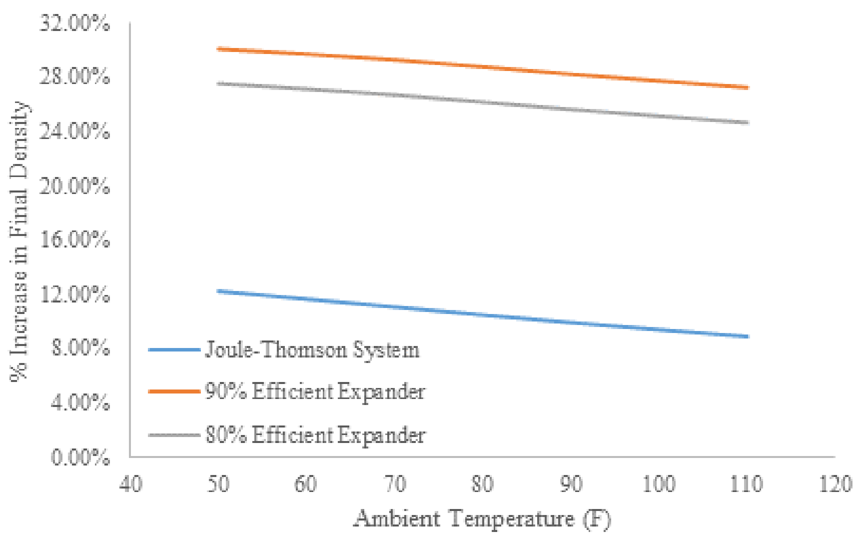
Source: Gas Technology Institute

Although, CNG refrigeration is technically feasible for the scenario that was evaluated, the real world practicality of this approach is unclear. The hottest day occurs in Phoenix, Arizona and requires the compressor to run for 14 hours in cooling mode to generate enough cooling for Case 2. The energy to compress 1 GGE to 3600 psig is roughly 1 kilowatt hour, while the energy to chill 1 GGE from 120˚F to 20˚F is about 0.15 kilowatt hours. A commercial chiller uses significantly less energy to chill the gas. However, these energy savings would need to be weighed against the potential cost savings of eliminating the capital cost of the commercial chiller. GTI did not continue pursuing CNG refrigeration after evaluating the approach's technical feasibility and estimating the compressor run time required to achieve the necessary cooling. If NGV stakeholders see this approach as attractive in the future, the analysis could be expanded to compare the economics of a commercial chiller to the CNG chilling approach.

Expanders

Although similar to the J-T cooling approach that uses isenthalpic (no change in enthalpy) cooling across a valve or orifice, expanders extract energy from the gas as it drops in pressure to approach isentropic (no change in entropy) cooling. Since energy is being extracted from the gas before it enters the vehicle, the gas goes in colder and does not heat up as much as the vehicle increases in pressure. GTI evaluated the theoretical performance, shown in Figure 13, of an isentropic fill at 80 percent and 90 percent efficiency compared to a J-T fill and direct fill. Figure 13 uses a baseline case representing a direct fill of a CNG vehicle, which is common for heavy-duty vehicles, fleets, and virtual pipelines. The results show that J-T cooling provides some benefit through isenthalpic gas cooling; however, an expander provides greater improved performance by providing near-isentropic cooling that enables full fills across a wide range of ambient conditions. A 90 percent efficient expander can improve a fill compared to direct filling by about 28 percent. GTI believes this may be sufficient to achieve a full fill at any ambient temperature; however, additional modeling is required to fully understand the performance of an expander within a CNG station.

Figure 13: Increase in Final Density of Compressed Natural Gas Fueling Event over Range of Ambient Temperatures



Source: Gas Technology Institute

GTI looked for a commercial expander that worked at the pressures and flows seen in the CNG industry; however, the closest commercial design identified was a turbine that had a pressure limit of 3,000 psig at the inlet. In addition, turbines are designed for much higher flow rates than a typical CNG station, and are designed to operate at a single flow and pressure ratio, which is far from the operating conditions seen at a CNG station.

GTI believes it may be possible to use an alternative expander geometry to handle the high CNG pressure and variable flow rate, but this was not explored in depth.

Pre-Cooling Summary

GTI believes the most viable pre-cooling option to guarantee full fills in the short term is to use a commercial chiller system. These systems are expensive, but there is little or no risk that they will not deliver the required cooling to get a full fill. In the long term, the expander approach may be the best solution because it is more efficient than the chiller since it does not require any electricity to run, and may be significantly less expensive depending on the design. Expanders also eliminate the need for a heat transfer fluid such as glycol since it cools the CNG directly.

