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Compressed natural gas (CNG) transit bus experience survey: April 2009—April 2010

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A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory
Innovation for Our Energy Future

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Subcontract Report
NREL/SR-7A2-48814
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Executive Summary

The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) commissioned this survey to collect and analyze experiential data from U.S. transit agencies with varying degrees of compressed natural gas (CNG) bus and station experience. This information helps DOE and NREL determine areas of CNG transit bus success and priority areas for which further technical or other assistance might be required to enable success.

Clean Vehicle Education Foundation (CVEF) staff and subcontractors developed a battery of questions and identified 10 transit agencies to represent all U.S. transit agencies that use CNG buses, accounting for the diversity in characteristics such as fleet size, management system, station ownership and operation, and geographic location. The survey was conducted onsite.

The study found that the average fuel economy in CNG buses is approximately 20% lower than in diesel buses, although there is reason to believe that this gap will be narrower for new CNG and diesel engines. Based on a recent 12-month period—and after adjusting for energy content, bus fuel efficiency, station maintenance and power costs, and fuel-cost subsidies—the average CNG cost was $1.06 per diesel gallon equivalent.

The survey also captured qualitative information from the transit agencies in the following areas:

- CNG bus specification
- CNG bus operations
- CNG station specification/design
- CNG station operation
- CNG garage upgrades.

Transit agencies that are operating newer CNG buses reported adequate power and improving fuel economy. The following were reported as the main engine issues requiring additional development:

- Reliability of engine sensors
- Further fuel economy improvement
- Increasing the number of mainstream engine suppliers (there is now only one) and support for engines supplied by companies that have left the CNG engine market
- Addressing high engine temperatures (developments such as electric-drive fan systems have addressed some high-temperature issues).

Most agencies had limited concerns related to the design and reliability of their CNG stations, although some acknowledge that an inoperable station could ground their fleet (whereas a bus problem would ground only a few buses). Infrastructure observations included the following:

- Agencies with gas-engine-driven CNG compressors generally indicated a future preference for electric-drive compressors to eliminate the high maintenance and low reliability related to gas-engine drives.
- Several agencies continue to see oil carryover problems that must be addressed through research.
- Agencies stressed the need for redundancy in station equipment and the need to ensure that dispensing systems are designed to independently fill all buses simultaneously to avoid batching, which slows fueling.
- Agencies employed a variety of CNG station operation strategies—some providing maintenance in-house and some contracting out. Agencies tended to be very satisfied with whichever strategy they had selected, and there was no clear best approach.

Agency-identified needs for government assistance included the following:

- Agencies were universally pleased with the $0.50 per gasoline gallon equivalent fuel subsidy, praising the extent of the subsidy and the efficient means by which it is delivered. Some agencies wanted the subsidy to be made permanent because their bus purchases are 12-year commitments, and they must quantify operating costs.
- Agencies identified a need for government to assist engine manufacturers in entering the CNG market and developing durable products.
- Agencies indicated a need for more durability and fuel economy testing.
- Many agencies expressed a need for help in training existing employees and increasing the pool of CNG-trained technicians.

This report is limited to CNG-specific issues and does not address other bus issues. It is a summary of information collected from the surveys and thus does not necessarily reflect the opinion of CVEF or the author, and it is not necessarily exhaustive and complete in all areas discussed. Therefore, this report should not be considered a code or a specification, and its use should not preclude the use of other resources and professional advice.

Acknowledgements
Although the individuals and agencies surveyed and quoted herein are not named (to allow them to remain anonymous), the author thanks the many staff members of transit agencies who gave their time. The author also thanks Charles (Brooks) McAllister, who played a very significant role in the planning of this survey and in the design of survey questions.

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Survey Background and Purpose

The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) provide technical research and implementation support for a variety of alternative fuels, including compressed natural gas (CNG). The transit industry is a major segment of the CNG vehicle market, with CNG bus purchases often accounting for 20%–25% of U.S. transit bus sales over the past 10–15 years. Based on recent NREL data, the use of CNG in transit fleets has resulted in a reduction in petroleum consumption of more than 200 million gal/yr.

To illustrate lessons learned by CNG transit agencies and to help focus future support of the CNG market, DOE and NREL sponsored the survey-based collection of quantitative and qualitative information from a representative sample of CNG transit fleets, including the following:

- **Vehicle and engine information:** bus manufacturer, date purchased, engine make and model, fuel storage system design (tank size, make location, etc.), total mileage, and drive cycle
- **Operational information:** total mileage, duty cycle, major maintenance issues for each bus, additional preventive maintenance specific to the natural gas fuel system and engine, information (causes and solutions) about natural gas system failures
- **Vehicle and engine modifications to support the natural gas system:** including modifications to the engine required by the original equipment manufacturer (OEM) or converter
- **Fueling information:** fueling station type, capacity, performance history, maintenance schedule and history, ownership, fueling location (indoors or outdoors)
- **Facility information:** facility modifications necessary for fueling/maintenance of CNG buses
- **Other issues:** outstanding issues with natural gas vehicle (NGV) technology (engines, storage, fueling systems, performance) that require additional development.
- Future work could examine other CNG markets such as garbage trucks, school buses, and light-duty vehicle fleets.

Survey Approach and Methodology

Given the depth and breadth of information desired, the project team decided that onsite interviews were the most practical and efficient method for collecting data from a representative sample of U.S. CNG transit fleets. The team assembled a battery of approximately 300 questions and data requests, understanding that not all respondents would complete all requests owing to applicability and data availability issues. NREL and DOE reviewed the survey questions. Appendix A shows the final survey form.

The team chose a sample of transit agencies to meet the following requirements:

- Geographic and climatic diversity
- A range of fleet sizes
- Different fleet-management approaches
- Different CNG station operational approaches
- CNG programs with several to many years of experience.

Although both liquefied natural gas (LNG) and LNG-to-CNG stations are used in the transit industry, this survey focused solely on CNG stations to maintain consistency in the data collected. Of the 11 potential agencies originally selected for the survey, three were unable to participate and were replaced with two other agencies, for a total of 10 survey participants. The participants chosen were representative of the requirements listed above.

Several fleets operated a combination of heavy transit buses (including 35-, 40-, and 45-ft buses—referred to in this report collectively as 40-ft buses), articulated buses (referred to in this report collectively as 60-ft buses), and small buses such as cutaway vans for paratransit. To keep the focus on the target 35–60-ft buses, paratransit bus data were removed from the survey data. To the extent possible, the fuel economy data for 40- and 60-ft buses were recorded separately, although fleet-average fuel data comingles 40- and 60-ft buses.

Survey questions were emailed to each participant shortly before the onsite survey. The onsite survey was conducted in person, usually on the transit property site with transit agency (and/or bus operations contractor) staff who are involved with bus maintenance, station operation, and general operations management. After the survey interview, the interviewer transcribed the information collected into a spreadsheet. This spreadsheet was emailed to respondents so they could confirm the transcribed data and provide data unavailable at the time of the survey.

The transcribed files were compiled into one master file for analysis. This master file is not provided with this report to maintain the anonymity of participants.

This final report summarizes data collected, itemizes lessons learned and best practices, and provides operational statistical information where available. This information informs current or prospective CNG transit agencies of design and operational issues that might affect the successful implementation of CNG in their fleets. This report also identifies areas in which further development of technology or policy could assist in the implementation of CNG as a transit bus fuel.

Practical Limitations to Data Collection and Reporting

In designing and executing a targeted small sample survey such as this, the project team acknowledged the limitations of data collected, including the following:

- Although many questions were asked, respondents tended to focus on items that are current issues. Thus, this report tends to reflect current issues and experience rather than issues that are no longer considered relevant or pressing. For example, a fleet may be experiencing an issue with older technology, but, because they understand the issue and know it is related to obsolete technology, they might not comment on it.

- All agencies were not expected to respond to all questions. Some data do not apply to some agencies, and some data that are not tracked directly would require prohibitive amounts of time to assemble. Efforts were made to collect readily available data without imposing onerous requests on the participants. The project team also moved toward an emphasis on qualitative or anecdotal information—these "war stories" or lessons learned often summarized the most critical issues faced by agencies.
- There was interest in benchmarking CNG against diesel in terms of operating costs, fuel economy, and reliability. However, this comparison was found to be impractical with the sample fleets because many have retired all or most of their diesel fleet and, in many cases, the diesel buses that remain are not comparable to the CNG buses.
- There were limitations in comparing CNG fleets with each other in some areas. For example, different fleets calculate the commonly used benchmark mean distance between failure (MDBF) using widely varying criteria; a range of MDBF values from 1,778–7,376 miles was observed, precluding direct comparison.
- Recommendations in this report are a summary of responses and may not provide a comprehensive, exhaustive source of all best practices or industry or code standards. Readers are encouraged to use this report in combination with other sources and professional advice.

