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TASK ORDER **KLDO-5-55636-01**
PROPANE TANK OVERFILL ANALYSIS: QUANTIFYING THE SCOPE OF THE ISSUE AND OUTLINING BEST PRACTICES TO PREVENT OVERFILLS
TECHNICAL REPORT ON FIELD TESTING
TECHNICAL MONITOR: MS. MARGO MELENDEZ
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I. Background

The use of propane vehicles can enhance our energy security and improve air quality. Today, propane vehicles are most often used for school and shuttle bus applications, mass transit as well as light -duty truck applications throughout the United States. To maximize the emissions and energy security benefits, as well as to ensure safe operation, the on-board propane tanks must be refueled properly. The National Renewable Energy Laboratory (NREL), Department of Energy (DOE), and the National Propane Gas Association (NPGA) have recently become aware of reported cases where fuel tanks on propane vehicles have been overfilled, potentially resulting in emissions from pressure release valves (fuel consumption and local and global air pollution issues); or, in rare cases, cause a potential safety hazard.

The frequency of overfilling on-board tanks is not well understood. Liquefied petroleum gas (LPG, LP Gas, or propane) has a high thermal coefficient of expansion. This means that when there is a high rise in temperature the liquid in the tanks will significantly expand. Most tanks are designed to vent LP Gas in such case as to avoid significant pressure build-up in the tank. This release however, leads to wasted fuel and negative environmental impacts. To avoid undesirable releases, the common practice is to fill on-board tanks to a maximum of eighty percent of total volumetric capacity.

Work conducted since mid-2005 by the ADEPT Group, Inc. (ADEPT) and earlier by South West Research Institute (SwRI) [PERC Docket 11200: "Motor-Fuel OPD Failure Mode Evaluation", 2004) and CEODEUX (dominant maker of Overfill Prevention Devices – or OPD's) [per conversation with D. Lawson, CEODEUX, 2008] indicates that vehicular propane tanks are occasionally filled above the eighty percent mark. These "overfilled" tanks, when venting, pose environmental and potential safety risks, as well as a safety risk if the release valve fails to open when it's supposed to do so.

ADEPT and Adept Science & Technologies, LLC (ASCENT), completed a technology demonstration project for the Propane Education & Research Council

(PERC) in 2005 which documented that at VIA Metropolitan Transit (VIA) in San Antonio, TX, ~16% of their on-board tanks were regularly overfilled [PERC Docket 11653: Acoustic Stop-Fill Instrument for LP Gas Tanks, 2006]. In 2006 and 2007, similar investigative and diagnostic work [ADEPT] on transit buses operated by the Los Angeles Department of Transportation DASH buses and by Port Arthur Transit demonstrated that this problem was not limited to VIA. These findings confirmed the need to assess the extent of "overfilling" in propane vehicles across the country.

II. Project Objective

This project's objective is to conduct a statistically significant survey to answer two questions: (1) Are LP Gas on-board tanks overfilled throughout the US, and (2) If the answer to the first question is "Yes", then answer the question of how significant this condition might be.

This objective did not include diagnosis of the problem, just an evaluation of fleets to determine the extent to which the situation exists. Based on the findings, a "best practices" guideline for refueling will be prepared. Subsequent work to diagnose the root cause/s of on-board tank overfilling may be indicated.

III. Statistical Approach

A. Propane Vehicle Market

This study is to estimate the frequency of the "tank overfilled" condition in LP Gas powered vehicles in US based fleets.

On-road LP Gas vehicles operating as fleets in the US include: transit buses, school buses, shuttles, small pick-up trucks, and sedans. To make the study as comprehensive as possible, the selection of the fleets for this project was made to include a variety of vehicular end-uses. This tested fleets included:

- school buses
- bottled water delivery trucks
- utility pick up trucks
- limousines
- shuttle buses

Fleets were of varying size and function. No mass transit fleets were included in this study as three such fleets were previously tested under another program [PERC Docket 11653, 2006]. The original project scope called for five (5) fleets to be tested. Seven (7) fleets were actually tested within the same budget.

Within the LP gas fleets vehicle population, there are "natural" classes of fleets. These fleets were previously classified as "Small", "Medium" and "Large". Within a class, fleets share common characteristics in terms of number of vehicles in a fleet, type of vehicles, OEM, type of service and type of routes.