CHAPTER 3: Testing and Validation

Given the promising simulation results of the GTI pressure-temperature full-fill algorithm, the researchers conducted laboratory testing to validate some assumptions of the simulation. The main limitation of the simulation is the assumption of uniform tank conditions during the fill. To implement fill termination using on-board measurement of vehicle cylinder conditions, the team must first understand the variations in temperature within the cylinder and how these variations impact density calculations. The testing must also identify any transient effects in the wireless communication or in the program execution of the algorithm that could impact the accuracy of the fill termination. To understand these areas, the test plan was designed to achieve the following goals:

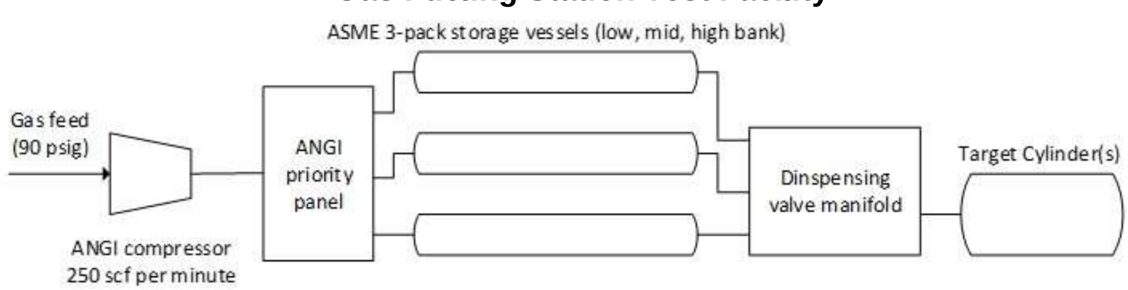
1) Quantify the difference between cylinder temperature measured on the centerline of the cylinder and the volume-average temperature of the entire tank volume
2) Quantify the accuracy of fill algorithm when implemented in a control program
3) Establish wireless connection protocol and quantify time delay between vehicle and dispenser

The testing results are described in the sections below.

Test Setup

The test programs were achieved through modifications to GTI's existing CNG station test facility. This facility is fed by 100 psig supply gas, which is compressed into 4,200 psig storage banks through the use of a 250 SCFM ANGI compressor package. An ANGI priority panel directs the gas into the appropriate storage bank. A CT-5000 high-flow nozzle dispenses the gas into the target cylinder.

Figure 14: Schematic Drawing of Gas Technology Institute Compressed Natural Gas Fueling Station Test Facility



Source: Gas Technology Institute

To achieve the goals of this project, multiple target cylinders were required to test large and small fills in various types of cylinders. The main target cylinder was an Agility 155DGE back-of-cab fuel storage system that represented a typical system installed onboard heavy-duty CNG trucks (Figure 15).

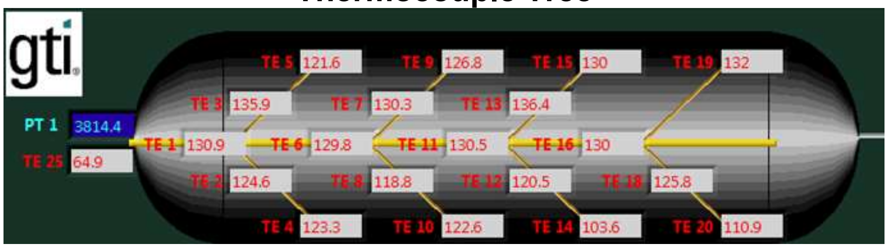
Figure 15: Agility Back-of-Cab 4-Cylinder Compressed Natural Gas Storage Pack

Source: Gas Technology Institute

This was comprised of four 523-liter Type 4 storage vessels packaged with a common feed manifold, relief valve manifold, and several filters and gauges. Prior to delivery to GTI, Agility installed a thermocouple "tree" in one of the four cylinders. The thermocouple tree included 20 type E thermocouples spread in a pattern designed to accurately measure the temperatures at different heights inside the vessel. This was necessary to understand the temperature distribution in the cylinder, both during a fill and the time after the fill as the temperatures equilibrate and cool down.

Figure 16 gives a representation of the location of the thermocouples in the cylinder. Figure 17 shows borescope images of the location of the thermocouple arms inside the cylinder. There is some variability in the position of the thermocouples, but most were located along a vertical plane down the center of the cylinder. Additionally, two Type 3 (aluminum liner with carbon fiber wrap), 20 GGE, cylinders already present at GTI's test facility were filled to determine the differences in behavior between the two tank types. The aluminum liner of a Type 3 and the plastic liner of a Type 4 cylinder can have different impacts on the internal gas temperature. Lastly, a small Type 2 10 GGE cylinder was used for some of the baseline testing early in the project.

Figure 16: LabView Control Screen showing Schematic Representation of Thermocouple Tree



Source: Gas Technology Institute

Figure 17: Borescope Images of Thermocouple Tree

Source: Gas Technology Institute

Test Plan

Matching the experimental objectives, GTI split the test plan into three parts:

1) Quantifying the temperature variation inside the test cylinder
2) Quantifying the performance of the proposed algorithm
3) Establishing and filling through a wireless connection

Quantifying Temperature Variation

GTI completed fill tests with a range of initial conditions and fill rates in order to quantify the temperature variation at several points within the vessel. This data helped determine where a thermocouple could be located within the cylinder to best represent the average cylinder temperature, and quantify the error between the thermocouple reading when compared to the volume average temperature. Table 5 shows the test matrix for this portion of the experimental program. Fast fill (3 minutes), slow fill (30 minutes), and timed fill (3 hour) tests were completed to ensure the impacts of flow rate were accounted for. The type of tank filled was also varied between a type 3 and type 4, the two most predominant CNG tank types for vehicles. Lastly, the initial pressure and the initial temperature were varied to account for different types of fills. Although it was desired to test the variability with ambient temperature as well, no means of controlling ambient temperature were available.