Analysis and Findings—Quantitative Data

This survey included 10 transit agencies with CNG fleet sizes of 15–2,509 CNG buses. The survey covered a total of 24 garages and 4,071 CNG buses.

To facilitate easier comparison with diesel data, CNG consumption is converted to diesel gallon equivalents (DGE) using a conversion of 137 standard cubic feet (scf) or 1.37 therms of CNG per DGE.

Fuel-Efficiency Data

Benchmark drive train/fuel efficiencies (i.e., fuel economies) were taken from data supplied by North American Bus Industries for a number of bus manufacturers tested over several years at the Altoona Bus Research and Testing Center. These data may not exactly reflect the duty cycle of the buses in a given fleet application; however, the various tests were performed under controlled conditions, so the *relative* fuel economy from the tests should be accurate. Altoona CNG fuel economy lagged diesel by 20%, although anecdotal industry experience has indicated that CNG is closing the gap with diesel in terms of fuel economy.[1] The historical Altoona figures are summarized in the table below:

Historical-Test Fuel Economy Data			
		Altoona Bus Testing (mpg/mpg DE)	Efficiency Compared to Diesel
40-ft bus	Diesel	4.33	100%
	CNG	3.48	80%
60-ft bus	Diesel	3.16	100%
	CNG	2.51	79%

Fuel economy data collected in the survey ranged from 2.5 mpg DE (miles per gallon diesel equivalent) to 3.9 mpg DE, with an **unweighted[2] average of 3.2 mpg DE[3]**—corresponding closely with Altoona testing. Although this average does not include light-duty vehicles such as cutaway vans, some 60-ft articulated buses are included. The survey attempted to collect data on individual bus/engine combinations to determine the effect of newer technology; however, this information was, in most cases, unavailable without significant analysis on the part of the agency. Recent tests at Altoona are a source for this type of data based on controlled testing and well-characterized bus technology.

The previously mentioned value is based on raw numbers for total miles driven and total fuel consumed within each fleet for which data were provided, so this is a bulk average using a recent 12 months of data. The survey also asked "What is your average fuel economy?" In all cases for which both raw numbers and calculated fuel economy data (as reported by the agency on the survey) were provided, the raw data indicated higher fuel economy than the calculated data—by as much as 1 mpg DE. Thus, it appears that the CNG fleets are delivering higher fuel economy than the operators believe. The drive-cycle fuel economy testing recommended in this report would help to determine a realistic fuel economy for new CNG bus fleets.

As previously indicated, there were very few diesel buses left in the fleets included in the survey. Those that remained were not typically operating side by side with CNG buses, so a comparison of fuel economy would be flawed.

Average Natural Gas Fuel Cost

The average fuel cost was calculated over a recent 12-month period by dividing the total gas cost by total gas use for each agency. The range of costs was \$0.71–\$0.94/DGE, with

[1] New CNG engines are achieving efficiency penalties of less than 10% compared with their diesel equivalents in full-load laboratory engine dynamometer testing (data from Cummins for CNG and diesel ISL engines); there is a need to use chassis/drive-cycle testing to compare the fuel economy of current CNG and diesel buses.

[2] This average does not adjust for the number of buses in various fleets and thus it is "unweighted"—the per-bus fuel economy for a 50-bus fleet is given the same weight as the per-bus fuel economy of a 2,000-bus fleet. This approach more accurately reflects drive-cycle and bus-equipment differences between fleets.

[3] Caution must be observed in calculating fuel economy. If gas engines are used to power the CNG compressors, their fuel consumption must be either backed out of the total or separately metered. Not accounting for this could increase the apparent bus fuel consumption by approximately 5%–10%. This is addressed in the fuel economy numbers presented herein.

an **unweighted average of $0.85/DGE**, for commodity gas delivered to site.[4] Several factors account for this range (outlined below); there is also additional cost for properties that are more remote from the source.

These fleets purchased little or no diesel fuel, so no direct fleet comparison of diesel cost to CNG cost was attempted. The study did not research outside fleet diesel fuel costs for comparison, although this would be useful for future studies.

The 12-month period used was closely overlapping but not identical for all agencies. This influences fuel costs because the cost of natural gas has been unusually volatile during the past 2 years.

A number of gas commodity purchasing plans are used by the agencies surveyed, including the following:

- No contract—monthly purchases from the local utility
- Six- to 12-month contract for half or all of expected consumption, additional fuel purchased monthly at spot prices
- All commodity gas purchased through contract, usually with a state agency managing purchasing for a large group of state and municipal fleets.

There does not appear to be a singular correct approach to gas purchasing because each approach can be the low-cost method, depending on the timing and trajectory of gas commodity costs. In the time frame included in this survey, it appears that agencies that purchased gas monthly had lower gas costs than those that contracted. This is intuitively correct because the past 12–18 months have seen a rapid decline in gas commodity prices followed recently by a modest rebound. Conversely, contracts may have been signed at higher prices, and new contracts would price in this volatility by charging a premium to cover the risk of commodity price escalation.

Agencies that had part or all of their gas under contract enjoyed protection from spiking prices in 2008, and they reported an additional benefit of being able to accurately budget for fuel costs over the next 12 months.

Station Power Costs

The survey collected a small sample of data on electrical costs to operate a CNG station from agencies that meter this power separately from the rest of their facility. The costs include energy and demand charges, metering charges, and any penalties for peak-period operation. The costs were $0.13–$0.23/DGE, with an **unweighted average of $0.18/DGE**. Electrical costs are driven primarily by several factors:

- Certain areas, such as California and New York, tend to have very high electrical costs and very high peak-period charges. This factor is essentially out of the agency's control.

[4] Caution must be exercised in calculating the gas cost because there are agencies that bundle this cost with maintenance and capital recovery for station construction. It is believed that the costs provided are net of these factors, which are addressed separately. The costs include any pipeline or utility transportation and metering charges.

- Station inlet gas pressure can have a marked effect not only on the power required but also on the capital cost of compression equipment. Using all available gas pressure at a site, or bringing in higher-pressure gas, can pay dividends initially, and every day the station is operated by reducing the compressor horsepower required to provide a specified flow. However, there may be an additional "pressure charge" from the gas utility, or a capital cost to pay for the extension of high-pressure lines to the site, for any increase in normal service pressure.
- Hours of station operation/type of operation affect the electrical cost. Agencies may consider limiting the amount of station equipment permitted to operate during high or mid peak periods to control this aspect of the cost. This factor should be considered in the design of a new station.

Of the surveyed agencies, the fueling sites included 11 electric-drive compressor stations and 13 gas-engine-driven compressor stations. Although the survey team was unable to collect actual natural gas consumption and cost data for natural-gas-engine-powered compressors, previous calculations have indicated that the engines consume 5%–10% of station throughput. Based on the average commodity gas cost of $0.85/DGE, the fuel gas cost would be in the range of $0.043–$0.085/DGE. As was the case with electric motors, this is influenced by local gas rates, inlet gas pressure, and the efficiency of the station design. Although the energy cost of using gas engines is attractive, there are significant other costs and complications, which are addressed later in this report.

Station Maintenance Costs

Care was taken in collecting maintenance costs, because there are many factors that could skew the costs from one agency to the next, such as the following:

- Agencies that perform most of their own maintenance did not always include this staff time in the maintenance total. This was added to these numbers to ensure uniformity.
- Some agencies that contract out maintenance on a throughput-charge basis have capital-recovery and/or power costs included in these numbers. Because these individual cost components were not available, these numbers were removed from the average calculation and are addressed separately.
- Some agencies have an effective extended warranty included in their bundled maintenance costs. These total costs were used for analysis because agencies that performed their own maintenance included all subcontracting and parts even if those included major repairs in a given year. Costs were averaged over a 3-year period to smooth out unusual or infrequent expenditures.

Comprehensive station maintenance cost was calculated on a per-DGE basis for those agencies not currently contracting on this basis and was compared with agencies that did contract on a per-unit-of-throughput basis. The range of values was $0.06–$0.23/DGE. It is believed that the $0.06/DGE number may not be fully representative; removing this value from the range results in an **unweighted average cost of $0.18/DGE**. Some of the maintenance data involve very-long-term station maintenance contracts, whose cost may not be reflective of the current market. Work done outside of this survey suggests that current maintenance contracts are generally in the **$0.20–$0.30/DGE range**. One agency reported much higher rates, but this included power and capital recovery.

Total Delivered CNG Costs

Based on the cost factors listed above, and assuming that a sum of average costs is a valid total cost, the average compressed cost of CNG at the nozzle is $1.30/DGE (using $0.27/DGE for maintenance) without accounting for capital cost recovery, which may be primarily paid through non-agency funds (e.g., Federal Transit Administration funding). For accurate comparison to diesel, the difference in fuel economy must also be included. Using a 20% efficiency penalty results in an energy- and efficiency-equivalent cost of $1.63/DGE for CNG. The current $0.50 per gasoline gallon equivalent (GGE) fuel tax credit would reduce this cost by $0.57/DGE to give a **net energy—and efficiency—equivalent cost of $1.06/DGE.** It should be noted that in many cases the price for diesel includes only the commodity cost, applicable additives plus delivery, and any surcharges that might be levied in a given state. Ongoing maintenance is traditionally absorbed in a general shop maintenance budget and not calculated in the overall per-diesel-gallon cost.