The EIA published the below table for alternative fueled vehicles. Our own research in mid-2007 indicates that this table most likely underreports by ~20% the number of actual fleet vehicles running on LP Gas in the US. Based on our own mid-2007 survey of fleets operating throughout the US, we believe that there are ~2,400 on-road fleet vehicles running on LP Gas in the US today.

	Medium Duty				Heavy Duty		
Fuel Type	**Vans**	**Pickups**	**Trucks**	**Total**	**Trucks**	**Buses**	**Total**
Compressed Natural Gas (CNG)	629	189	55	**873**	50	461	**511**
Dedicated	298	58	12	**368**	35	451	**486**
Nondedicated	331	131	43	**505**	15	10	**25**
Electric (EVC) /a/	0	0	5	**5**	0	3	**3**
Ethanol, 85 Percent (E85) /b/	132	65	0	**197**	0	0	**0**
Hydrogen (HYD) /c/	1	0	0	**1**	0	0	**0**
Liquefied Natural Gas (LNG)	0	10	1	**11**	0	0	**0**
Dedicated	0	0	0	**0**	0	0	**0**
Nondedicated	0	10	1	**11**	0	0	**0**
Liquefied Petroleum Gas (LPG)	683	181	522	**1,386**	169	465	**634**
Dedicated	23	92	8	**123**	9	448	**457**
Nondedicated	660	89	514	**1,263**	160	17	**177**
TOTAL	**1,445**	**445**	**583**	**2,473**	**219**	**929**	**1,148**
Dedicated	**322**	**150**	**25**	**497**	**44**	**902**	**946**
Nondedicated	**1,123**	**295**	**558**	**1,976**	**175**	**27**	**202**

/a/ Electric vehicles are battery powered and are considered dedicated.
/b/ Ethanol vehicles are flexible-fueled and are considered nondedicated; the remaining portion of 85-percent ethanol is gasoline.
/c/ Hydrogen fuel cells are considered dedicated hydrogen because hydrogen is the input fuel.
Notes:
Dedicated vehicles are designed to operate exclusively on one alternative fuel.
Nondedicated vehicles are configured to operate on more than one fuel.
Medium duty includes vehicles with a GVWR of 8,501 to 26,000 lbs.
Heavy Duty includes vehicles with a GVWR greater than 26,000 lbs.

Source: Energy Information Administration, Form EIA-886, "Annual Survey of Alternative Fuel Vehicle Suppliers and Users"

The statistical technique known as cluster sampling is indicated when the environment is not completely known and the basic units being analyzed are “clustered” into groups sharing common characteristics (i.e. vehicle type, function served, area served, etc.) [See the classic reference “Cochran, William, *Sampling Techniques* (2nd edition), John Wiley & Sons Inc, New-York, 1963”].

B. Cluster Sampling

The cluster sampling technique consists of selecting a small number of clusters (fleets in this case) and, within a cluster, analyzing the units of interest either exhaustively (single-stage cluster sampling) or by drawing a random sample of units within each cluster (two-stage cluster sampling). Here, the units of interest are the on-board tanks and the two-stage random sampling was used.

Notations:
N = total number of clusters (fleets)
M_i = number of units (tanks) within cluster i
n = number of clusters sampled
m_i = number of units sampled in cluster i
p_i = estimate of the proportion of units satisfying the criterion (tank overfilled)

The unbiased estimate of the proportion of units of interest is given by the formula:

Equation III.1

$$\hat{p} = \frac{N}{nM} \sum_i M_i p_i$$

and the formula for the variance is:

Equation III.2

$$\hat{V} = \frac{1}{M^2} \left[N^2 \frac{N-n}{N} \frac{1}{n} \frac{1}{n-1} \sum_i \left(M_i p_i - \frac{1}{n} \sum_j M_j p_j \right)^2 + \frac{N}{n} \sum_i M_i^2 \frac{M_i - m_i}{M_i} \frac{1}{m_i - 1} p_i (1 - p_i) \right]$$

To obtain a good estimate of p it is desirable that all clusters be of approximately equal size. For that reason, the classes “Large”, “Medium” and “Small” are analyzed separately. The results of the above described statistical analysis methodology are shown below in **Section VII. Statistical Analysis of the Collected Data.**

IV. Field Tests Methodology

The testing protocol was developed from prior experience with three propane powered mass transit fleets as well as with help from members of a special task force (TEF-1714) of the Technology, Standards and Safety (TS&S) Committee of the National Propane Gas Association (NPGA). TS&S created this task force after learning of the overfilled tanks findings on the first three tested fleets.