Table 5: Test Plan 1 – Quantifying Temperature Variation

Test	Initial Pressure (psig)	Initial Temp (F)	Target Fill Time (min)	Target Tank Type
1	150	Ambient	3	4
2	1250	Ambient	3	4
3	2500	Ambient	3	4
4	150	Ambient	30	4
5	1250	Ambient	30	4
6	2500	Ambient	30	4
7	150	Ambient	180	4
8	1250	Ambient	180	4
9	2500	Ambient	180	4
10	150	Sub-cooled	3	4
11	1250	Sub-cooled	3	4
12	2500	Sub-cooled	3	4
13	150	Ambient	30	3
14	150	Ambient	30	3
15	150	Ambient	3	3
16	150	Ambient	3	3

Source: Gas Technology Institute

Quantifying Algorithm Performance

Once the temperature variation within the test cylinder was understood, GTI finalized and programmed an algorithm into the control software (LabView) to determine the end point of a fill an algorithm. Several fills were then conducted according to Test Plan 2, which is outlined in Table 6, to test the performance of the fill algorithm.

Table 6: Test Plan 2 – Quantifying Algorithm Performance

Test	Initial Pressure (psig)	Initial Temp (F)	Target Fill Time (min)	Target Tank Type
1	2900	Ambient	3	4
2	2900	Ambient	30	4
3	2900	Ambient	3	3
4	1800	Sub-cooled	3	4
5	2900	Sub-cooled	3	4
6	2000	Sub-cooled	3	4
7	2900	Ambient	3	3

Source: Gas Technology Institute

Similar to Test Plan 1, the tests for this section were designed to expose the system to as much variability in flow and initial conditions as possible. GTI conducted this testing in the summer months with high ambient temperature, which severely limited the initial pressures under which the target cylinder was still able to achieve a full fill. Most initial pressures were required to be around 2,900 psig or higher to ensure the algorithm would achieve 100 percent full fills before the dispenser would reach the high pressure shutoff at 4,250 psig. Testing at sub-freezing ambient temperatures would be required fill the cylinder from empty. GTI also completed two sub-cooled tank tests by lowering the pressure in the target cylinder, causing it to cool, then completing a fill before the gas could heat up again.

Establishing and Filling through Wireless Connection

Lastly, GTI planned testing to validate the wireless connection protocol developed in this project. Results from this testing were also used to quantify the time required to establish a connection and the time delay due to wireless data transfer. Most of the testing in this area consisted of troubleshooting efforts, with two fills completed once the connection protocol was finalized.

Test Data

Test Plan 1 was completed between late March and early May 2018. Ambient temperatures during the testing ranged between 27°F and 75°F, although most of the testing was completed between 30°F and 40°F. Key data from these tests are shown in Table 7.

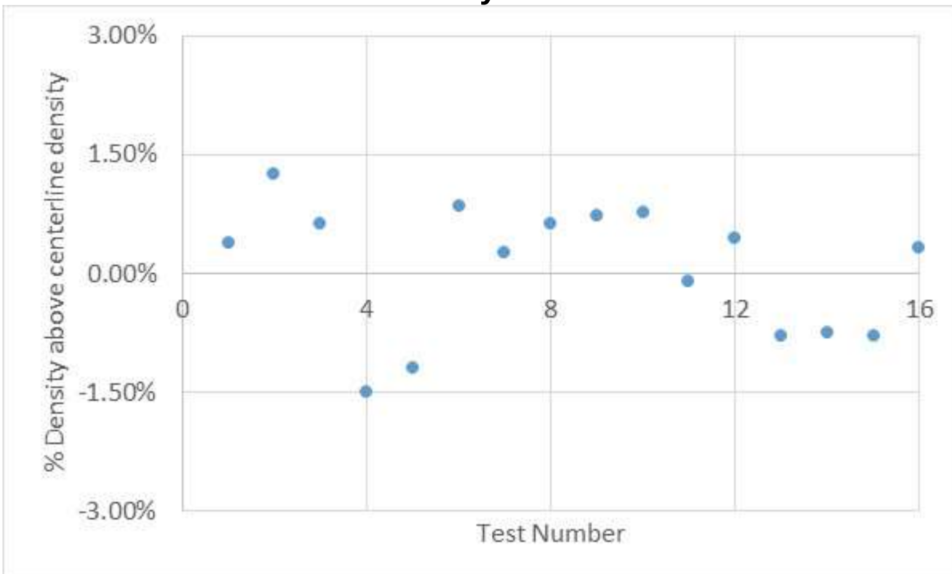
Table 7: Key Data from Test Plan 1 Experiments

Test	Ambient Temp (F)	Initial Cylinder Temp (F	Initial Cylinder Pressure (psig)	Final Centerline Temp (F)
1	31	31	140	98
2	62	64	1253	136
3	28	23	2295	63
4	31	27	154	91
5	41	35	1214	97
6	29	30	2427	71
7	42	23	143	123
8	49	49	1295	121
9	40	44	2409	86
10	55	-36	298	110
11	55	-13	1257	92
12	62	35	2498	76
13	65	62	152	114
14	67	59	146	120
15	72	71	148	127
16	76	69	142	143