Bus Reliability

Most respondents stated that diesel buses would achieve higher MDBF than CNG buses. In fleets where both diesel and CNG data were available, the CNG MDBF was as low as 58% of the diesel value and as high as 80% of the diesel value. Respondents indicated they were not surprised by this statistic because the conventional (older-technology) diesel buses being compared to the CNG buses are simpler, with no ignition systems and very few engine sensors—the two areas that cause most CNG breakdowns.

MDBF addresses the entire bus and not just the CNG components, leaving the possibility that CNG buses have non-CNG components that might be reducing their MDBF. Several agencies estimated that about 30% of their breakdowns were related to CNG components—primarily sensors and ignition. Adjusting for this 30% would make CNG and diesel MDBF approximately equivalent. Two respondents expressed concern that new clean diesel buses using sophisticated exhaust aftertreatment systems are likely to be similar, or perhaps lower, in reliability than current CNG buses. This reinforces the importance of comparing equivalent-generation technologies to make robust comparisons between diesel and CNG buses. With 2010 bringing a significant change in diesel technologies, previous data must be used carefully.

Best Practices—Qualitative Data

The qualitative survey data and some numerical data have been distilled into recommended best practices related to new equipment purchases. Many of the recommendations below have become common practice in the industry and are often included in the applicable specifications. The recommendations are a summary of advice and comments provided by survey respondents—they are not intended to be exhaustive specifications. Readers of this report are encouraged to consult other sources of information, including qualified professionals, when specifying or operating CNG equipment.

Best Practices Related to Bus Specifications

Roof-mounted cylinders

Roof-mounted cylinders are widely used to facilitate lower floors in modern transit buses. The placement of cylinders on the roof has also proven to be desirable from a cylinder-safety perspective because agencies feel that these cylinders are less vulnerable to impact from road debris or collision. Although less vulnerable to normal hazards, several agencies related stories of impacts when the vehicles were being towed or when they were redirected to unapproved routes—standard operating procedures should be developed and implemented to mitigate these impact risks. Although not specifically raised as a current problem, given the history of problems with old pressure relief device (PRD) designs and installations, bus purchasers should ensure that PRDs are installed and vented in a manner that ensures that the gas release blows clear of the bus and cannot accumulate moisture on the vent side of the PRD.

20-year-life cylinders

Given that transit agencies are experiencing budget compression, a number of agencies are contemplating extending their bus life beyond the originally planned 12–15 years. If buses are kept beyond 15 years, the 15-year life on the cylinders will expire, and there is no mechanism available to extend the life of these cylinders. Agencies are recommending the purchase of 20-year-life cylinders on new buses to guard against this potential future cost.

Maximized gas storage

A number of agencies promoted equipping buses with the maximum number of gas-storage cylinders possible (typically eight cylinders per bus with approximately 3,000 scf each, a total of 24,000 scf on a 40-ft bus). This additional capacity ensures that all buses can operate on any route. The additional cylinders also allow some of these agencies the possibility of skipping a night's fueling in the event of a hard station outage.

Cylinder types

Transit agencies often had a mix of buses, some with Type 3 gas storage cylinders (lightweight aluminum liner with fiber overwrap) and some with Type 4 cylinders (polyethylene liner with fiber overwrap). None of the survey respondents indicated any concern or strong preference for one technology over the other.

External solenoid valves on each cylinder

Most CNG buses are now equipped with solenoid valves on each cylinder, and they should be incorporated into the specification. These solenoid valves greatly reduce the maximum potential release or leak if a bus vents gas. This is particularly important for buses entering buildings.

Addressing higher operating temperatures

To address the higher temperatures in CNG engines and exhaust systems (the energy that is not converted to power—the efficiency penalty—is converted to heat):

- Some agencies have had to retrofit older buses to reduce heat trapped in compartments housing exhaust system components.
- On new designs, bus manufacturers should be required to validate the installation of natural-gas-powered engines into buses to ensure that a buildup of heat does not occur.

Hydraulic line placement

Specifications should require the placement/routing of wiring and hydraulic lines, particularly in the engine compartment, in a manner that minimizes the possibility that the lines or wires would be compromised by the high heat in that compartment. Damaged hydraulic lines have been the cause of many of the fires that have occurred in CNG and diesel buses.

Fire-extinguishing system

Most agencies surveyed include a fire-extinguishing system on their CNG buses—a practice shared with most diesel buses. CNG systems often include gas (leak) detection sensors in the cylinder compartment and engine compartment with an alarm at the driver console. Dry-chemical extinguishing nozzles are generally provided in the engine and exhaust system compartments. Respondents advised that the location of the nozzles be reviewed because some of their buses had nozzle positions that did not address the highest-risk areas—the turbo and the exhaust manifold. Most of these systems include a manual release, often placed above the front bumper. Some early CNG buses with fire-extinguishing systems included nozzles in the cylinder compartment; this practice generally has been abandoned because there is little risk of a fire starting in this compartment.

Survey respondents indicated that bus fires are unusual on both diesel and CNG buses, and most respondents did not consider CNG buses to be any more likely to have a fire than a diesel bus; most did not consider their own CNG bus fires to have been CNG related. Fires on diesel and CNG buses are typically attributable to the following general categories:

- Exhaust system heat that builds up and causes the ignition of adjacent materials
- Hydraulic system leaks on hot components such as exhaust manifolds and turbochargers
- Electrical-system short circuits
- Operator error (brake or tire fire) or an accident.

Electric accessory systems

Four of the 10 agencies surveyed are testing electric accessory systems retrofitted to buses. The systems are supplied by Engineered Machined Products, Inc. and include a larger alternator, larger battery pack, and electric-drive radiator fan bank. All the agencies surveyed were positive to enthusiastic in their assessment of such a system, which is reported to improve fuel economy in excess of 5%, improve battery life (by keeping batteries charged more fully), and significantly reduce the possibility of an engine-compartment fire by eliminating the hydraulic hoses to the fan. All the agencies that are testing these systems indicated that they will specify this system on future bus orders. Two agencies indicated interest in expanding the system to include other parasitic loads (air conditioning compressor, air compressor, and power steering pump).

Fueling location

The fueling location on buses is typically curbside rear. Some early designs had the fill point on the rear of the bus and too high for easy access—most are now standardized to the side, in the area of the engine compartment. Most agencies require the fuel compartment door on the bus to be equipped with a proximity switch to prevent the bus from starting if it is shut down or to activate an alarm at the driver's console and shut the bus down after 15 minutes if the bus is running. Immediate shutdown was not recommended because agencies have experienced opening of this compartment by the public at bus stops.

Fueling connections

Most agencies now purchase buses with both the OPW 5,000 (high flow) and the NGV1 (light-duty vehicle) connectors. The light-duty vehicle fueling receptacle allows for off-site fueling, and, if the transit fueling station is equipped with a defueling system, the bus can be partially or fully defueled through the NGV1 receptacle using an OPW defueling nozzle. The NGV1 receptacle should be the type with an internal check valve (rather than an in-line external check valve) for this defueling nozzle to function correctly.

Gas flow tubing

Gas flow tubing from the fueling connection to the rooftop cylinders is recommended to be a minimum of 3/4-in outside diameter to minimize pressure drop and fill time. Connections to individual cylinders may be 3/8-in or 1/2-in outside diameter tubing, depending on the bus manufacturer. Valves and other components in the gas fill path should be selected to optimize fill speed.

Coalescing filters

Buses are now typically equipped with high-pressure and low-pressure coalescing filters on the lines feeding the engine. These filters are designed to operate at engine fuel gas flow rates and are intended as a last line of defense to remove CNG-station compressor oil from the gas stored on the bus. Several agencies have reported compressor-oil-related problems on engines—primarily with sensors and injectors. Specifying oversized filters (preferably by requiring the filters to be rated for at least twice the maximum flow rate at the minimum expected gas pressure) on the bus, and that each filter is equipped with a manual drain valve that is easily accessible and robust enough to facilitate frequent drainage, will ensure that the gas stream is as oil free as possible.

Best Practices Related to Bus Operations

The overriding comment from many agencies was that, unlike conventional diesel technology, CNG engines are less forgiving of extended service intervals. This is particularly true of ignition-system maintenance (plugs, wires, and boots) because a failure of these components can result in a melted piston or other expensive problem. Bus operators are therefore strongly encouraged to follow manufacturer-recommended minimum service intervals and be vigilant in identifying buses that require unscheduled repairs—power loss is often the first sign of an impending problem. This section outlines respondents' typical approaches to several common maintenance issues, but agencies are encouraged to closely follow manufacturer recommendations if they are more stringent than common industry practice.