At each site (except Metro Cars in Taylor, MI which issued printed receipts of the volume pumped rather than a meter display) the below 12 steps were followed:

1. The vehicle was verified to be on level ground when it pulled up to the fuel dispensing unit (pump). The driver, or person who refilled the vehicle, hereafter “operator”, was told that the refueling event would be observed.

2. The operator was asked to report the on-the-dash level gauge dial reading, which was verified by the ADEPT. The level indication on the on-tank gauge dial was also recorded, if one was present and accessible.

3. The Maximus™ Overfill Diagnostic Instrument (ODI) and/or the Maximus™ Continuous Level Gauge (CLG) were used to get accurate liquid level readings from the on-vehicle propane tanks on all tanks suspected to be overfilled. An oscilloscope was periodically used to validate the Maximus™ instruments. The sequence of vehicles being fueled was not predetermined; vehicles were tested in the random order that they pulled to the pump. These readings were compared with the level indications on the dash board and/or on the on-tank dial/s. The reliability of on-dash or on-tank level indicator dials is significant to the extent that, if reliable, they could provide a secondary means to check the liquid level in the event of OPD failure. However, 47% of these level indicators did not function reliably [based on checks with the Maximus™ instruments, and/or on reports from the driver / fueling operator]. At the request of LP Gas industry representatives, the initial volume of fuel in the tank was included as part of the data sheet. As the project progressed, the frequency of this particular step was lowered and then eliminated as it became apparent that it was sufficient, in a single tank system, to retroactively calculate, if needed, what the liquid level was at the start of the refueling process inside the tank. To collect data for this calculation required recording the number of gallons pumped in (from the calibrated pump meter) at the time when liquid came out of the Fixed Liquid Level Gauge (FLLG) and/or the number of gallons pumped in (from the print ticket if a pump gallons in dynamic display was not available), the max capacity of the tank being filled, and the final amount of gallons inside the tank (measured with the ODI and/or the CLG instrument/s).

4. The refueling process was observed with the FLLG open. The FLLG is a valve attached to a dip tube which extends into the LP Gas tank. The lower

end of this dip tube is typically located at the 80% full level (although there is an accepted tank manufacturer tolerance of 75% to 82% full for the position of the lower end of the dip tube). During filling, once liquid reaches the bottom of the dip tube, liquid LP Gas is released through the open valve (as a white cloud) which indicates that the 80% full level has been reached.

5. The # of gallons pumped into the tank when the OPD triggered was recorded.

6. We also noted in the comments section if the OPD stopped the flow before or soon after liquid LP Gas spewed through the FLLG. We frequently noted the # of gallons pumped in when liquid first came out of the FLLG (in case this information might later be useful).

7. If the OPD did not stop the in-flow of LP Gas into the vehicle after liquid LP Gas was released for some time through the FLLG, we asked the operator to stop the pump and recorded the amount of fuel pumped in up to that point.

8. With the FLLG still open, the operator was asked to try to pump a few more gallons in the tank (the actual # of gallons added depended on the maximum tank capacity and was limited to less than 10% of this capacity to avoid severe overfilling, if possible) to attempt to force the OPD to trigger. The gallons pumped in this additional refueling step were recorded.

9. The liquid level indicators were read and recorded, if accessible and operational.

10. Vehicles suspected to have an overfilled tank were pulled away from the pump and parked on level ground. Fuel level indicating instruments were then properly positioned. Five to ten minutes were allowed to pass before the readings were taken. This was to ensure that any lingering sloshing inside the tank did not affect the readings, and to allow for further level equalization between multi-cylinder tanks. The tank temperature was recorded. With the ODI and the CLG, and occasionally the oscilloscope, the liquid level inside the cylinder was accurately measured. Readings from these two different acoustic instruments (which use different measuring techniques) were compared to double-check the LP Gas volume in the tank. The fuel levels were recorded.

