Economic Evaluation of Compressed Natural Gas Fleet Conversion and Operation

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Increased public concern about energy efficiency and air quality has led to a number of state and federal initiatives that examine the use of alternative fuels for motor vehicles. Texas instituted an alternative fuels program for public fleet operations beginning in FY 1991-1992. A life-cycle benefit/cost model for evaluating the economic implications of fleet conversion and operation on compressed natural gas (CNG) is presented. The principal benefit in a CNG-fleet operation is the fuel cost savings resulting from the price difference between gasoline/diesel and natural gas. The costs are classified according to capital infrastructure costs, capital vehicle costs, and operating costs. The benefits and costs are driven by fleet-specific demand parameters, including number and type of vehicles, annual mileage, fuel consumption, and fueling procedures. Sample fleets similar to those of the Texas Department of Transportation are analyzed to identify critical benefit/cost elements in the model. The sample analysis confirms that fuel prices, fueling infrastructure, and vehicle conversion costs are the key factors in the life-cycle economic evaluation.

During the 1980s it became increasingly apparent that transportation professionals would have to respond to new environmental mandates. At the forefront of these mandates was the recognition that motor vehicle fuels are a great source of undesirable emissions (*1*). A number of states and the federal government took action to investigate alternatives to gasoline and diesel fuels. Inherent in these policy directives were not only air quality issues but also national security concerns about U.S. dependence on foreign oil. Consequently, there has been a growing volume of research and demonstration projects on the use of alternative fuels.

Texas, a state rich in natural gas, adopted alternative fuels legislation (*2*) requiring all school districts with more than 50 buses, state agencies with more than 15 vehicles (excluding emergency vehicles), and metropolitan transit authorities to buy new vehicles that operate on natural gas, propane, methanol, or electricity. Affected agencies can receive a waiver of this requirement if they can demonstrate that (a) operation of an alternatively fueled fleet is more expensive than operation of a gasoline/diesel fleet or (b) alternative fuels are not available in sufficient supply. This paper analyzes the first area for natural gas. As the analysis demonstrates, it is difficult to show cost-effectiveness for compressed natural gas (CNG) as an alternative fuel when excluding externalities. This is a serious limitation to an otherwise progressive legislative action.

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On the basis of research at the Center for Transportation Research for the Texas Department of Transportation (TxDOT), the authors have developed a model for analyzing the cost-effectiveness of CNG as an alternative fuel for fleet operations. Basically, the model examines the benefits and costs of a CNG-fueled operation over the life cycle of a CNG fast-fill station. It is important to note that in this paper the model is used only for fleet analysis, not general public policy analysis.

CONCEPTUAL COSTS AND BENEFITS

As already noted, several positive social impacts result from the use of alternative fuels for motor vehicles. Although the focus of the benefit/cost analysis is on fleets, it is still important to consider the larger social impacts even if they are not dealt with in financial terms for the fleet analysis. In the long run, all benefits and costs must be considered in evaluating alternative fuel policies and their consistency with broader societal issues. However, it is important to determine what agencies or segments of society incur particular costs or benefits, as an input to public policy and budgetary allocation.

Societal benefits from natural gas may accrue in the following areas: urban air pollution, global warming, national energy security, regional economic stimulus, fuel toxicity, land and water pollution, vehicle safety, and transitions to future vehicular fuels, such as hydrogen. These benefits are difficult to quantify and incorporate into a fleet-level benefit/cost analysis. Rather than attempt to place a monetary value on these benefits, one can determine the minimum value that the broader social benefits must assume in order to overcome costs. This value could be used as a basis for developing a tax or fee to accommodate externalities that typically are not included in economic analysis.

In evaluating the economic feasibility or implications of operating a fleet of vehicles on natural gas, a life-cycle benefit/cost analysis is necessary. The main focus of this analysis is from the fleet operator's viewpoint, in particular on cost-effectiveness. Therefore, the narrower monetary benefits and costs (listed in Figure 1) to the fleet are analyzed. The benefits associated with other important policy goals are not included.

