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EVALUATION AND APPLICATION OF DATA SOURCES FOR ASSESSING OPERATING COSTS FOR MECHANICAL DRIVE GAS TURBINES IN PIPELINE SERVICE

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ABSTRACT

This paper evaluates and demonstrates how the public domain data provided by individual interstate pipeline companies to FERC, when combined with individual company equipment lists, can be used to regress industry information on cost of operations and maintenance, fuel gas used, and cost of fuel and power. The paper describes the methods of analysis and identifies their limitations. The paper presents results of such regression analysis as average and variance of cost and fuel usage for industrial gas turbines and aeroderivative gas turbines. It provides further comparisons between gas turbine prime movers, reciprocating engine prime movers, and electric motor drives, and presents annual costs per installed horsepower as a function of turbine size. The paper is based on work performed for PRC International and the Gas Research Institute.

INTRODUCTION

Mechanical drives for centrifugal compressors provided an early application for land based gas turbine engines. Tnday the gas transmission industry has deployed both industrial and aeroderivative gas turbines widely. Reciprocating integral engine compressors still dominate the U.S.A. installed base, but many companies now prefer a gas turbine driven centrifugal compressor for new installations. In 1994, gas turbines represented about 20 percent by number of the U.S. installed gas transmission fleet, and 30 percent by horsepower. In the rest of the world, including Canada, gas turbines dominate the fleet more heavily with over 90 percent of the installed horsepower. As a recent trend worthy of note, pipeline companies in both the U.S. and Canada, have chosen to install motor driven compressors as a significant fraction of their new or replacement horsepower.

The U.S. gas transmission industry continues to deregulate and faces increasingly aggressive competition. Reducing the cost of gas operations offers a way to compete more effectively, and to maintain profitability. Knowledge of current costs can help a company control these costs especially when expressed as an intensity (which relates cost to business activity). However, the need for individuals to document and gather specific cost data conflicts directly with increasing demands for individual productivity.

The following results show how public domain information, combined with the most readily available company information, can help profile the industry's compressor operations and maintenance costs; it further uses linear regression to infer cost intensities by type of driver (even without cost data recorded to this level of detail). The results of the paper emphasize gas turbine costs, but also provide data for comparison between gas turbine, reciprocating engine, and electric motor drives. Operating costs addressed include compressor station maintenance, compressor operation, and fuel usage. The paper presents results with particular relevance to gas turbine operation from a detailed investigation of compressor operating costs by Smalley, et al (1997).

DATA SOURCES

The Federal Energy Regulatory Commission (FERC) requires all U.S. interstate pipelines to file detailed operating statements each year. This data includes the following details of compressor operations by pipeline company, for each calendar year:

- Pipeline total compressor station maintenance costs for gas transmission.
- Pipeline total gas deliveries.
- Station-by-station fuel use.
- Station-by-station O&M costs.
- Station-by-station power and fuel costs.

Perseverance will lead to success in downloading this data! It provides a basis for normalizing corporate performance (e.g., costs and fuel burned per unit volume delivered); however, it provides no direct basis for normalizing cost and fuel use relative to work done (horsepower hours) or installed power; this lack of

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measures for engine size and operation, could limit the basis for assessing and controlling costs.

Fortunately, however, most operating companies have, in readily transferable electronic form, a detailed definition of their installed horsepower, comprising at each compressor station:

- Unit number or identifier.
- Driver type.
- Model number.
- Installed horsepower.
- Year installed.

Assuming cost or consumption by station varies linearly with installed horsepower, linear regression provides the constants of proportionality, and measures of variance. By combining data for all companies, we can infer the costs and fuel use per horsepower for each compressor type and model which has sufficient representation in the database.

The FERC data base does not contain maintenance cost alone at the station level (just at the company total level); thus while most companies keep records of this quantity by station for rolling up into the company total, acquiring data on maintenance cost by station requires contact with each individual company, and a request to provide this detail.

Further review shows that the FERC data base does not include horsepower hours; thus establishing a measure of compression work done at the company, station, or unit level (whichever might be available) also requires direct contact. In summary then, the following information was obtained by request from individual companies:

Company Horsepower Totals:	28 Companies	17 Million Horsepower
Horsepower Details at Each Transmission Compressor Station:	20 Companies	14 Million Horsepower
Total Annual Horsepower Hours:	15 Companies	10 Million Horsepower
Horsepower Hours by Compressor Station:	5 Cnmpanies	8 Million Horsepower

METHODS OF ANALYSIS

Linear regression provides the primary analytical technique used to extract information from the data base, yielding constants of proportionality or slopes, standard deviations, and standard errors. The company level analysis profiles the industry with regressed constants of proportionality linking measures of company cost to measures of company size or activity. It further helps assess consistency in relationships between these measures as a guide to their application for station level analysis.