Source: Gas Technology Institute

The key finding from each of these tests was the difference between the volume-average temperature and the centerline temperature. The volume-average temperature accurately represents average gas density, but it is difficult to measure. The centerline temperature represents local gas density, but it is simple to measure along the center axis of the cylinder. The difference between these two measurements determines the maximum error between the actual and measured density, which will determine the level of conservatism needed for the algorithm’s stopping point. Figure 18 shows the calculated density difference. The maximum difference between the measured density using the centerline temperature compared to the actual density is observed to be 1.5 percent. This indicates a vast improvement over the error in density with conventional NGV fueling protocols. The conclusion from this testing is that the fueling algorithm should conclude a fill at 98.5 percent of target fill density to ensure the cylinder is not overfilled.

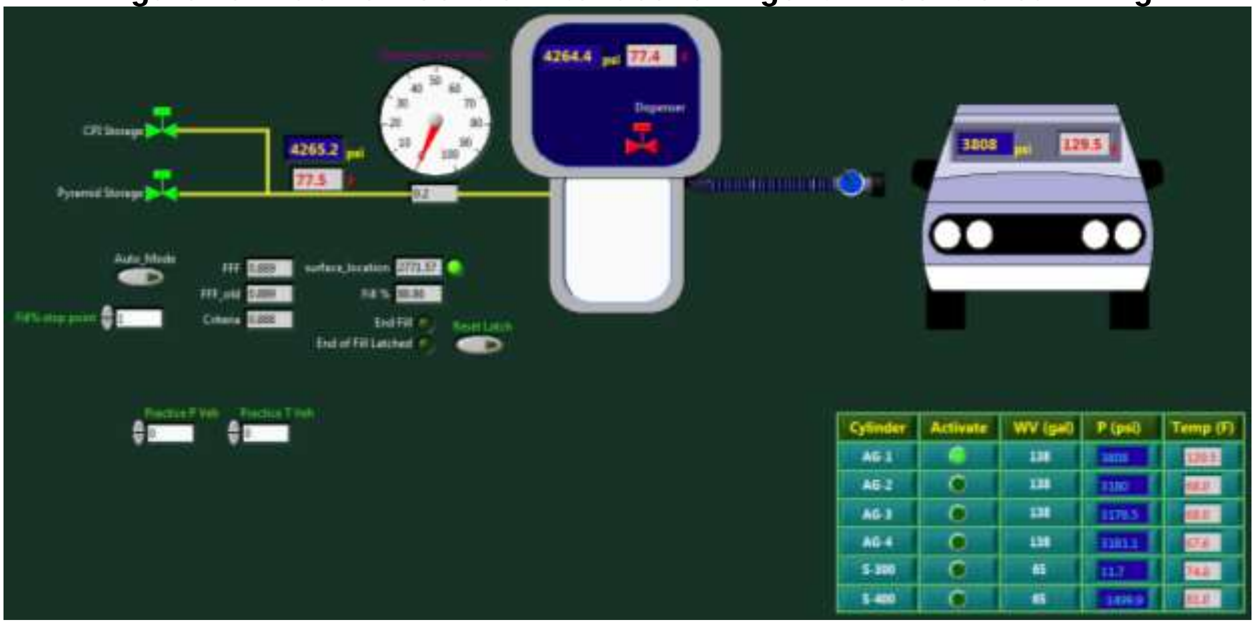
Figure 18: Error between Average Density and Density Measured on Centerline of Test Cylinder



Source: Gas Technology Institute

Test Plan 2 validated the preferred pressure-temperature fueling algorithm developed in this project. For simplicity, GTI tested the algorithm using hard-wired transmitters; the last portion of the testing validated wireless data transmission. The algorithm was programmed into the LabView control code. The "Full Fill Fraction" (FFF), or current fill level divided by target fill level, was displayed on the control screen and a trigger was programmed to automatically close the dispenser fueling valve when the FFF calculation reached 1.00. Although the results from Test Plan 1 concluded that the algorithm should target a shut off at a FFF of 0.985, GTI decided to start with 1.00 to determine if overfills occurred. Figure 19shows the control screen built for this calculation and dispenser shutoff. The programming in an actual dispenser would be conducted in a programmable logic controller (PLC), which would complete all of these calculations and control functions in the background without an interface.