Benefits

Monetary fleet benefits are derived from the fuel price difference between natural gas and gasoline (or diesel) and from

BENEFITS
- A. Fuel cost savings
- B. Maintenance cost savings

COSTS
- A. Capital infrastructure
  1. Compressor
  2. Storage
  3. Dispenser
  4. Dryer
  5. Setup
  6. Land
- B. Capital vehicle
  1. If converted
     - a. Conversion kit equipment
     - b. Storage tank(s)
     - c. Labor
  2. If OEM
     - a. Cost differential
- C. Operating
  1. Station maintenance
  2. Power to drive compressor
  3. Cylinder recertification
  4. Driver and mechanic training
  5. Labor losses from fueling
  6. Texas state natural gas vehicle fuel tax

FIGURE 1 Summary of principal monetary fleet costs and benefits.

potential maintenance savings. The former is the primary source of monetary benefits, since natural gas is currently cheaper on an energy-equivalent basis. Adjusting for possible differences in fuel efficiencies between natural gas and gasoline or diesel vehicles, savings are accrued on the basis of the differential in price between the fuels. Maintenance savings (increased oil and spark-plug life are two possibilities) is the other potential monetary benefit. Documented proof of maintenance savings or of its magnitude is currently lacking, though anecdotal and theoretical evidence suggest the possibility of some savings. It is assumed that the fleet already has gasoline or diesel fueling capabilities on-site. These facilities will be used less while dual-fuel converted vehicles are used and may be eliminated if dedicated original equipment manufacturer (OEM) vehicles are fully phased in, but no benefit is given in this analysis for reduced operating and maintenance costs or for the possible elimination of those facilities.

Costs

Monetary fleet costs can be categorized into capital infrastructure costs, capital vehicle costs, and operating costs.

Capital Infrastructure Costs

Capital infrastructure costs represent the initial investment for an on-site natural gas fueling station and future additions for increased capacity. The station design could be slow-fill, nurse truck, fast-fill, or a combination. If fast-fill, the station design will vary according to the particular fueling scenario for a given fleet (for instance, whether all vehicles fill daily, in one session, or several sessions, etc.). The station itself has six cost components: compressor, storage, dispenser, dryer, setup, and land. Setup costs include all miscellaneous costs, such as those for priority and sequencer panels, piping, installation labor, and managerial soft costs.

Capital Vehicle Costs

Capital vehicle costs are those above what would be spent on a comparable gasoline or diesel vehicle. If the vehicle is converted from a gasoline or diesel vehicle, these differential costs are divided into three categories: conversion kit equipment, storage tank, and labor. The conversion kit costs include those for all "under the hood" parts such as air and fuel mixers, regulators, and piping. Storage tank costs include the cost of on-board tanks and mounting equipment. Labor costs are incurred in performing the conversion. If the vehicle is replaced with an OEM natural gas vehicle, then the capital vehicle cost is the price difference between the comparable OEM natural gas and gasoline (or diesel) vehicle.

Operating Costs

Operating costs include station maintenance, which is performed mainly on the compressor; power to drive the compressor; costs to recertify cylinders to conform with U.S. Department of Transportation (DOT) regulations; additional training for drivers and mechanics; labor losses from fueling; and the Texas state natural gas vehicle fuel tax.

Labor losses are incurred with fast-fill fueling, because of longer and more frequent fills (a result of current technology). If slow-fill is used, labor time savings may result, because time is required only to connect and disconnect the fueling probe, which is minimal compared with the downtime resulting from filling and switching (driving the vehicle up to and away from the fueling probe and getting in and out of the vehicle). Moreover, the fueling occurs during idle periods, so no person hours are lost due to waiting.

Texas law requires some state fleets to pay a fuel tax on vehicular use of natural gas. TxDOT vehicles are not exempt from this tax, and they must also pay state gasoline and diesel taxes. Currently, TxDOT vehicles are exempt from federal gasoline and diesel taxes, and there is no federal tax on natural gas use for vehicles.