Fuel filter maintenance

Agencies reported a wide variety of bus gas filter-draining and media-replacement intervals, ranging from daily while fueling (which is reportedly advocated by one or more bus manufacturers), to monthly, to approximately each 6,000 miles coordinated with engine oil changes. The need for filter drainage is very dependent on the type of compressor oil used and the sophistication of the filtration system at the CNG station. It is not practical to recommend one interval as the best practice; rather, based on suggestions by respondents, it appears that daily or weekly draining may be required initially (particularly because several agencies reported high quantities of oil from the trip from the bus manufacturer to the transit agency), then, as experience dictates, this interval could be extended to monthly or to coordinate with oil changes or other scheduled maintenance. The main determinant in extending the inspection interval is the quantity of oil collected; only very small quantities should be present at the time of draining. Using the manufacturer's recommendation as a guide, the experience of the fleet personnel should be the dominant factor in determining the selection of the maintenance frequency. This area may benefit from additional independent research. Additional comments are provided below in the station design and operations section.

Spark plug replacement

Spark plug replacement intervals ranged from 10,000–36,000 miles, with 18,000 miles being the most common. Intervals depended on engine type, and several agencies have adopted the use of iridium plugs to extend plug life. One agency indicated that, when it first used iridium plugs, it experienced very low life until a "clean" procedure was implemented—ensuring that the plug area was vacuumed and wiped, the boot was clean, and the new plug was not soiled prior to installation. This procedure resulted in a marked improvement in plug life to 30,000 miles. Many agencies reported that, although they try to keep plug change-out intervals at 18,000 miles or higher, they are often forced to change plugs at 10,000 miles. Other tune-up work, including valve lash adjustment, is generally scheduled to coincide with spark plug replacement at 18,000 or 36,000 miles.

Turbo chargers

There has been a significant history of failure of turbo chargers on Detroit Diesel Corporation (DDC) Series 50 CNG engines. These failures have escalated to bus fires on several occasions. Several agencies have attempted to implement proactive scheduled replacement campaigns to replace turbo chargers before failure. This was reported to be unsuccessful because the turbo life proved difficult to predict, and many failed before replacement. These agencies have reverted to a run-to-failure approach to this problem.

Hydraulic hoses

The hoses and wiring inside the engine compartment should be inspected at regular maintenance intervals and replaced if there is indication of wear or breakdown. One of the agencies indicated that it proactively changed hydraulic hoses within the engine compartment to reduce the risk of fire from hoses that have degraded.

Cylinder inspection

Most agencies have their own staff (or the staff of their bus operations contractor) trained to perform the required in-house inspection of CNG cylinders. The training program is provided by several entities and covers inspection techniques, various levels of damage, and safe cylinder disposal if a cylinder damage level is determined to require removal from service. Whether an agency uses its own staff or outside contractors, it is very important that:

- All cylinders are inspected at 36-month or 36,000-mile intervals as required by the governing code (NGV2).
- Records for each cylinder inspection are kept on file until the bus is retired from service or longer if there is concern the cylinders may be repurposed.

Best Practices Related to CNG Station Design

A major concern that causes agency operation personnel to "lose sleep" is the operational reliability of the CNG station. Several agencies noted that a bus problem may ground one or more buses on a given day, but a serious station problem may prevent fleet rollout. This concern has driven the need for redundancy of certain components, as noted below.

Expansion capability

In addition to providing some level of redundancy (as outlined below), agencies reported that they would advise new station owners to design for expansion capability. This might be done in several ways:

- Over sizing the station initially—this must be done carefully because equipment that is too large will tend to cycle more, causing reliability problems.
- Sizing the dryer, piping, and electrical systems so that the redundant compressor(s) can be operated simultaneously with all other compressors.
- "Roughing in" an additional pad and services and sizing the dryer, piping, and electrical systems for a future additional compressor(s).
- Providing space for additional dispensers and compressors to be installed at some future date.

Inlet dryer

An inlet dryer with a manual or automatic regeneration package is generally required to meet code-mandated gas quality and to prevent condensation problems that would impact fueling and bus performance. Although both types of dryer will prevent condensation problems, agencies should give consideration to using a single-tower or twin-tower *manually* regenerated dryer to reduce initial cost and to reduce the complexity of the dryer—leading to higher reliability. Manually regenerated dryers may be the best option in small- to medium-sized fleets and where gas water content is low.

Compressor size

Compressors are generally sized to meet the average fuel load per bus, multiplied by the number of buses fueled per night, divided by the productive time during a fueling shift. It is recommended that stations be equipped with enough compressors that the flow can be "scaled" to the fueling demand. For example, using one large compressor may require the compressor to cycle (load and unload) frequently when buses are fueling at less than design conditions, whereas using two half-size compressors allows the station to operate with one compressor only under partial load. Reduced cycling increases compressor reliability, and this arrangement may reduce electrical demand charges and increase the redundancy of the station.

Redundant compressors

It is preferable to provide redundancy by adding at least one more redundant compressor. For example, if the required flow to fill a fleet in the allotted time is 2,000 scf per minute (scfm), then a preferred design would be to supply three 1,000- scfm compressors—two to meet the fueling need plus one for redundancy. This arrangement typically will be more reliable and potentially lower cost providing two 2,000 scfm compressors—one for flow and one for redundancy.

Filtration system

Gas-filtration-system design is often overlooked but can pay large dividends. Most natural gas compressors inject oil into the gas during compression to lubricate compressor parts. Most agencies reported evidence of oil downstream of the compressors. In some cases, the quantity of oil was extreme, and the presence of oil is commonly cited by engine manufacturers in refusing warranty claims. With regard to the filters required to remove oil from the gas stream (note that other filters on the dryer and compressor inlet are also required), the best practice noted by agencies in this survey and best practice in the industry is to:

- Install interstage separators on compressors that are automatically drained to a collection tank
- Specify a pre-coalescing filter and a coalescing filter in series on each compressor discharge—automatically drained to a collection tank
- Design and orient storage to allow drainage of any condensate in each vessel
- Include with each dispenser one or two coalescing filters in series that can be manually drained
- Oversize filters by a factor of two or more (on a flow basis) to increase efficiency and increase media life
- Specify filtration systems to protect against damage to the media from rapid depressurization.

This level of filtration is conservative but will provide the best chance to minimize oil carryover levels to the buses.

One other issue related to filtration is the use of non-lubricated compressors. At least two brands of non-lubricated compressors are still available, although less widely used, in the transit CNG station market. Non-lubricated compressors can still experience oil carryover because oil migrates from the crankcase into the compressor cylinders; thus, although the volume of oil should be significantly lower, non-lubricated compressors still require oil filtration in the gas stream. Station owners have reported mixed reliability with non-lubricated compressors; thus, this report does not make a purchasing recommendation for or against non-lubricated compressors.

Electric compressors

Seven of the 10 respondents either currently or previously owned CNG stations with natural-gas-engine-driven compressors. Two of these agencies have already converted to electric-drive compressors, and two more indicated that they would go electric if they could do it over. Electric-drive compressors have several advantages over engine-driven packages: they are smaller, quieter, more reliable, more durable, have lower capital and maintenance costs, and require no special environmental permit. Engine-driven packages have the advantage of lower energy cost, no demand cost, and no need for a large power upgrade onsite during installation. Overall, the current industry trend is toward electric-drive packages. One of the agencies that converted to electric from gas implemented several energy-cost-saving technologies in its design to shift load away from peak periods.

System design

Two agencies expressed frustration with the design of the dispensing system. The system in question was a simple manifold that connected all of the compressors to the buffer storage and to all of the dispensers. When the system operates, it fills all of the connected buses at the same time, which results in a batching of the buses, in turn resulting in inefficient use of hostler labor. Several alternative dispensing-control systems are available—specifications should clearly require a system that ensures *independent and simultaneous* fueling of each bus and avoids batching. Transit fleet personnel specifying the installation of the dispensing system should carefully review the needs of their fleet to assure a proper match because this decision has significant functional and economic implications.

Standby generator

Given the current trend toward electric-drive compressors, there is also a trend toward the inclusion of a diesel or natural gas powered standby generator, either permanently installed or trailered to the site to address power outages that would prevent fueling.

Enhanced infrastructure design

Although respondents that contracted out the maintenance of their stations had lower expectations for the level of CNG station control and instrumentation sophistication required, several of those that maintained their own equipment recommended "all of the bells and whistles" to allow enhanced remote support and troubleshooting. Current industry best practice that provides these "bells and whistles" is to include analog instrumentation of critical pressures and temperatures in the dryer, compressors, storage, and dispensers with a controller that can be remotely accessed for monitoring and control over the Internet.