Figure 19: LabView Control Interface for Algorithm-Controlled Filling

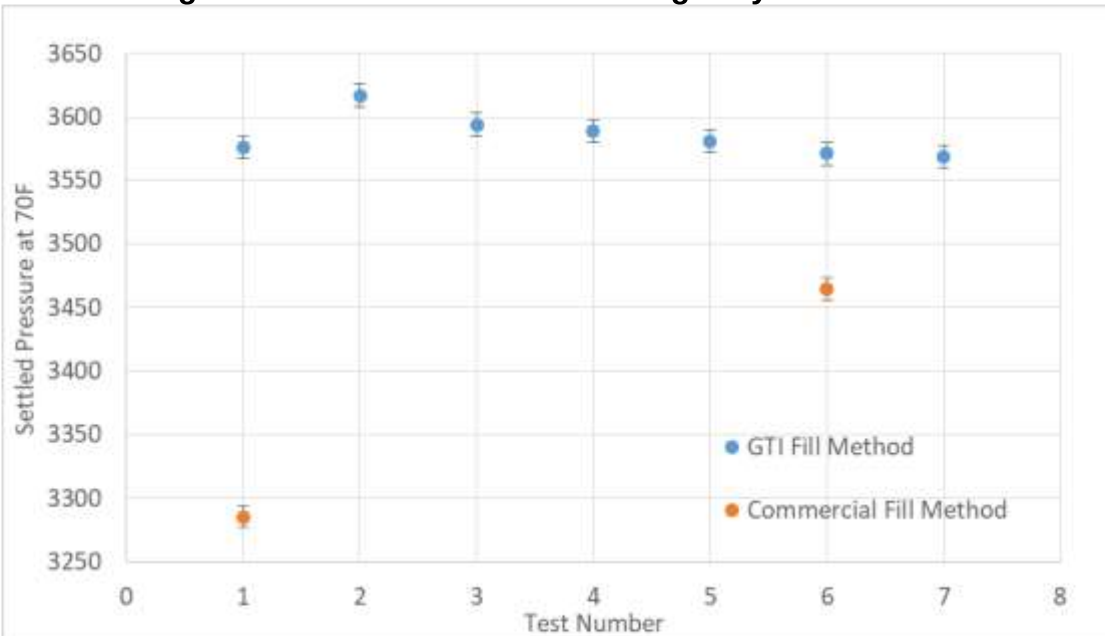


Source: Gas Technology Institute

The temperature and pressure blending table is shown at the bottom right of the LabView control interface shown in Figure 19. This table reads the measured pressures and temperatures of each cylinder and calculates an average temperature and pressure weighted by the water volume of each cylinder (the GGE capacity could also be used for weighting). For systems with multiple cylinders, this weight-averaging will need to be completed prior to calculating the full fill fraction for the system.

Due to the high ambient temperatures at the time of the testing, the initial target cylinder pressure needed to be very high to achieve a full fill within the pressure limits of the dispenser. Following the fill, the cylinder was allowed to settle overnight with data monitoring in progress, which allowed the measurement of the settled pressure at 70°F. Figure 20 shows the settled pressure for the seven tests in the test plan. Two fills using a commercial CNG dispenser were conducted with identical initial conditions and compared to the GTI algorithm results. The first of the two fills using the commercial CNG dispenser started with the target cylinder at ambient temperature. This resulted in a significant under-fill of approximately 10 percent. The second of these commercial fills started with the cylinder in a subcooled condition (initial temperature was 49°F). This test achieved close to a full fill, about 3.5 percent under-filled. These results highlight the effect of variability in initial cylinder conditions. Without measurement of the internal temperature, the dispenser must make the most conservative estimate (sub-cooled initial condition), usually resulting in an under-fill of the cylinder.

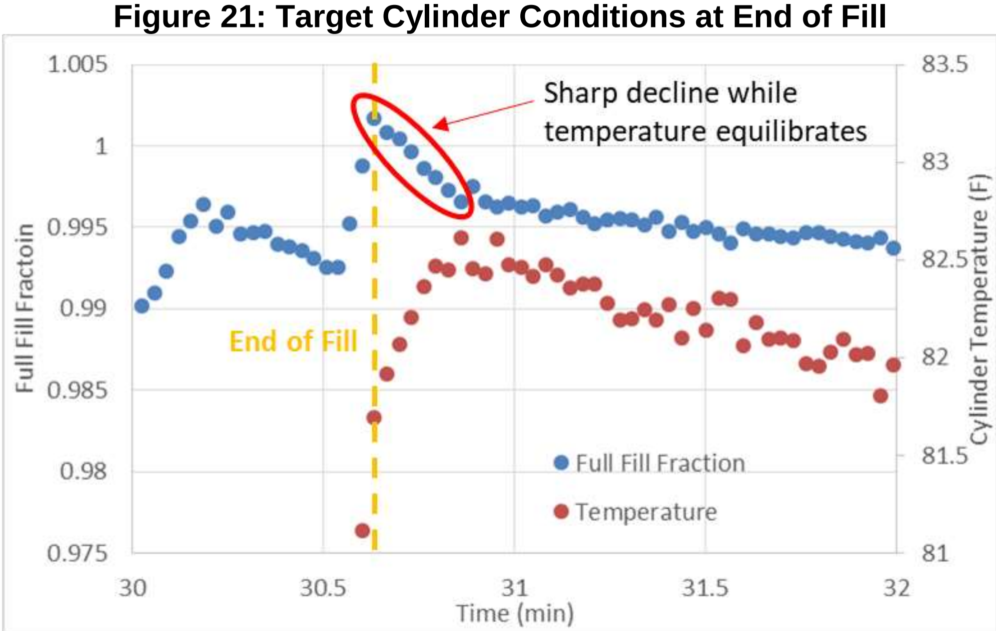
Figure 20: Settled Pressure of Target Cylinder at 70°F



Source: Gas Technology Institute

The test results in Figure 20 do not show the 1.5 percent overfill that was expected based on the results from Test Plan 1. Instead, the test data shows a minimum of 98.99 percent full and a maximum of 100.07 percent full. A closer look at the final few seconds of the fill helps understand what is preventing the overfill. Figure 21 shows the pressure and temperature readings for the last few seconds of the fill and the first few seconds after conclusion of the fill around 30.6 minutes.