Fleet conversions also generate some nonmonetary costs and benefits. Because of the difficulty in quantifying them, they are not included in the main economic analysis. Possible benefits include safer vehicles and improved public relations from capitalizing on the clean air benefits of natural gas. Possible costs include the risk involved in investing in a new technology (although there are more than 700,000 natural gas vehicles operating worldwide, there are only about 30,000 in the United States) and the negative impact from perceived safety problems.

The costs and benefits discussed represent the significant factor for evaluating the economic feasibility of a CNG-fueled fleet. Additional work is needed in valuing broader social impacts. These issues, although critical from a policy perspective, are often excluded in more limited applications.

FRAMEWORK DEVELOPMENT

This section presents an overview of the cost-effectiveness analysis framework and discusses the underlying assumptions and required input data. The analysis applies at the fleet level. A fleet is composed of different types of vehicles, each with a given set of attributes reflecting performance characteristics and use, both of which influence fuel consumption. Most of the cost and benefit items are incurred at the individual vehicle level, independent of other fleet characteristics. The major exceptions are infrastructure capital costs, for which some fixed costs are incurred regardless of actual fleet size.

The detailed expressions for each cost time are not presented here. These are mostly straightforward, and they would be too tedious and space-consuming; they have been implemented in spreadsheet format and documented elsewhere (*3*). Instead, this section focuses on the principal conceptual relations and assumptions, as well as on the input data required and the manner in which the various data items affect the calculations. Of particular interest is the approach devised in this study to estimate the fueling infrastructure requirements of the fleet under consideration; these requirements are translated into approximate sizes for the various station components on the basis of fundamental engineering principles (*4*).

The discussion in this section follows the order in which the principal benefit and cost elements are presented in the previous section. The principal input data requirements and assumptions are then discussed.

Benefit and Cost Calculations

The monetary cost/benefit fleet analysis uses a net present value (NPV) approach whereby all future costs and benefits over the time horizon of interest are discounted to the present using a rate that reflects the opportunity cost of capital for the particular fleet operating agency. In addition, the cost (or saving) per vehicle per year is computed by dividing the annualized NPV by the fleet size, in order to compare cost-effectiveness for different fleet sizes and to assist in identifying the offsetting level of societal benefits.

As explained in the previous section, monetary benefits derive primarily from fuel cost savings under CNG operation relative to gasoline and diesel. At the fleet level, then, savings depend on fleet size and composition (in terms of the different vehicle categories described). For a given vehicle type, the annual fuel cost savings are given by

$$\text{savings} = [\eta_{GAS,U}p_{GAS} - \alpha_{CNG}\eta_{CNG,C}p_{CNG} - (1 - \alpha_{CNG})\,\eta_{GAS,C}p_{GAS}] \times \text{miles} \quad (1)$$

where

α_{CNG} = fraction of total annual miles driven on CNG, $0 \leq \alpha_{CNG} \leq 1$;
p_{CNG}, p_{GAS} = respective prices of CNG and gasoline (per gasoline gallon equivalent), for the year under consideration;
$\eta_{CNG,C}$, $\eta_{GAS,C}$ = respective CNG and gasoline fuel consumption characteristics (in gasoline gallon equivalents per mile) of the vehicle after conversion to dual-fuel operation;
$\eta_{GAS,U}$ = gasoline fuel consumption for the vehicle before conversion; and
miles = annual mileage of the vehicle.

The given expression is modified appropriately to consider conversions of diesel-fueled vehicles as well as OEM vehicles. It is applied to each year separately over the time horizon of interest, allowing increased reliance on CNG over time as users become more familiar with converted vehicles and as the reliability of the technology is established. This can be reflected by increasing the value of α_{CNG} over time, or simply by using a lower value for the first few years.

In developing fleet-level estimates, average values (for each vehicle type) are used for the vehicle use and consumption characteristics. Letting the subscript k denote a particular vehicle type, the total fuel cost savings are given by

$$\sum_k (\text{savings})_k N_k \quad (2)$$

where N_k is the number of fleet vehicles of type k.