In the company level analyses, each pipeline company provides pairs of dependent and independent variables. For example, to regress compressor station maintenance cost against deliveries requires extracting from the data base values for each companies maintenance cost and deliveries over the year in questinn. Because the completeness of the database varies slightly for the different quantities, a typical regression involves 26 to 30 companies, and in the case of horsepower hour regressions, it only involves about 15 companies.

The station level analysis extracts information below the level at which most companies keep records - by inferring dependence of cost and consumption on prime mover type, and on individual model.

The station level analyses involve a larger, more complete database of information than the company analyses. In general, the station level analysis uses multiple linear regression involving significantly more than one independent variable. The simplest station level analysis seeks constants of proportionality between cost and horsepower for six prime mover types:

- Two-stroke reciprocating engine.
- Four-stroke reciprocating engine.
- Separable reciprocating engine.
- Electric motor.
- Aeroderivative gas turbine.
- Industrial gas turbine.

Every station with available cost information comprises one or more of these engine types, quantified by the installed horsepower for that type. The analysis assumes cost varies linearly with horsepower, and extracts constants of proportionality, which minimize the RMS deviation between station cost and predictions using these constants. The database contains a large number of compressor stations (many hundreds). Many stations comprise only one or two types and for more sparsely represented types, it was found beneficial to regress the constants of proportionality from a series of subsets of the data base, each of which contained only stations with the particular type of interest; thus in particular, we regressed electric motor information only from the reduced set of stations which contain electric motor drives.

Similar station level regression analysis was performed to extract maintenance costs for individual models, and to infer maintenance costs as a function of size within a particular type.

As will be seen, all regression analyses produced results with uncertainty, subject to limitations imposed by the implied assumption that cost depends linearly on horsepower installed. A more desirable regression would be to seek size, type, and model information by horsepower hour regressions, but unfortunately, the available data did not support this.

RESULTS

Figure 1 shows how a company's combined operations and maintenance cost for 1994 (on the vertical axis) correlates with deliveries for that year (on the horizontal axis). Each point on this figure corresponds to an individual U.S. interstate pipeline company; the line represents the regressed line which "best fits" the data by minimizing the root mean square total of deviations from that line. The quantity R^2 measures how strongly the dependent variable depends on the independent variable - $R^2 =$ 100 percent would imply "perfect dependence" with no scatter; $R^2 = 0$ would imply no dependence. The value of 82.44 percent for R^2 in Fig. 1 indicates relatively strong dependence. The slope ($16.22/MMCF) represents the constant of proportionately between O&M cost and deliveries. The standard error ($6.55 million) measures the RMS deviation of the data points from the line, and provides a different measure of scatter.

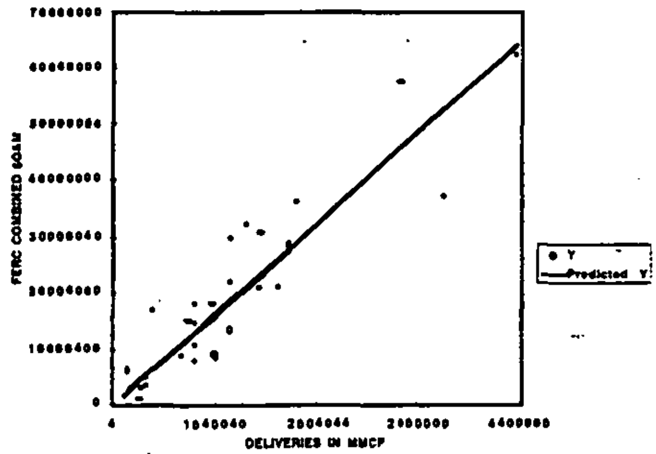

Figure 1. Correlation of FERC Combined $O&M with Deliveries in MMCF - FERC Filing U.S. Interstate Pipelines Only - R^2=82.44%; Std. Error=$6.55 MM; Slope=$16.22/MMCF

Figure 2 shows how total fuel burned in gas transmission correlates with total horsepower hours. Here the R^2 has a value of 96.05 percent (for a set which includes nine U.S. interstate companies; three Canadian companies; and two U.S. intrastate companies). This indicates strong dependence, with a standard error of 3.19 billion cubic feet, and a slope of 7.25 MCF per thousand horsepower hours. Both Figs. 1 and 2 represent industry-wide profiles for gas transmission, undifferentiated by engine type, and comprising inevitably a mix of reciprocating and turbine engines.