Figure 21: Target Cylinder Conditions at End of Fill

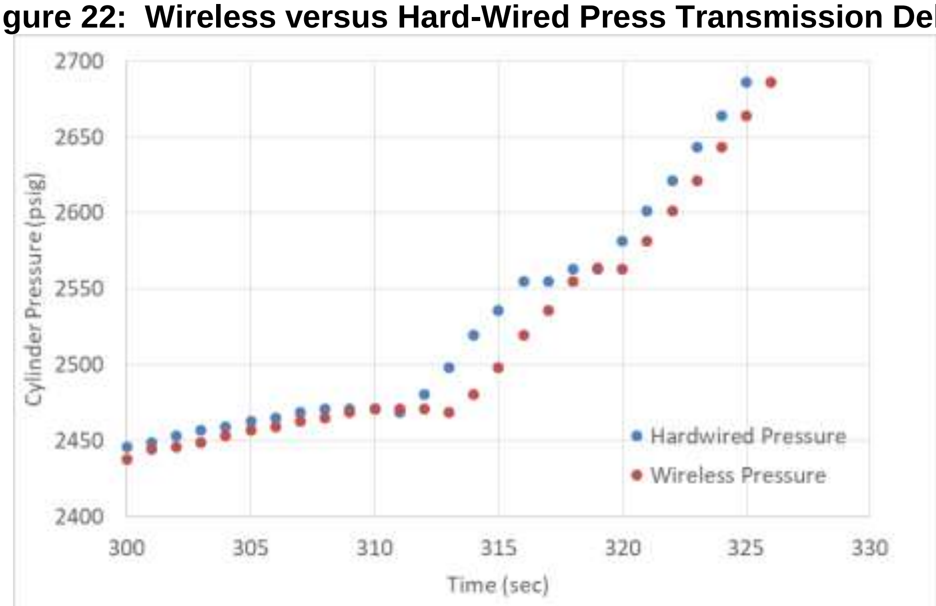


Source: Gas Technology Institute

When the fill concludes, the pressure immediately begins to decrease while the temperature continues to increase for about 10 seconds. This shows the delay time it takes for the thermocouples in the cylinder to come up to the temperature of the gas. This slight lag in the temperature measurement causes the FFF to calculate a slightly higher (~1 percent) density than actual, resulting in a slightly conservative fill termination. This effect will be reduced in slow fill cases, which is why test #2 (30 minute fill time) shows the highest settled pressure. This effect will need to be described more completely prior to deploying a commercial version of this algorithm.

Lastly, GTI completed tests to validate the wireless connection protocol developed during the project. To evaluate the wireless connection protocol, GTI used both a hardwire and Bluetooth wireless transmitter device to connect the pressure and temperature sensors to the LabView control software. A second Bluetooth receiving device received and reported the data into a separate LabView channel. Two key factors were validated during the testing: 1) connection between the two Bluetooth devices could be established within 5 seconds of the devices being activated, and 2) the delay time in transmitting the measured signal was minimal. The LabView software used for this validation created an automatic delay of 1 second due to the control software taking around 1 second to solve its control loop. Therefore, the system could only achieve a minimum delay of 1 second. Any delays longer than 1 second would not be measured until the second loop was completed, 2 seconds past the initial measurement time. As shown in Figure 22, the wireless-transmitted signal was recorded 1-2 seconds after the hard-wired signal. While it is valuable to know that there were no unexpected delays in transferring the signal wirelessly, an actual dispenser would employ a programmable logic controller which will solve up to 10 times per second and the delays shown here are expected to be much shorter.

Figure 22: Wireless versus Hard-Wired Press Transmission Delay



Source: Gas Technology Institute

Test Conclusions

There are three conclusions drawn from the data presented above:

1) Measuring the temperature at the centerline of the cylinder results in a maximum error in the measured gas density of less than 1.5 percent.
2) The algorithm developed on this project has demonstrated termination of all fills above 99 percent full, with only one very slight overfill (within the error of the pressure transmitter).
3) The testing demonstrated establishing a wireless connection between a vehicle and a dispenser and performing a fill using data transmitted from the vehicle.

With these demonstrated results, the researchers concluded that the algorithm developed during this project is capable of fueling a vehicle to very near 100 percent full in every thermodynamically possible case. Further development should be focused around packaging this algorithm, along with the wireless data transmitting hardware, for inclusion in dispensers and vehicles, respectively. Developing a commercially viable communication protocol and algorithm will have an immediate impact on the accuracy and safety of CNG full fills, and will help to maximize the impact of any pre-cooling added to stations in the future.