Best Practices Related to CNG Station Operation

Respondents generally indicated satisfaction with the reliability of their CNG stations. Agencies that manage their own maintenance were more aware of the various breakdowns and were more involved in rectifying station-down situations. These agencies generally indicated that the major station equipment operated with reasonable reliability.

Instrumentation

The area mentioned most frequently as a cause for station faults was instrumentation. It is recommended that agencies specify high-quality components that have a long history of successful use in the CNG industry. It is also recommended that analog components (such as thermocouples and pressure transducers) be used to replace discrete mechanical switches. The analog devices have no moving parts, which enhances reliability and durability and enables remote monitoring—allowing agencies to have a remote contractor diagnose and correct some faults.

Inventory of key components

The agencies performing their own maintenance advised the purchase of an inventory of commonly used components including transducers, fuses, filter cartridges, control valves and actuators, relief valves, compressor valves, rings, packing, and other parts that the manufacturer might recommend.

Inlet gas drying/filtering

Several agencies reported the presence of a water/oil mixture that degrades the performance of engine sensors. This situation requires vigilance to ensure that the station inlet gas dryer is fully functional and that the coalescing filtration system is adequately designed and maintained to ensure that oil is being effectively removed from the gas stream. Many stations with older compressors and dispensers may lack an adequately designed filtration system and may require an upgrade.

Although not specifically mentioned by any of the survey respondents, it is highly desirable to track the oil added to the compressors and similarly to track oil drained from the various condensate receivers, filters, and storage. It is recommended that this tracking be done on an ongoing basis and based on the *weight* of oil added and drained—due to difficulties in accurately measuring the volume of oil. Over time, these records (kept in a spreadsheet) can be used to determine the efficiency of the filtration system.

Two respondents indicated that their dryers had been bypassed for extended periods due to unresolved repairs. Unlike the compressor, full dryer operation is not required to fuel buses—thus there is a temptation to de-prioritize dryer problems. This is potentially dangerous because there have been dryer fires and other incidents linked to inadequate service. Also, there can be nuisance problems in the station and on the bus related to moisture in the gas, and there is potential for catastrophic failure of some components if moisture is present. The desiccant degrades over time and with each regeneration. Most dryer manufacturers claim a 5-year lifespan on desiccant, at which point it will need to be safely disposed of (as a hazardous waste) and replaced with new desiccant, which should be immediately regenerated. Proper dryer service and repair is essential to meeting fuel specification codes—including SAE J1616, CARB, and NFPA 52—and to ensure that agencies do not experience collection of an oil-water emulsion that may plug bus fuel filters.

Compressor oil

CNG stations have long been known to contribute oil carryover, causing vehicle fuel-system problems. Previous research has indicated that compressor lubricator oil type would be a strong contributing factor in the degree of oil carryover. Conventional mineral-based oils were known to vaporize under the pressure and heat present in a compressor; this vaporized oil cannot be filtered with coalescing filters, which will only remove fine mist or aerosol oil. Synthetic oils were less volatile and therefore less likely to cause oil carryover because the oil remains in liquid form and can be filtered, assuming the filtration system is adequately and conservatively designed. Based on research at the Gas Technology Institute in the 1990s, a number of CNG station manufacturers and station operation contractors have adopted the use of polyalkylene glycol (PAG) based synthetic oils. PAG oils are very resistant to vaporizing in CNG applications, which allows them to be filtered very efficiently; however, they have shelf-life issues, and they are incompatible with some paints (used in crankcases), some seal materials, and mineral-based oils.

Most respondents used synthetic oils. About half used PAG oils, which can be a viable solution for a new bus fleet with no history of mineral-based oils. The other half used Diester-based synthetic oils, which are more volatile than PAG oils but are also more forgiving because they are compatible with both PAG and mineral-based oils and do not have the solvent effect that PAG oils have on some paint and seals. Some industry maintenance personnel suggest the use of Diester oils if an agency is looking to transition to PAG in the future.

Any decision to change oil types should be approved with the oil manufacturer, the compressor and CNG station manufacturers, and the bus and cylinder manufacturers.

Station maintenance

Many agencies contract some or all of their CNG station maintenance work to third parties. This approach is favored by some agencies because there is a high technical skill requirement that is outside of the agency’s core competency and mission—to operate reliable bus service. Respondents generally adopted one of the following approaches:

- Provide all or most of the CNG station maintenance using in-house personnel
- Provide light maintenance (walk-around inspections and possibly oil changes) using in-house personnel and contract specialized or more invasive maintenance and repair tasks on a fee-for-service basis

- Contract out most or all maintenance based on a fee-for-service or annual contract, which may include what amounts to an extended warranty on equipment.
- Contract out all maintenance based on a fuel-throughput charge, with minimum throughputs guaranteed by the agency; this contract typically includes what amounts to an extended warranty on equipment.

Agencies surveyed had 5–20 years of CNG station ownership experience. Thus, all agencies had time to develop and stabilize their maintenance approach, and most agencies were satisfied with their current maintenance approach.

Of the surveyed agencies, three used approach “a” above—providing most of their own maintenance. A fourth agency had used this approach on one of its two stations, but the retirement of a key employee caused the agency to switch to approach “d.” Agencies using the “a” approach were among the longer-term owners of CNG stations and tended to be small- to medium-sized agencies. This group liked the control that they experienced using their own staff, and their maintenance costs tended to be the lowest in absolute dollars but higher on a per-unit-of-fuel basis (because these are smaller stations). Two agencies indicated that they would like to be able give this responsibility to an outside contractor, but they were concerned that an outside contractor may not feel the urgency to make a down station operational, and they were concerned about the extra cost.

One respondent was using approach “b”; several other agencies had started with this approach and migrated toward the “a” approach. The agency using approach “b” was a smaller agency, and it appears that its maintenance costs were among the lowest in the survey.

Three small- to medium-sized agencies used approach “c,” contracting out all maintenance. These contracts took different forms, from fixed price to time and materials. The agencies using the time-and-materials basis had the lowest absolute and per-unit maintenance costs of the survey.

Those using approach “d” tended to be the largest transit agencies. This throughput-based maintenance program is most viable where large throughputs can spread the costs. Agencies using this approach were generally satisfied and felt that this method allowed them to budget more predictably and avoid unexpected, expensive equipment failures. These contracts generally include some type of damages clause ($X00.00 per bus that is not fueled by the end of the fill shift). There was no indication that any of the agencies had ever needed to claim these damages. Two large agencies that currently or previously used both approach “a” and “d” reported that they preferred approach “d” because it allowed them to focus on their core activities.

In summary, all agencies appeared to be satisfied with their current maintenance approach. Small- to medium-sized agencies tended to take on more of the maintenance responsibly in-house to reduce costs, whereas larger agencies tended toward contracting maintenance on a per-unit-of-fuel-throughput basis.

Best Practices Related to CNG Garage Upgrades

Data provided for this section of the survey tended to be of a general nature. Respondents were typically bus or station personnel with less involvement in the design, construction, and operation of garage facilities. The surveyor was unable to get building-upgrade costs from any agencies because this work would have been administered by others and may not have been exclusively to address CNG upgrades.

All of the agencies surveyed performed some level of building upgrade or, in the case of new facilities, some customization for CNG. This section summarizes features/approaches that were common to most facilities.

Sloped roofs

Agencies building new CNG garages tended to use sloped roofs with relatively open structural systems to prevent pocketing. Agencies modifying garages tried to use garages with relatively open structural systems such as open-web steel joists. In garages with precast concrete roof structures, the pockets that were created were equipped with ducted exhaust systems pulling from each pocket. Some agencies included fire doors to seal the bus garage from the non-bus areas of the building.

Ventilation systems

Ventilation systems varied depending on the climate. Although current industry practice is to provide continuous ventilation with exhaust points at the ceiling and makeup air units at the floor (there were several excellent garages designed around this system), some properties operating in warm climates did not use baseline ventilation, but they did operate with the doors open nearly year round.

Heating systems

All of the agencies surveyed had addressed the heating system to eliminate the risk of the heating system providing a source of ignition for a leak. Agencies used indirect-fired rooftop warm-air systems, low-density infrared tubes fully vented to the outside, hazardous-locations-rated gas-fired infrared-plate heaters, and hot-water heating systems. In one warm-climate garage, no heating system was used.

Gas detection

All the agencies used combustible-gas-detection systems. These detectors used either infrared or catalytic technology. Agencies expressed a preference for both technologies, so there is no clear recommendation; catalytic sensors are lower cost initially but require quarterly calibration and sensor replacement every 2–3 years. Infrared detectors do not require periodic replacement and require much less frequent calibration but are significantly more expensive initially.

The sensors are tied to a panel that typically sounds an alarm at 20% of the lower flammability limit (LFL; in this case, 20% LFL is 1% gas in air). In addition to alarming, the panel may open several overhead doors and start supplemental emergency exhaust systems. Some properties shut down power to certain building areas or circuits using breakers equipped with “shunt trips” that are activated by the gas-detection system at 40% LFL.