The other source of cost savings is maintenance costs savings. As noted earlier, these may or may not materialize. No particular methodology has been developed here to estimate such savings, given the absence of factual evidence to support such calculations. Such savings can be input directly in the spreadsheet as a per-vehicle amount for each type, allowing the analyst to conduct related sensitivity studies.

Three major cost items were described in the previous section: fueling (capital) infrastructure costs, vehicle conversion (capital) costs, and operating costs. The most challenging to estimate are the fueling infrastructure costs, as the literature contains little guidance in this regard. A new cost estimation methodology was developed for this application.

This analysis assumes that fleets will provide their own fueling infrastructure. Even if this is not the case, and the fleet is assumed to fuel at a public CNG filling station, this framework can still be used. The CNG fuel prices would then be adjusted to reflect public station prices, and all capital infrastructure, station maintenance, and station power costs would be removed, because they are now incurred by the public station and passed on to the fleet in the fuel price. The fleet can provide its own fueling infrastructure in several ways: (a) slow-fill from pipeline-supplied gas, (b) nurse truck–supplied gas/slow-fill, (c) nurse truck/fast-fill, (d) fast-fill from pipeline-supplied gas, and (e) combination slow-fill and fast-fill. Lower costs to the fleet may be possible with the slow-fill option, though one would have to change the fueling operation for the fleet. Such a change may not always be detrimental, as pointed out in the earlier discussion of possible gains in person-hour productivity associated with slow-fill. Though this analysis can be performed for any of the natural gas fueling options, the rest of this paper deals with the option that most closely replicates the service a fleet now receives with its own on-site gasoline or diesel stations, namely, continuous fast-fill with pipeline-supplied natural gas.

The most cost-effective fast-fill (with pipeline gas) fueling station design requires compression of natural gas into cascade storage [usually in three banks at about 3,600 psi gauge (psig)]. Vehicles are filled (nominally to 3,000 psig) from the storage in cascade fashion to get the maximum amount of gas out of storage while still retaining sufficient flow rates to fill vehicles in times comparable to those for gasoline and diesel. The size of the compressor and the size of the storage are chosen so that the storage is depleted when the last vehicle fuels. With depleted storage, another vehicle could still fuel, but it would take longer than the required maximum time allowed for fueling. It has often been suggested that minimizing the compressor size and maximizing the amount of storage will always be most cost-effective. Although we have not seen sufficient proof of this claim to generalize for all fleets, we assume it here for three reasons: (a) if the assumption is incorrect, costs are not significantly higher; (b) minimizing the compressor size minimizes the peak power required, which benefits electrical-rate-setting purposes; and (c) the assumption offers computation convenience.

This analysis features a new cost estimation approach that relies on a fueling station design methodology based on underlying engineering relationships (*4*). The compressor and storage sizes directly affect their costs according to cost-size relationships empirically calibrated using data reported in the literature and received from manufacturers and vendors (*5*; unpublished data, Christy Park, Inc.; Cherco Compressors, Inc.; Tri-Fuels, Inc., 1991). Following are some of the more important assumptions affecting these sizes and, therefore, costs.

The compressor cost-size relationship holds only for compressors designed to operate at input gas line (suction) pressures of 5 to 7 psig. Significant capital compressor and operating (power) costs savings are possible if the fleet has access to higher pipeline gas pressures. In fact, it has been reported that in Italy cost-effective natural gas filling stations require suction pressures of 150 psig (*6*). This analysis also assumes continuous filling of vehicles in one session per day. This maximizes the required storage. If it were assumed instead that vehicles fueled in two or three continuous sessions, with storage recharge time in between, then the storage size and cost would be less. The minimum storage cost occurs if vehicle fueling is uniformly distributed throughout the work day. The amount of fuel remaining in the vehicle's storage tank when fueling is performed must also be assumed. Another factor to consider is that these estimates are based on average daily fuel needs. In reality, a fleet may want to buy a compressor and storage that are slightly larger than estimated here (and therefore more expensive) in order to handle their worst-case days.