CHAPTER 4: Technology and Knowledge Transfer Activities

Sharing of Knowledge

This section explains how knowledge gained from the project will be made available to the public, including the targeted market sector and outreach to stakeholders.

GTI's 75 years of experience managing and reporting on research, development, and deployment projects like this will support appropriate reproduction and documentation of experimental results. GTI has also received almost 1,200 patents and has entered into 750 licensing agreements, along with equity positions in several portfolio companies, which is proof of its ability to move the results to the public domain.

A first step in disseminating the knowledge gained on this project will include publishing the findings with the CEC in publically accessible reports. These reports will detail the technologies that were studied as well as the results of the testing.

Utilities are also a critical stakeholder group for natural gas vehicles, so there is an emphasis on transferring information to them. The first point of contact will be sharing technology details with SoCalGas. SoCalGas is a leader in sponsoring natural gas vehicle research and development. Furthermore, they excel at the outreach and marketing of new technologies to their customers and their broader connections to end user natural gas vehicle fleets. SoCalGas was a member of the project Technical Advisory Committee and they are interested in the results of this project. Technology transfer to SoCalGas has been, and will continue to be, accomplished through several different means including sharing details on the technologies, capabilities, and testing results as well as through regular meetings to discuss the status of the technology. Moreover, it is expected that they could support further research and demonstrations in the future.

Industry suppliers and equipment providers are also a key component to the transferring of the technologies to the commercial market. GTI has worked closely with many of these industry stakeholders, including ANGI Energy Systems and Agility Fuel Solutions, throughout the duration of the project to ensure the technology being developed was viable, and of commercial interest. While there are no commercial agreements in place at this time, stakeholders have continued to express interest in further developing the technology and continuing to demonstrate the benefits across a range of operating conditions.

Another important avenue for disseminating the knowledge learned during this project is through presentations to industry at conferences, workshops, and forums. The Natural Gas Vehicle Technology Forum and the Alternative Clean Transportation Expo would be the type of events that this information could be shared with interested stakeholders such as gas utilities, tank manufacturers, dispenser and station manufacturers, and vehicle manufacturers. GTI has already presented some of the recommendations and results to industry members at these events in past years, and plans to continue providing updates in years to come.

Lastly, GTI has started to work with CSA Group to develop codes and standards surrounding some of the work discussed in this report. Areas that might benefit from standardization include communications and the algorithm used in conjunction with communication. A task force has been approved by CSA to begin taking a closer look at the required standards, and how they might fit into the existing landscape.

Intended Uses

This section of the report gives a description of the intended uses for and users of the project results. As described above, suppliers of dispensing equipment and vehicle fuel systems will need to be involved in the commercialization of the communications and sensing hardware, as well as the improved algorithm for achieving full fills. At this time, the preferred approach is to make the design standardized for utilization across the industry. To accomplish this goal, GTI is working with CSA group to develop standards and language describing the use and application of the technology to improve full fills across all vehicle segments.

Published Documents

To date, there have been no published journal of periodical articles that were based on project research. The project team will notify the CEC when articles are published. The team will also provide copies of any such documents, fact sheets, journal articles, press releases, and other documents prepared for public dissemination, when they become available.

Policy Development/Public Requests

GTI has presented a high-level overview of the work done in this project to CSA Group to consider development of standards surrounding communications methods between vehicles and dispensers, as well as possibly standardizing the algorithm to be used with communications. CSA Group hired GTI to write a guiding document discussing challenges with temperature compensation and full fills. This guiding document will be the start of a new standard that will cover safe full fills and dispensing algorithms, and may lead to additional standards for communications. The project team will notify the CEC if standards related to this project's work are published.

Technology Transfer Activities

The technology transfer activities to project stakeholders will follow the plan above. As the partners and stakeholders grow and activities continue, the project team will notify the CEC. The team will continue to work toward the near-term commercialization of these technologies. When directed by the CEC, the team will prepare presentation materials for CEC-sponsored conferences or workshops.

CHAPTER 5: Conclusions

This project validated that under-filling is a significant issue faced by the CNG industry, which results in increased vehicle costs and weight. To address the issue of under-filling, GTI conducted a detailed analysis of the CNG filling process, worked to develop an advanced full fill algorithm to improve the accuracy of the filling process, explored multiple pre-cooling options to address heat of compression, and validated the work with physical testing.

During the project, GTI successfully developed a safe, accurate filling algorithm capable of achieving a full fill across a wide range of filling conditions and gas compositions. The algorithm more accurately predicts a full fill compared to the state of the art while preventing overfilling. This algorithm required some additional temperature and pressure sensing on the vehicle, as well as a method of vehicle-to-dispenser communication to accurately determine the state of the fill. These additions were demonstrated to be feasible and accurate using real-world testing and validation, demonstrating that a CNG cylinder could be consistently filled to 3,600 psig at 70°F. GTI also investigated multiple pre-cooling strategies to overcome the heat of compression that prevents full fill as the ambient temperature increases. The best short-term solution for pre-cooling was found to be a commercial chiller system that is used to cool the dispensed gas to about 20°F before it enters the vehicle. The most promising long-term solution was the development of a gas expander that could be used to achieve isentropic cooling of the gas dropping in pressure as it flowed into the vehicle. The development of an expander has the potential to achieve full fills without the need for additional power and working fluids necessary for the operation of a chiller.