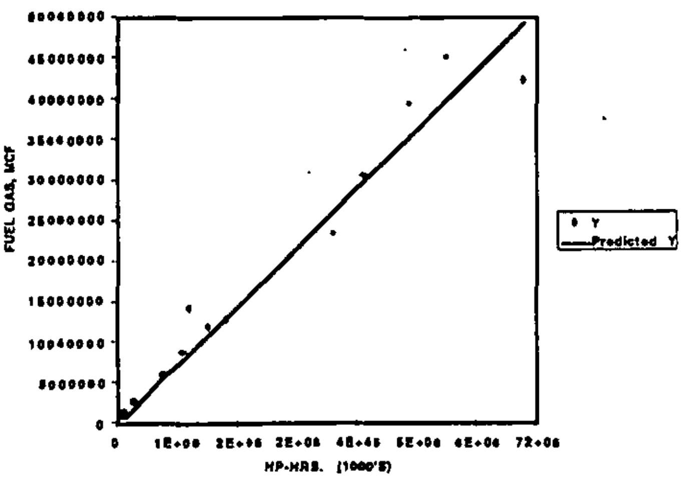

Figure 2. Correlation of Fuel Gas (MCF) with HP-Hrs. for Total Population with Data - Single Largest Outlier Eliminated - R^2=96.05%; Std. Error=3.19 BCF; Slope=7.25 MCF/1000 HP-Hr.

Figure 3 shows an alternative way to profile the industry via a histogram. Here the bars indicate on the vertical axis the fraction (percent) of all companies considered which fall into each range on the horizontal axis. It indicates that the largest number (33 percent) spent between $15 and $20 per installed horsepower on maintenance; with a range from between zero and $5 on the low end, and $30 to $35 per horsepower on the upper end; combining the largest two bars, well over 50 percent of companies spend between $10 and $20 per installed horsepower on maintenance. Again, this histogram profile does not differentiate engine type.

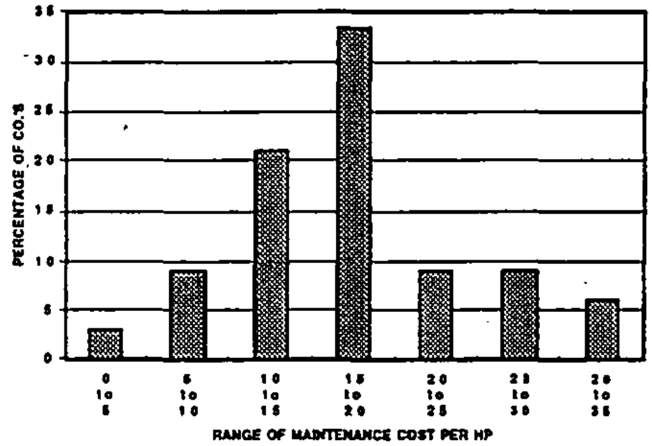

Figure 3. Histogram for CSM Cost Per HP, Showing Percentage of Co.'s in Each Indicated Range - Industry Mean=16.65; Median=17.61

Table 1 presents a broader summary of key correlation results for compressor station maintenance costs; it covers regression against deliveries (MMCF), installed horsepower, and 1000's of horsepower hours; it distinguishes between the entire population analyzed (which includes several million Canadian horsepower - 25 percent of the total, and two intrastate pipelines), and FERC filing interstates. It shows values for correlation coefficient (R^2), standard error, slope, standard error in slope, lower and upper limits for 95 percent of the population (based on Gaussian analysis), and size of the population analyzed. In general, the FERC companies alone, and total population provide similar values for slope, even though the variance may differ significantly.

Table 2 presents industry normalized averages, regression slope, and median ratios for maintenance cost, O&M cost, and fuel use versus deliveries, HP, and 1000's of HP-hours. An industry average equals the total industry cost divided by the total industry value of the normalizing quantity. The regression slope has previously been defined as the constant of proportionality, which best fits the individual company data points. The median ratio requires calculating the normalized cost for each company, then finding the median value for this normalized cost. While the values in each row of Table 2 have the same units, they indicate that significant variation exists as a result of differences in the method of calculation; thus the data should be applied with careful consideration of the quantity and its definition, and awareness of this variability.