Finally, the calibrated relation for storage implies that storage is available in continuous increments, and this is not so. In reality, the fleet will need to purchase an amount of storage that is commercially available. This will probably result in a slightly higher cost than predicted here. The same is true for compressors, because individual companies may offer specific compressors at a price lower than predicted here on the basis of average patterns.

Some elements in this methodology tend to underpredict and others tend to overpredict station costs. On balance, the resulting estimate should be sufficiently close to actual costs for the purpose of this analysis. In fact, it produces predictions that are similar to other reported natural gas fueling station costs (*5,7,8*). It also provides the fleet operator with an approximate station design (i.e., size of compressor and storage) and indications of how conversion to natural gas (fueling aspects only) will affect fleet operation, through comparison of fueling session times, number of vehicles fueling daily, and labor fueling losses between natural gas and gasoline/diesel.

The fueling station design methodology used in this analysis breaks each fueling cycle into two distinct time periods: the time of the continuous fueling session ($T_{session}$) and the time for storage recharge ($T_{recharge}$) before the next session. The minimum compressor size (C_{min}) is then computed from

$$C_{min} = D_{session}/(T_{session} + T_{recharge}) \tag{3}$$

where $D_{session}$ is the fleet demand per session.

The maximum storage size (S_{max}) is computed from

$$S_{max} = D_{session}/[U_{storage} \times (1 + T_{session}/T_{recharge})] \tag{4}$$

where $U_{storage}$ is usable storage or the proportion of storage deliverable to vehicles from cascade operation.

Equation 4 is derived from Equation 3 and from the fact that the amount of natural gas used from storage during the session must be replaced by the compressor during recharge, as shown here:

$$S_{max} \times U_{storage} = C_{min} \times T_{recharge} \tag{5}$$

The underlying assumption in each of these equations is that the compressor is running continuously in order to minimize its size and maximize its productivity. One must have values for $U_{storage}$, $T_{recharge}$, $T_{session}$, and $D_{session}$ in order to calculate compressor and storage sizes.

$U_{storage}$ is a function of desired flow rate and the initial vehicle tank pressures (*4*). Therefore, values for $U_{storage}$ and flow rate per dispenser hose (F_{hose}) must be assumed. $T_{recharge}$ can be found by subtracting $T_{session}$ from the fleet fueling cycle time, which is normally 24 hr, since fleets typically operate on daily cycles.

$T_{session}$ is computed by assuming that queues of vehicles (with vehicles uniformly distributed by type) form at each available dispenser hose and that each vehicle type requires a certain total fill time ($T_{vehicle}$), which consists of a transition time between vehicles (T_{switch}) and an actual filling time (T_{fill}). The latter is simply calculated as $D_{vehicle}/F_{hose}$, where $D_{vehicle}$ is the natural gas demand per fill.

The average number of vehicles of each type fueling daily and $D_{session}$ can be derived, if one knows the on-board storage capacity and average annual miles traveled for each. The average number of vehicles of each type fueling daily and the number of dispenser hoses then gives the number and type of vehicles in each fueling queue.

Dispenser and dryer costs are input directly by the analyst, and the station setup cost is considered to be equivalent to a percentage of the combined cost of the compressor, storage, and dispenser (*7,8*).

The other major capital costs are vehicle conversion costs. No particular calculations are required here, because the various cost items are supplied directly by the analyst, as will be discussed later.

As reported in the previous section, six operating cost components are included in the analysis.

Station Maintenance Costs

Costs for station maintenance are incurred primarily by the compressor and are taken to be directly proportional to the fuel consumed. The unit cost per gasoline gallon equivalent is an input to the procedure.