Ultimately, the project successfully demonstrated an improved full fill algorithm that can help to immediately improve fills for fleets and stations that choose to adopt the technology. However, the algorithm alone is not a complete solution, and must be paired with a cost-effective pre-cooling design to guarantee full fills year round. Accomplishing this long-term goal will provide significant benefits to the NGV industry, including consistent range and performance of NGVs, as well as cost and weight savings as the size of existing fuel systems can be significantly reduced.

CHAPTER 6: Benefits to Ratepayers

This project could dramatically improve fueling experience, cost (due to decreased vehicle storage requirements), and system efficiency for fleets that are most critical to rapid adoption of NGVs. Providing consistent, full fueling of NGVs will improve the satisfaction of fleet end users and potentially increase adoption in fleets that are sensitive to range. Challenging key markets are regional and long-haul trucking industries (Class 7 and 8 vehicles) because of demanding range specifications (more than 600 miles a day) and almost exclusively rely on fast-filling which has led to some disappointing trial experiences due to the poor fueling performance of current dispensing systems. After evaluating conservative estimates that improving full fills could affect 1 percent of the regional and long haul market to use CNG instead of diesel, it is clear that the potential benefits of this project are considerable.

According to the United States Department of Energy's Transportation Energy Data Book, in 2012 there were about 242,000 new Class 7 and 8 trucks sold in the United States [1]. If 1 percent of these trucks use CNG instead of diesel, there would be 2,420 new CNG trucks made every year. On average, Class 7 and 8 vehicles each use about 11,310 gallons of diesel annually [2], so this would lead to an annual reduction of 27,370,200 gallons of diesel nationwide. The environmental impact of this reduction can be calculated based on the California Low Carbon Fuel Standard's reduced carbon intensity factor of CNG over diesel (68 gCO2e/MJ vs. 98.03 gCO2e/MJ) [3], leading to a reduction of more than 120,000 tons of CO2e emissions per year nationwide. With 10 percent of all medium- and heavy-duty trucks in the nation registered in California, this could lead to annual reductions of 2,737,020 gallons of diesel and 12,000 tons of CO2e emissions [4]. Furthermore, a large fraction of the natural gas used in NGVs in California is renewable natural gas, resulting in further displacement of CO2e emissions.

For fleets that put increased incremental cost at more of a premium than increasing range, there is an opportunity to reduce their storage capacity by 20 percent and retain the same range. A reduction in storage capacity of 20 percent could lead to a reduced cost of the fuel storage system by about 10 percent, or $5,000 per vehicle for some heavy-duty storage systems. There will also be fuel economy advantages from having decreased storage and hence decreased weight. For example, removing 20 percent of the storage from a five-vessel back-of-cab system would remove 500 lbs. A Center for Transportation analysis estimates Class 8 trucks use between 6.5 to 8.7 gallons per thousand ton-miles [5]. This means a savings of 500 pounds in CNG cylinders will increase fuel economy, and reduce the fuel consumed by 1,625 gallons to 2,175 gallons over a million mile vehicle lifespan. This reduced fuel consumption translates to $3,932 to $5,263 in fuel savings (based on a CNG cost of $2.42/GGE) for drivers in California as well as provide significant emissions benefits [6].

LIST OF ACRONYMS

Term	Definition
˚F	Degrees Fahrenheit
CNG	Compressed natural gas
CO2e	Carbon dioxide equivalent
CSA	Canadian Standards Association
DGE	Diesel gallon equivalent
FFF	Full fill fraction
GGE	Gasoline gallon equivalent
GTI	Gas Technology Institute
J-T	Joule-Thomson
lbs	Pounds
MJ	Megajoule
MPa	Megapascal
NGV	Natural gas vehicle
NIST	National Institute of Standards and Technology
Psig	Pounds per square inch gauge
P-T	Pressure-Temperature
SCFM	Standard cubic foot per minute
TAC	Technical Advisory Committee

REFERENCES

[1] Davis, Stacy C., Susan W. Diegel, Robert G. Boundy. (2014). New Retail Truck Sales by Gross Vehicle Weight, 1970–2013. http://cta.ornl.gov/data/tedb33/Spreadsheets/Table5_03.xls

[2] Davis, Stacy C., Susan W. Diegel, Robert G. Boundy. (2014). Summary Statistics for Class 7-8 Combination Trucks, 1970-2012. http://cta.ornl.gov/data/tedb33/Spreadsheets/Table5_02.xls

[3] LCFS: http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf

[4] United States Census Bureau Vehicle Inventory, Use Survey, Table A: www.census.gov/prod/ec02/ec02tv-us.pdf

[5] Cost referenced from United States Department of Energy Clean Cities Alternative Fuel Price Report, June 2014, West Coast Avg

[6] Center for Transportation: http://cta.ornl.gov/vtmarketreport/pdf/chapter3_heavy_trucks.pdf

[7] CSA/ANSI NGV 4.1-2018: Natural Gas Vehicle (NGV) Dispensing Systems