Electrical upgrades

The approach to electrical upgrades varied. Some agencies simply lowered lighting to below 18 in. from the ceiling, while others upgraded the lighting to sealed (not explosion-proof) fixtures. Other electrical equipment in the ceiling area was typically relocated or upgraded. No garage visited had upgraded or built the electrical system in the ceiling to be fully Class 1, Division 2 compliant—nor is this required by code if certain other precautions are taken.

Standby generators

A standby generator was recommended by several agencies to maintain ventilation and gas-detection system operation, including power to doors, fans, and alarms.

Fall-arrest system

A small number of garages included one to two bays with a fall-arrest system to enhance the safety of workers on the roof of the bus during cylinder inspections and other rooftop work. This, or a work platform, is believed to be required by the U.S. Occupational Safety and Health Administration.

Best Practices Related to CNG Training

As with any new technology, it is critical to the success and safety of a CNG program that personnel and other stakeholders receive adequate training. Agencies noted that technicians that had more current computer/electronics training adapted better to CNG engine work than others that lacked this training. Most agencies stressed the need for initial and ongoing technician training to ensure that technicians are adequately prepared when new CNG buses arrive.

Training must include some level of practice/drill to provide the desired level of knowledge. Most agencies used equipment vendors to provide *initial* training and then provided *annual/periodic refreshers and new employee training* using in-house trainers. The following is a summary of training best practices of the surveyed agencies.

Bus training

Bus training (usually provided initially by bus manufacturer) includes the following considerations:

- 160–200 hours with each new bus order, of which approximately 40–60 is engine related
- Cylinder inspection training (typically 2 days) for two or more technicians that will be inspecting cylinders; it is useful to rotate new staff through this training annually to increase the number of qualified staff and to increase the number of informed eyes looking at cylinders between inspection intervals
- Driver training related to the unique aspects of operating a CNG bus, including emergency response.

Station training

Station training (usually provided initially by station manufacturer) includes the following considerations:

- Amount of training closely linked to the degree of agency involvement in the maintenance of the facility
- Basic training in the safe fueling of CNG buses for all affected staff

- Training in how to deal with emergency situations—emergency shutdown procedures, fire response, gas leak response, etc.—for all staff.

Emergency responder training

Emergency responder training (usually provided by the transit agency) includes the following considerations:

- Orientation shortly after commissioning of the CNG station for local fire departments, including location of shutoffs, hydrants, etc. (there will be multiple shifts per department)
- Possible additional orientation for fire departments for each new series of bus, including general bus training to caution fire fighters against the use of an axe near cylinders or high-pressure lines and the proper function of the PRD
- One agency with a large bus population produced a binder with laminated, picture-rich, emergency-response information for each series of bus they operate—showing the location of isolation valves, fire-system controls, contact numbers, and other information of interest to a first responder. These binders are available to the fire and police departments in their area. This concept has been adopted by other agencies and has been appreciated by first responders
- Police should be contacted and trained initially and periodically as required.

Perception of CNG Buses and CNG Incidents

Public and Staff Perception

The survey looked at the general public as a distinct group from the ridership; however, agencies essentially found the two groups to be the same. In both cases, the agencies tended to enjoy a "halo" effect when they first introduced CNG buses into service. There was a positive reaction because the buses were noticeably cleaner than the old diesels that they replaced. As time has progressed, the public and ridership have come to accept the CNG buses as the norm and are indifferent—they no longer notice the benefit, and they do not appear to have any safety or other concerns regarding riding CNG buses.

Driver acceptance of CNG buses is very similar to the ridership acceptance. Most drivers now consider CNG to be business as usual. Driver preference is mostly driven by the newness of a particular bus and the available power. Early CNG buses were regarded by many drivers as being underpowered, but more recent buses are considered to be adequately powered. Underpowered complaints are now usually related to buses that need repair.

Most agencies reported that technicians had openly accepted CNG technology early on and that many technicians find the learning curve to be interesting and fulfilling.

Incidents—Bus

There have been a number of bus fires in the agencies surveyed. Most of the agencies have considered this to be a normal occurrence because their experience indicated a similar percentage of fires in diesel buses.

Fires on CNG buses have been caused by (in approximately descending order of frequency):

- Hydraulic hose failure spraying oil on hot engine components
- Turbocharger failure resulting in oil leakage initiating a fire
- Heat from the exhaust system causing adjacent materials to ignite
- Impact of the cylinders on an overpass on an unapproved route
- Brake fire that engulfed the bus.

In each of these fires, the PRDs on the cylinders performed as designed and prevented a cylinder rupture under pressure. The bus incidents reported in this survey did not result in a serious injury or loss of life; however, one agency noted the inherent risk of having to quickly evacuate a bus on a highway or busy street.

The most significant non-fire bus incident among respondents involved the rupture of two Type 4 cylinders that were belly mounted, below the bus with virtually no protection from road debris. The cylinders failed during fueling presumably due to damage from road debris. No personnel were injured. The fleet inspected all similar buses and installed shields under the cylinders—these shields were inspected frequently with mirrors. Personnel were not allowed inside this series of bus during fueling. Subsequent bus designs with roof-mounted cylinders are considered to have addressed this hazard.

These incidents underscore a need for personnel and emergency training.

Incidents—CNG Station and Bus Garage

Although there have been several incidents at other transit CNG stations and garages, the surveyed agencies had not experienced reportable incidents.

Recommendations

The survey included a block of questions for respondents to identify issues that need further technical research and development and areas where policy or financial support are required. The responses from these questions were combined with other issues identified in the technical portions of the survey and organized into the following recommendations. These recommendations have been broken down into areas where the government can *directly* provide assistance and areas where industry players will need to take a leading role and government can provide a supportive role.

Industry Needs and Concerns Not Directly Related to the Government

A major concern for most agencies is that there is only one domestic engine supplier at this time. When John Deere and DDC exited the market, they left legacy issues that agencies continue to struggle with. Agencies feel very vulnerable with only one supplier because there is reduced incentive for Cummins to improve their product. The entry of a new engine supplier is welcomed, and the early reports from respondent agencies are very promising with regard to Doosan engine power and fuel economy. However, several agencies are concerned that Doosan will also split the already very small market with Cummins, and this could reduce Cummins' interest in the market.

Most agencies noted engine reliability is lacking. Some agencies are seeing the newest engines as less reliable than slightly older engines (the last Cummins 8.3 engines being held as an example of a reliable engine). Engine reliability complaints centered around:

- Sensors that fail frequently
- Short turbo charger life in some cases
- Failure of parts that should be utterly reliable such as exhaust manifolds (DDC—followed by a non-availability of replacement part manifolds) and gas high-pressure regulators
- Engines that must be more tolerant of compressor oil
- Improved life of frequent replacement parts such as spark plugs.

Several agencies noted that CNG buses are more expensive to operate in large part because of the premium price on engine parts. Agencies complained that they are not allowed to rebuild certain parts—they must buy a new assembly, or they must buy OEM parts such as spark plugs and turbo chargers where non-OEM plugs are much cheaper (and likely comparable), and diesel turbo chargers are much lower cost.

Agencies would like to see engines and buses designed to manage heat more effectively to reduce fire risk and perhaps to reclaim heat lost in exhaust.

Although most agencies noted that significant improvement in power and fuel economy has already taken place, they would still like to see improvement in performance—particularly in fuel efficiency. The CVEF believes that the industry would benefit from testing equal CNG and diesel engines in chassis under controlled drive cycles to determine the real fuel economy difference.

In CNG stations, several agencies still view oil carryover as a problem that must be addressed. Previous work has been done on oil vaporization and dew-point requirements; however, it is apparent that the industry would benefit from a more comprehensive best practices document addressing dryer selection and maintenance, station filtration system design and operation, and best oil type for specific applications. This report could be used by agencies when specifying new station equipment or when contemplating an upgrade to station equipment to address an oil carryover issue.

All agencies surveyed used OPW Series 5000 nozzles for their transit bus fueling. This nozzle is essentially the industry standard and has evolved to a design with acceptable durability. Agencies indicated that they would like to see a lighter-weight high-flow nozzle, perhaps with a swivel to make operation more ergonomically friendly. A new nozzle manufactured by Weh of Germany claims to include these attributes, but the author has no direct knowledge or experience with its use, safety, or durability.

Industry Needs and Concerns for Government Policy and Assistance

There was unanimous approval of the federal $0.50/GGE fuel subsidy. This program was a pleasant surprise to many of the agencies that were already involved in CNG, and it has made the business case to remain with and expand CNG use in their fleet much more compelling. The only concern was that the agencies wanted to see this program locked in over the long term because the decision to continue with CNG is a 12–15 year commitment.

A number of agencies called for permanent funding assistance in capital areas, including infrastructure cost, incremental bus cost compared with diesel (this may be addressed if currently proposed federal legislation is passed), and, in California, the very high impending cost as agencies attempt to comply with the 15% zero-emission-vehicle requirement coming in 2012.