Table 1. Compressor Station Maintenance - Summary of Regression Parameters

Regression	R^2, %	Std. Error	Slope	Std. Error in Slope	Std. Slope Error, %	Lower 95% Limit on Slope	Upper 95% Limit on Slope	Size
SCSM vs. MMCF	43.81	3811613	6.20	0.63	10.21	4.91	7.50	31
SCSM vs. HP	79.39	3504008	14.87	0.84	5.64	13.16	16.57	33
SCSM vs. 1000's of HP-Hrs.	58.90	4479962	3.33	0.37	11.11	2.53	6.13	16
SCSM vs. MMCF (fO)(1)	62.00	3782176	6.26	0.48	7.75	5.26	7.26	27
SCSM vs. HP (fO)	62.84	3740344	16.86	1.14	7.65	12.52	17.20	27
SCSM vs. 1000's of HP-Hrs. (fO)	71.20	3809422	3.97	0.39	9.77	3.13	4.82	11
SCSM vs. MMCF (1 outlier removed)	52.95	4126503	5.59	0.46	8.23	4.64	6.53	30

(1) fO = FERC filing interstate pipelines only.

Table 2. Industry Normalized Averages, Regression Slopes, and Medians

Normalization	Population	Industry Average	Regressed Slope	Median Ratio
Maint. Cost vs. Deliveries	Total	$6.90/ MMCF	$5.59/ MMCF	$6.31/ MMCF
Maint. Cost vs. HP	Total	$16.65/ HP	$14.87/ HP	$17.61/ HP
Maint. Cost vs. 1000's of HP-Hrs.	Total	$3.98/ 1000 HP-Hr.	$3.33/ 1000 HP-Hr.	$5.26/ 1000 HP-Hr.
Maint. Cost vs. Deliveries	FERC Only	$6.94/ MMCF	$6.26/ MMCF	$6.42/ MMCF
Maint. Cost vs. HP	FERC Only	$17.43/ HP	$14.86/ HP	$17.61/ HP
Maint. Cost vs. 1000's of HP-Hr.	FERC Only	$4.44/ 1000 HP-Hr.	$3.97/ 1000 HP-Hr.	$5.25/ 1000 HP-Hr.
Combined O&M vs. Deliveries	FERC Only	16.64/ MMCF	$16.22/ MMCF	$15.22/ MMCF
Combined O&M vs. HP	FERC Only	$44.66/ HP	$38.64/ HP	$44.96/ HP
Combined O&M vs. 1000's of HP-Hrs.	FERC Only	$11.28/ 1000 HP-Hrs.	$10.92/ 1000 HP-Hrs.	$12.63/ 1000 HP-Hrs.
Fuel Gas vs. Deliveries	Total	1.42%	1.15%	1.06%
Fuel Gas vs. HP	Total	34.14 MCF/ HP	30.39 MCF/ HP	31.70 MCF/ HP
Fuel Gas vs. 1000's of HP-Hrs.	Total	8.25 MCF/ 1000 HP-Hr.	7.25 MCF/ 1000 HP-Hr.	7.92 MCF/ 1000 HP-Hr.
Fuel/Power Cost vs. HP	FERC Only	$62.23/ HP	$62.75/ HP	$58.5/ HP

Figure 4 presents results of compressor station regression analysis; it shows how inferred maintenance cost per horsepower varies with driver type, and includes error bars which indicate the range of mean ± one standard deviation for:

- Electric motor;
- Two-stroke reciprocating engine, integral with the compressor;
- Four-stroke reciprocating engine, integral with the compressor;
- Separable engine (not integral with the compressor);
- Aeroderivative gas turbine; and
- Industrial gas turbine.

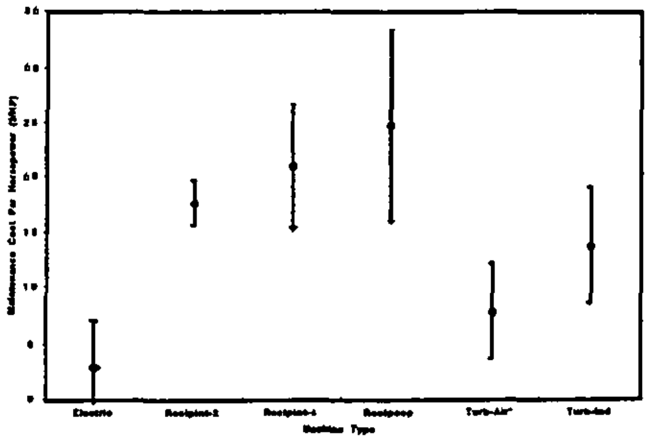

Figure 4. Maintenance Cost Per HP as a Function of Machine Type

Figure 5 presents a similar comparison by type of drivers - this time for combined operations and maintenance cost per horsepower (without fuel cost). Comparison with Fig. 4 for maintenance alone indicates that combined cost of O&M is approximately 2.5 times the cost of maintenance alone; it also shows the error bands are a substantially smaller fraction of the average than the error bands for maintenance cost alone. In other words, the combined O&M cost produced a much tighter regression that maintenance alone.