11. Vehicles with confirmed (from step 10) overfilled tanks, if not already filled to ~100%, were brought back to the pump to try to trigger the OPD with additional fueling. If the OPD triggered on this third refueling attempt, the vehicle was not recorded as having an overfilled tank, however, the fleet manager was notified. If the OPD did not trigger on this third pumping action, the vehicle was recorded as having an overfilled tank.

(12) Comments (e.g. the presence of an unreliable mechanical level indicator dial) were occasionally noted on the data sheet.

All the vehicles tested had only one tank systems on-board, so no isolation in-between cylinders were needed. A one tank system means that, although it may have multiple cylinders, it was equipped with one OPD, one pressure relief valve, one outage gauge, and its cylinders were connected with welded metal pipes that allow unimpeded and rapid equalization of liquid and vapor between cylinders.

The above described procedure added little time to the normal refill process at each fleet/s site on vehicles where the possibility of an overfill was not indicated. On vehicles where overfills were indicated, the tank examination with ultrasonic instrument/s (ODI and/or the CLG) took anywhere from 24 to 33 minutes.

V. Test Sites

The fleets included in this study are shown below. These fleets were selected because of their type of operation, type of vehicles, and willingness to participate.

Fleet Name	Fleet Site	Fleet Size	# of vehicles in fleet	Minimum # of vehicles to be tested	Tanks/ vehicle
Dallas County Schools - Pat Raney Service Center	Lancaster, TX	Large	168	17	1 or 2
Dallas County Schools - Don Shields Service Center	Dallas, TX	Large	154	15	1 or 2
Metro Cars - Van Fleet	Taylor, MI	Medium	47	5	1
Metro Cars - Town Car Fleet	Taylor, MI	Small	20	2	1
Sparkletts - Gardena Distribution Center	Gardena, CA	Medium	30	3	1 or 2
Sparkletts - Van Nuys Distribution Center	Van Nuys, CA	Medium	24	2	1 or 2
UCLA CTS - United Rentals	Los Angeles, CA	Small	1	1	1

The number of vehicles sampled at each site was based on the total number of vehicles in the fleet. To be statistically meaningful, sample sizes should be proportionally similar to overall fleet size. Given the total available time at each site, the number of LP Gas powered vehicles in each fleet to be tested and the anticipated test duration, a sample size of 10% of the fleet population was used.

VI. Field Test Data Summary

The below table summarizes the field data collected from seven fleets:

Fleet	Location	Test Date	LP Gas Vehicles in Fleet	Tanks Tested	Tanks per Vehicle	% of Fleet Tested	Tanks Overfilled	% Overfilled	Overfills Verified with CLG
Dallas County Schools - Pat Raney Service Center	Lancaster, TX	10/28/2007	168	31	1	18%	4	12.9%	2
Dallas County Schools - Don Shields Service Center	Dallas, TX	10/29/2007	154	48	1	31%	5	10.4%	5
Metro Cars - Van Fleet	Taylor, MI	11/14/2007	20	7	1	35%	1	14.3%	1
Metro Cars - Town Car Fleet	Taylor, MI	11/14/2007	47	3	1	6%	0	0.0%	NA
Sparkletts - Gardena Distribution Center	Gardena, CA	11/28/2007	36	9	1	25%	4	44.4%	4
Sparkletts - Van Nuys Distribution Center	Van Nuys, CA	11/29/2007	36	6	1	17%	3	50.0%	3
UCLA CTS - United Rentals	Van Nuys, CA	11/29/2007	1	1	1	100%	1	100.0%	1
Total			462	105			18	17.1%	16

In total, seven (7) fleets and 105 vehicles were tested.

VII. Statistical Analysis of the Collected Data

As discussed above, a cluster sampling technique was used. The data contained two outliers: (1) Metro Cars Medium fleet of Town Cars) with a sizable number of vehicles but only three vehicles/tanks could be properly tested, and (2) UCLA CTS pick-up truck fleet had only one vehicle and thus belongs in the "Small" category. Consequently, the "Small" category was eliminated as a "cluster" because a cluster, by definition, must have at least two elements.