A number of California agencies were very concerned about environmental regulations at the state level that require engine manufacturers to continue to tweak and redesign engines. This has prevented the engine design stability necessary to reach designs that are reliable and durable.

The point above has also contributed to the exit of two of the three domestic natural gas engine suppliers. Several agencies suggested that the government continue to assist, or expand their assistance, for engine suppliers to adapt engines for CNG or to improve the reliability of existing designs.

Agencies supported continued investments in technician training so technicians can become more than "parts changers." This would apply to transit agency and engine supplier staff.

More rigorous testing of the reliability and durability of engine components was desired—perhaps by funding additional testing at Altoona. Again it was noted that the transit market is very small, and there are limited interest and resources with engine manufacturers to develop CNG bus engines. One respondent suggested that greater assistance to the trash industry would spur that industry to use CNG, and this would improve demand for heavy-duty CNG engines.

Developing bus designs that address the additional heat generated by natural gas engines—and possibly capturing and using the additional heat—could merit a focused research project. Areas such as under-hood temperatures, airflow patterns, and under-hood material specifications could be studied. Note that the areas of bus incidents were dominated by non-natural gas related causes.

Agencies that currently have buses with 15-year gas-storage cylinders would like to find a way to extend this life to 20 years without cylinder replacement. At this time, no such mechanism exists. One suggestion was made to address timed-out cylinders with a disposal credit from the government to subsidize the cost of new cylinders—similar to the recent "Cash for Clunkers" automobile trade-in program.

Conclusions

This survey was intended to focus on the problems, mistakes, and lessons learned the hard way. By focusing on and reporting the negative experiences, it is hoped that others can avoid these pitfalls and learn from the experience of the pioneers in the industry.

For this reason, the report concludes with several positive comments. The survey asked what respondents felt were the unexpected benefits of CNG. The following is a sample of the responses:

- Fuel costs were sometimes much lower than diesel and then further subsidized by the federal rebate of $0.50/GGE.
- The cost of CNG has been much more stable than the cost of diesel, and it appears that it will remain at relatively low levels for some time to come. Agencies have enjoyed the ability to budget short and medium term with stable or locked-in fuel prices.
- Some respondents indicated a preference for CNG as a domestically sourced fuel that displaces foreign fuel.
- Operators of certain engines (particularly the Cummins 8.3) felt that the durability of the engine was very high. One agency indicated that it had avoided mid-life overhauls that would have been required for diesel, while another indicated that it was seeing engine life comparable to or better than conventional diesel. Still another agency with some clean diesel engines indicated that CNG may prove more reliable than new diesel technology.
- Agencies liked the fact that there were no issues of diesel spills—agencies had experienced the cost and inconvenience of tank replacement in the 1990s.
- Respondents noted much improved indoor air quality and cleanliness in their garages.
- Agencies feel that CNG has an environmental benefit and that their use of CNG demonstrates environmental stewardship that gives their transit agency brand a positive environmental image.

Appendix A: CNG Transit Experience Survey Template

CNG Transit Property Site Survey Version 8-Interview date: December ___ 2009			
General Information:		***Site 1***	
Question #	**Question**	**Data Field**	**Clarifying Data Field**
1000	Property Name:		
1001	Site Name:		
1002	Street Address:		
1003	City:		
1004	State:		
1005	ZIP Code:		
1006	Primary Contact:		
1007	Phone Number:		
1008	Extension:		
1009	Email Address:		
1010	Additional Contact:		
1011	Phone Number:		
1012	Extension:		
1013	Email Address:		
1014	Additional Contact:		
1015	Phone Number:		
1016	Extension:		
1017	Email Address:		

Fleet Information:			
Question #	**Question**	**Primary Data Field**	**Clarifying Data Field**
2000	Total number of CNG buses in fleet:		
2001	Total number of CNG garages:		
2002	Total number of CNG buses at this location:		
2003	Bus spare ratio at this garage.		
2004	Total CNG miles driven over last 12 months by fleet:		
2005	Total CNG Fuel Cost over last 12 months--for total fleet		
2006	Total CNG Fuel by Volume--for total fleet		
2020	Total CNG Fuel by Volume--for this garage:		
2021	Total CNG miles driven over last 12 months for this garage:		
2040	Average mileage for CNG buses (mpg-DE)		
2050	Do you have a fuel contract?--details:		
2060	Average mileage for diesel buses (mpg) (if diesels in fleet)		
	Bus Type 1-Description (35, 40, 45, 60 foot)		
2100	Total number of CNG Bus Type A at this location:		
2101	Manufacturer of CNG Bus Type A:		
2102	Model Year of Bus Type A:		
2103	Engine make and model of bus type A:		
2104	Model year of Engine in bus type A:		
2105	Make of CNG cylinders in bus type A:		
2106	Nominal pressure rating of cylinders in bus type A:		
2107	Number of cylinders in bus type A:		
2109	SCF per cylinder		
2110	Total capacity of storage on bus type A:		
2111	Estimated fuel economy of bus type A (mpg-DE):		
2120	**Bus Type 2-Description (35, 40, 45, 60 foot)**		
2121	Total number of CNG Bus Type B at this location:		
2122	Manufacturer of CNG Bus Type B:		
2123	Model Year of Bus Type B:		
2124	Engine make and model of bus type B:		
2125	Model year of Engine in bus type B:		
2126	Make of CNG cylinders in bus type B:		
2127	Nominal pressure rating of cylinders in bus type B:		
2128	Number of cylinders in bus type B:		
2129	SCF per cylinder		
2130	Total capacity of storage on bus type B:		
2131	Estimated fuel economy of bus type B (mpg-DE):		

2501	What is your maximum allowable fill pressure:		
2502	Do your cylinders have redundant shut off capability, i.e. solenoid and manual devices:		
2503	Are your required cylinder inspections done in house or contracted out:		
2504	Do you have any indicator lights that tell you if a solenoid is not working properly or if the tank is manually shut off:		
2600	**Fuel Lines**		
2601	What is the outside diameter of your bus fuel lines		
2602	What brand of high pressure fittings do you use:		
2603	Is your fuel fill port on the rear or curb side of the bus:		
2604	Does your fuel port have a manual shut off valve:		
2605	Does your fuel port have a pressure gauge:		
2606	Is your fuel fill port door equipped with an engine shut down interlock:		
2607	If so, when the fuel door is opened, how many seconds lag before the engine shuts down?		
2608	Does your fuel fill port have an NGV1 fill fitting:		
2609	Does your fuel fill port have a de-fuel fitting:		
2700	**Power Train**		
2701	Do you have in line coalescing filters between the fuel cylinders and the engine:		
2702	If so, how many:		
2703	If so, how often do you drain or change the filter media:		
2704	What is your spark plug change out interval:		
2705	What is your dyno/tune up interval in miles:		
2706	Do you have any predictive maintenance items set up for the power train:		
2707	What type of engine cooling or thermal management system do you use for your power train:		
2708	Have you ever performed a power train retrofit:		
2709	If so was the work performed in house of by a contractor		
2710	If so were the results positive or negative		
2711	Why were the results positive or negative		
2712	Are your vehicles equipped with fire suppression:		
2713	If so, is the engine compartment suppressed:		
2714	If so, are the CNG tanks suppressed:		
2715	If your fuel storage tanks are equipped with fire suppression, why		
2716	What manufacturer provides your fire suppression system:		
2717	Is the system maintained in house:		
2718	Is the system maintained by a contractor		
2719	Are your vehicles equipped with a low fuel signal/alarm:		
2720	If so, at what pressure does it activate		