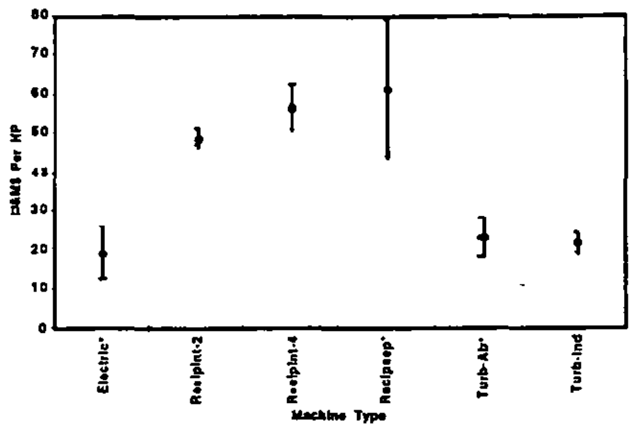

Figure 5. O&M Cost Per HP as a Function of Machine Type

It is possible to extract values for various costs as a function of model, as Smalley, et al (1997) demonstrates. This paper seeks to demonstrate methods and data sources, rather than compare products, and presents these results as mean maintenance cost per year as a function of size for industrial turbine models. Each data point in Fig. 6 corresponds to a model; the size ranges from just over 1,000 HP to about 25,000 HP. The figure includes a regression line. This figure, while exhibiting some scatter, suggests that the variation of cost with size has a non-zero intercept - that is a cost per turbine which does not depend on size. Linear regression quantifies the "per turbine" maintenance cost as $20,136 with a slope of $8.27/HP, and a standard error of $27,072; while this standard error confirms the scatter in the data, the general trends of the regression are as expected.

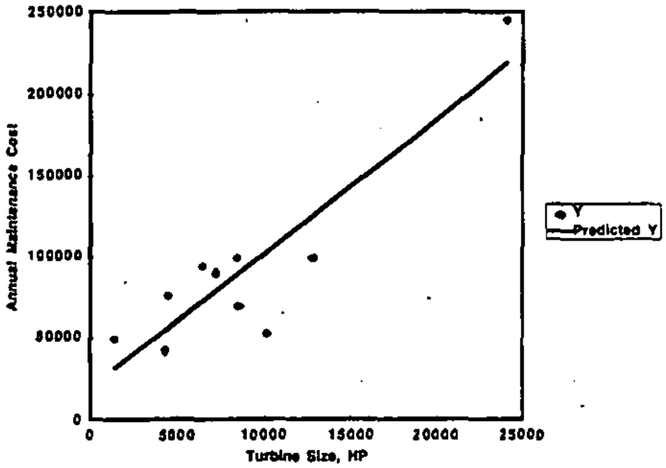

Figure 6. Annual Maintenance Cost vs. Industrial Gas Turbine Size, HP

DISCUSSION

The illustrative analyses based on the data from FERC, and data from individual companies indicate that much can be learned about the gas transmissions cost of compression, including turbine drives, both in comparative and absolute terms. Linear regression techniques can provide information to a level below that of record keeping practices. Information can be extracted on cost of maintenance, cost of O&M combined, and fuel use. Smalley, et al (1997) provides a more comprehensive presentation of possible results and methods of analysis.

CONCLUSIONS

Useful information regarding gas transmission maintenance can be extracted from public domain data in combination with supplementary information provided by individual companies.

1994 industry average values available include $16.65/HP for maintenance cost; $3.98/1000 HP-hours for maintenance cost; 8.25 MCF per 1000 HP-hours for fuel gas burned, and 1.42 percent for fuel gas volume per volume delivered.

The methods discussed in this paper can be applied with benefit to more recent years of operation.

For aeroderivative gas turbines regressed values for 1994 were $7.83 and $22.81 per HP for maintenance alone and for combined O&M cost, respectively. For industrial gas turbines, these regressed costs for maintenance alone and for combined O&M were $13.75 and 21.50, respectively.

When regressed for individual models, the average maintenance cost for industrial gas turbines has the form:

$$\$Maint. = \$20{,}136 + \$8.27/HP$$

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