There were two phases of fleet inspection work: [Phase I: Sampling of 3 fleets (PERC Docket 11653, 2006 and related ADEPT work conducted during the testing of the Maximus™ODI); and Phase II: Sampling of 7 fleets (the DOE study)]. The distribution of the data collected over a two (2) year period allowed for five (5) separate studies. Phase I data was included in the studies indicated to provide greater significance for the statistical analysis:

Study 1: Phase I excluded / Metro Cars (Med) Town Car fleet (TMM) included (6 fleets sampled)
Study 2: Phase I excluded / TMM excluded (5 fleets sampled)
Study 3: Both Phases are included / TMM included (9 fleets sampled)
Study 4: Both Phases are included / TMM excluded (8 fleets sampled)
Study 5: Both Phases,/TMM and TMC excluded (7 fleets sampled). (TMC = Taylor, MI, Metro Cars - Small fleet of shuttle vans)

Each of these analyses provided a unique probability of the "tank overfilled" condition (the likelihood that a tank would be overfilled). These probabilities were calculated by Equation III.1 (above).

	Large	Medium	Small
Study 1	0.083	0.147	N/A
Study 2	0.042	0.196	N/A
Study 3	0.159	0.147	0.111
Study 4	0.159	0.196	0.111
Study 5	0.159	0.176	0.111

Studies 1 and 2 do not contain a "Small" as the "Small" fleets from Phase I studies were not included. Also of note is that for the "Small" category, in Studies 3 and 4, a simple random sampling estimate was used taking PAT to be representative of the entire "Small" population.

Study 5 is shown in the event an estimate of the "tank overfilled" condition is of interest without the fleets at Taylor, MI. This is provided because the findings were later disputed by the Metro Cars fleet manager and the LP Gas provider to Metro Cars.

Using the population sizes for "Large", "Medium" and "Small" as relative, estimates of the probability for the overall population of LPG vehicles was calculated, using Equation III.1 (above).

	p est.
Study 1	0.11
Study 2	0.11
Study 3	0.15
Study 4	0.17
Study 5	0.16

The most reliable study is Study 4, as it contains the largest number of observations and excludes outliers that introduce undue variability to the estimates and also cause large variances.

The confidence intervals for “Large”, “Medium” and “Small” fleets are shown below:

p-large:	11% ± 7%
p-med:	19% ± 13%
p-small:	11% ± 11%

A 0.70 confidence level applies to the above results. This means that for each of the fleet size categories above, there is a 70% chance that the probability of a tank being overfilled is within the indicated confidence interval.

VIII. Conclusions & Findings

1. A little more than one out of every six fleet vehicles tested was overfilled.
2. Tanks are significantly overfilled in Small, Medium and Large fleets, regardless of their end-use or of OEM.
3. Driver and/or re-fueling staff can benefit from additional training on safe refueling practices. Very few, if any, were aware of the risks associated with overfilling.
4. Mechanical liquid level gauges on the tested vehicles had a very high failure rate (nearly 50%). The fact that the driver and/or the re-fueler cannot rely on the level indicator in the vehicle and/or on the tank/s aggravates the overfilled situation.
5. Tanks were overfilled due to apparent failure of the Overfill Prevention Device (OPD) as well as in one case where the OPD was intentionally removed because it stopped filling too soon (on previous occasions the fuel ran out and the delivery truck could not finish its route).

IX. Recommended Next Steps

ADEPT will:

1. Prepare a “Best Practices” outline for fleet vehicles re-fueling.
2. Submit this outline and the final report to NPGA and to leaders of the automotive sector of the US LP Gas industry, as well as to the supervisors of the tested fleets.
3. Submit this outline and the final report to the Texas Railroad Commission (TRC). TRC oversees the safety of all LP Gas vehicles in Texas. Texas has about half of all the LP Gas powered vehicles in the US.
4. Suggest to the LP Gas industry to: (a) intensify training for safe refueling practices, and (b) conduct periodic verification of the proper functioning of OPD’s.
5. Submit a Tentative Interim Amendment (TIA) to NFPA (National Fire Protection Association) recommending that NFPA 58 (the “Bible” for the LP gas industry) require that OPD’s be periodically checked for proper performance.

6. Make CSA and UL aware of this study's findings. CSA and UL both test and certify OPD's.
7. Make the on-board tank manufacturers aware of this study's findings.

Additional Follow-on Work
OPD's are mechanical devices. There are several factors that could lead to the failure of such devices including the length of service (one hypothesis from this work is that more recently installed OPDs fail less than older OPDs), presence of contaminants in the fuel tank, device design, installation, tank orientation, etc. It is recommended that these failure modes be further investigated.

X. Acknowledgements

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