Station Information:			
Question #	**Question**	**Data Field**	**Clarifying Data Field**
4000	Average productive minutes in fill shift (typically 300 to 360):		
4001	What hours do you fuel your vehicles		
4002	Number of equivalent days of full operation (typically 6)		
4003	What is your average fill/bus in either GGE or DGE		
4004	What is your average fill time/bus		
4005	Total CNG purchased over last 12 months (therms)--this garage--**based on Utility Bills**.		
4006	Total CNG dispensed over last 12 months (DGE)--this garage--**based on Card lock** (fuel management) records.		
4007	Station inlet gas pressure or pressure range: (psig)		
4008	Compressor station supplier:		
4009	Year of Station Installation:		
4010	Is station operated by transit property or 3rd Party:		
4011	If 3rd Party--list supplier (Clean Energy, Trillium, etc.):		
4100	Is an inlet gas dryer used:		
4101	Provide make and model:		
4102	Gas Dryer pressure rating:		
4103	Gas dryer flow rating:		
4104	Dryer configuration: (twin tower-fully auto regen, twin tower-manual regen, single tower-manual regen, single tower-no regen)		
4200	Brand of compressor (Ariel, Greenfield, Gemini, etc.):		
4201	Number of compressors:		
4202	Flow per compressor:		
4203	Compressor discharge pressure:		
4204	Hours per year of operation per compressor:		
4205	Current hours on each compressor:		
4206	Are compressors electric drive or Gas engine drive:		
4207	If gas engine, what is the make and model of the engine.		
4208	If gas engine, is fuel gas separately metered		
4209	Is this fuel gas included in the total CNG purchased above or separate:		
4210	If electric drive, what is the voltage and horsepower of the motor.		
4211	If electric drive, what is the total demand charge per year:		
4212	If electric, what is the total electrical bill for the year.		
4300	Is compressor lubricated:		
4301	Brand and type of compressor oil:		
4302	Is the compressor equipped with a coalescing filter, or 2 filters in series?		
4303	What is the make and model of the filter?		
4304	How often are these filters drained?--Manually or automatically?		
4305	How often are the filter elements changed?		
4306	Do you collect any oil from the drains of the storage?		
4307	Is the dispenser equipped with a coalescing filter, or 2 filters in series?		
4308	What is the make and model of the filter?		
4309	How often are these filters drained?--Manually or automatically?		
4310	How often are the filter elements changed?		
4311	Do you keep records of oil added and oil drained (collected) from each compressor:		
4312	Do these records indicate that oil is being effectively removed from gas:		
4313	Do you see evidence of oil downstream of the compressors (in storage, at dispenser, in bus):		
4314	Have you experienced problems as a result of oil carryover?		
4400	SCF of buffer storage:		
4401	Pressure rating of buffer storage: (typically 5000 or 5500 psig)		
4402	Maximum operating pressure of buffer storage: (typically 4000 or 4200 psig)		
4500	Number of transit dispenser hoses:		
4501	Number of dispensers wide (typically, 2, 3 or 4)		
4502	Number of Dispensers deep (typically 1 or 2)		
4503	Size of tubing or piping to and in dispenser		
4504	Size of valving in dispenser		
4505	Type of automated valves in dispenser (high pressure solenoid, or actuated ball valve)		
4506	Make and model of meter in dispenser		

Maintenance/Repair/Incident Information:			
Question #	**Question**	**Data Field**	**Clarifying Data Field**
6000	#1 most common cause of station fault		
6001	Typical downtime caused by #1 fault		
6002	#2 most common cause of station fault		
6003	Typical downtime caused by #2 fault		
6004	#3 most common cause of station fault		
6005	Typical downtime caused by #3 fault		
6006	#4 most common cause of station fault		
6007	Typical downtime caused by #4 fault		
6008	#5 most common cause of station fault		
6009	Typical downtime caused by #5 fault		
6100	Annual maintenance cost for station for 2006:		
6101	Annual maintenance cost for station for 2007:		
6102	Annual maintenance cost for station for 2008:		
6103	What maintenance tasks are performed by staff:		
6104	What maintenance tasks are performed by contractors:		
6105	What is the typical interval between compressor oil changes?		
6106	What is the typical interval between compressor ring changes?		
6107	What is the typical interval between compressor packing changes?		
6108	What is the typical interval between compressor valve changes?		
6109	What is the most frequent maintenance or repair item?		
6110	What is the typical cost of the above maintenance item or repair?		
6111	What is the typical interval of the above maintenance item or repair?		
6112	What is the 2nd most frequent maintenance or repair item?		
6113	What is the typical cost of the above maintenance item or repair?		
6114	What is the typical interval of the above maintenance item or repair?		
6115	What is the 3rd most frequent maintenance or repair item?		
6116	What is the typical cost of the above maintenance item or repair?		
6117	What is the typical interval of the above maintenance item or repair?		
6200	Other maintenance comments or concerns?		
6300	Have you experienced any serious incidents at this site that required dispatch of emergency response (Fire, police, ambulance):		
6301	What was the cause of the incident?		
6302	What was the nature and extent of injury/damage:		
6303	What changes in operations or equipment have been made to address this experience:		
6400	What training programs have your staff been given to assist them in servicing your CNG station?		
6500	**Operations**		
6501	How many miles do your vehicles average/year		
6502	What is your mean distance between failure (MDBF) for CNG buses.		
6503	What is your mean distance between failure (MDBF) for Diesel buses.		
6504	How do you calculate your MDBF		
6505	What percentage of your in service failures are caused by a CNG related problem		
6506	Of the CNG related problems, is there a particular system or sub system that fails more frequently that the rest		
6507	Do you have vehicle fires directly caused by the use of CNG as a fuel		
6508	If so, please specify the three most common causes, most frequent first		

Garage Information: (only areas occupied by buses)			
Question #	**Question**	**Data Field**	**Clarifying Data Field**
8000	Area of Garage (ft2)		
8001	Number of service bays:		
8002	Was garage built for CNG buses originally (i.e. new construction):		
8003	If built for CNG buses, please estimate the incremental cost to make the garage CNG capable:		
8004	Was the garage modified from a diesel only garage to make it CNG safe:		
8005	If modified for CNG buses, what was the total cost of design, construction of the modifications:		
8100	Describe roof structure of building (flat roof with open web steel joists, flat roof with solid steel or concrete beams creating pockets, pitched roof):		
8101	If the roof structure creates pockets, what is the typical Length x Width x Depth of the pockets:		
8200	Make of CNG detectors: (Detronics, Scott, etc.):		
8201	Type of detectors (catalytic, Infra Red):		
8202	If IR-are they point detectors, open path, or a combination:		
8203	Total cost of Detection system:		
8204	Calibration Frequency:		
8205	Calibration time required:		
8206	What does the Gas detection system control (horns, strobes, start emergency exhaust, shut down heaters, open garage doors, etc.)		
8300	Type of heating system used (hydronic floor heat, hydronic unit heaters, indirect fired gas heat with roof top units, indirect gas heat with unit heaters, IR tube heaters, other)		
8400	Baseline ventilation system Air Changes Per Hour (ACH):		
8401	Is air recirculated:		
8402	Where is fresh air introduced (near floor, near ceiling, split of both)		
8403	If the roof structure contains pockets, how are they ventilated:		
8500	Emergency exhaust system--is additional air exhaust provided:		
8501	If so, at what ACH:		
8502	How is the system configured (roof mounted exhaust fans, two speed baseline fans, other):		
8600	What changes to the electrical design were incorporated due to the CNG buses (Example-Division 2 location at ceiling, explosion proof lights, other special equipment, etc.):		
8700	What other hardware precautions were taken (example-automated fabric doors to relieve pressure and to open automatically in a gas release event):		
8800	Is a standby generator provided to power the garage in a power outage?		
8801	What equipment does it power?		
9000	What special operating procedures or training have been instituted to address the special considerations of CNG:		
9100	Have you experienced any serious incidents at this site that required dispatch of emergency response (Fire, police, ambulance):		
9101	What was the cause of the incident?		
9102	What was the nature and extent of injury/damage:		
9103	What changes in operations or equipment have been made to address this experience:		
9500	**Training**		
9501	Is your training generally provided by the OEM, in house personnel or a third party		
9502	How much initial CNG training (hours/tech) did your technicians receive during start up		
9503	How many hours/year CNG/vehicle sustainment or skills upgrade do your techs receive per year		
9504	How many hours new equipment training do your technicians receive when new vehicles are purchased		
9505	Is the training targeted to CNG systems and safety, or is it just a general orientation of the vehicle		
9508	Do your First Responders receive CNG safety and incident response training		
9509	If so, how many hours		

Miscellaneous Information:			
Question #	**Question**	**Data Field**	**Clarifying Data Field**
10000	Special Vehicle Certifications/Inspections (Cylinders, Police, etc.)		
10001	Public Acceptance of CNG Buses		
10002	Public Complaints of CNG Buses		
10003	Ridership acceptance/preference for CNG Buses.		
10004	Ridership Complaints with CNG Buses		
10005	Driver acceptance/preference for CNG Buses		
10006	Driver Complaints with CNG Buses		
10007	Mechanic/Technician Acceptance of CNG Technology		
10008	Unexpected Benefits of CNG buses:		
10009	Unexpected Problems or Costs of CNG Buses:		
10010	What is your single biggest issue/worry/complaint:		

10011	If you could go back in time and change your station equipment, buses or the way your project unfolded, what changes would you make:		
10012	What are your main "Wish List" items for technology improvement on CNG Buses:		
10013	What are your main "Wish List" items for technology improvement on CNG Stations:		
10014	What are your main "Wish List" items for government support of CNG industry (policy support, technical support, etc.):--where would you want the first dollar of government assistance to go?		

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This survey was commissioned by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) to collect and analyze experiential data and information from a cross-section of U.S. transit agencies with varying degrees of compressed natural gas (CNG) bus and station experience. This information will be used to assist DOE and NREL in determining areas of success and areas where further technical or other assistance might be required, and to assist them in focusing on areas judged by the CNG transit community as priority items.

15. SUBJECT TERMS
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