Power Costs

Power costs, a significant operating cost component, are a function of the cost of electricity per kilowatthour and the energy required by the compressor. The cost per kilowatthour is an input for the procedure. The energy required by the compressor is a function of its motor horsepower (HP), its duty-cycle, and the number of hours of operation (obtained from the station design methodology). The compressor HP is computed from an equation empirically calibrated from published data and data obtained directly from manufacturers and vendors (*3,5*). Note that in years when tank recertification is required for a given vehicle, the consumption of natural gas (and therefore the compressor operating hours and fuel price savings) is reduced accordingly to account for the number of days that the vehicle cannot be operated on CNG, as current methods require that the tank be removed from the vehicle and taken off-site for hydrostatic testing.

Cylinder Recertification Costs

Costs for cylinder recertification are incurred periodically (every 3 years for composite cylinders and every 5 years for steel). They are computed on a per-cylinder basis and include costs for labor (to remove and replace the cylinder on the vehicle), for transportation (to the testing facility), and for the test itself. The total cost per cylinder is an input to the procedure. Recertification is required by DOT regulations.

Additional Training

Additional training, encompassing both driver and mechanic training, is directly entered by the analyst in the appropriate year it is incurred, if applicable.

Fueling Labor Lost Time

The natural gas fueling process is more time-consuming because of its slower fuel dispensing rate and lower on-board fuel capacity that requires these vehicles to fuel more frequently than gasoline and diesel vehicles (and thus incur the switching time between vehicles). The additional CNG fueling time relative to gasoline is multiplied by an hourly labor rate to obtain the corresponding labor costs. Any differences in queue waiting times between CNG and gasoline/diesel are ignored.

Texas State Natural Gas Vehicle Fuel Tax

This is a tax required for TxDOT and many other state fleets by Texas law. The tax is based on the annual mileage driven on natural gas and the weight of the vehicle.

As noted, these calculations have been implemented in spreadsheet format. The calculations require fleet data and several assumed values that must be supplied by the analyst. These are discussed next.

Input Data Requirements

The input data can be broken into five categories: vehicle data, fuel prices, fueling station data, fueling labor loss data, and miscellaneous factors.

Vehicle Data

Four vehicle types are considered in this framework: automobile, light truck (pickups and vans), heavy-duty gasoline, and heavy-duty diesel. Each type is characterized by different attributes that affect the costs and benefits of CNG conversion and operation. The data for a specific fleet consists of its composition (number of vehicles, year they are converted or an OEM natural gas vehicle replacement is purchased, and current gasoline fuel efficiency) and vehicle utilization (average annual miles traveled and percentage of this mileage using natural gas) by type. Factors to adjust fuel efficiency for comparable converted and OEM natural gas vehicles are also included here, as are the costs of conversion kit equipment, tanks, and labor for conversion and an OEM price differential. Other vehicle data include on-board gasoline storage capacity, maintenance cost differential, tank recertification cost, number of CNG tanks per vehicle, and salvage value differentials.

Fuel Prices

Fuel prices are used to calculate the major monetary fleet benefit. The pipeline price of natural gas to the fleet in dollars per thousand cubic feet (mcf) is used along with the natural gas-to-gasoline and natural gas-to-diesel energy conversion factors (in the miscellaneous factors section) to compute the price of natural gas per gasoline and diesel gallon equivalents. These prices are for an amount of natural gas with the energy equivalence of a gallon of gasoline or diesel. Also needed are the gasoline and diesel prices per gallon.

Because of the uncertainty involved in predicting natural gas, gasoline, and diesel prices over the next year—much less over the next 30 years—this paper does not present any elaborate future predictions. Because natural gas price trends have tracked gasoline price trend fairly closely over the past 20 years (see Figure 2), it is not unreasonable to assume that they will continue to do so in the future. This assumption might be incorrect if natural gas vehicles take over a significant share of the gasoline and/or diesel vehicle market. For flexibility and sensitivity analysis purposes, the analysis framework permits the consideration of any forecast profile and the comparison of different macroeconomic scenario forecasts, thereby allowing an assessment of the robustness of a particular fleet conversion decision.

Fueling Station Data

The principal parameters introduced in the station cost estimation procedure must be supplied by the analyst. In partic-

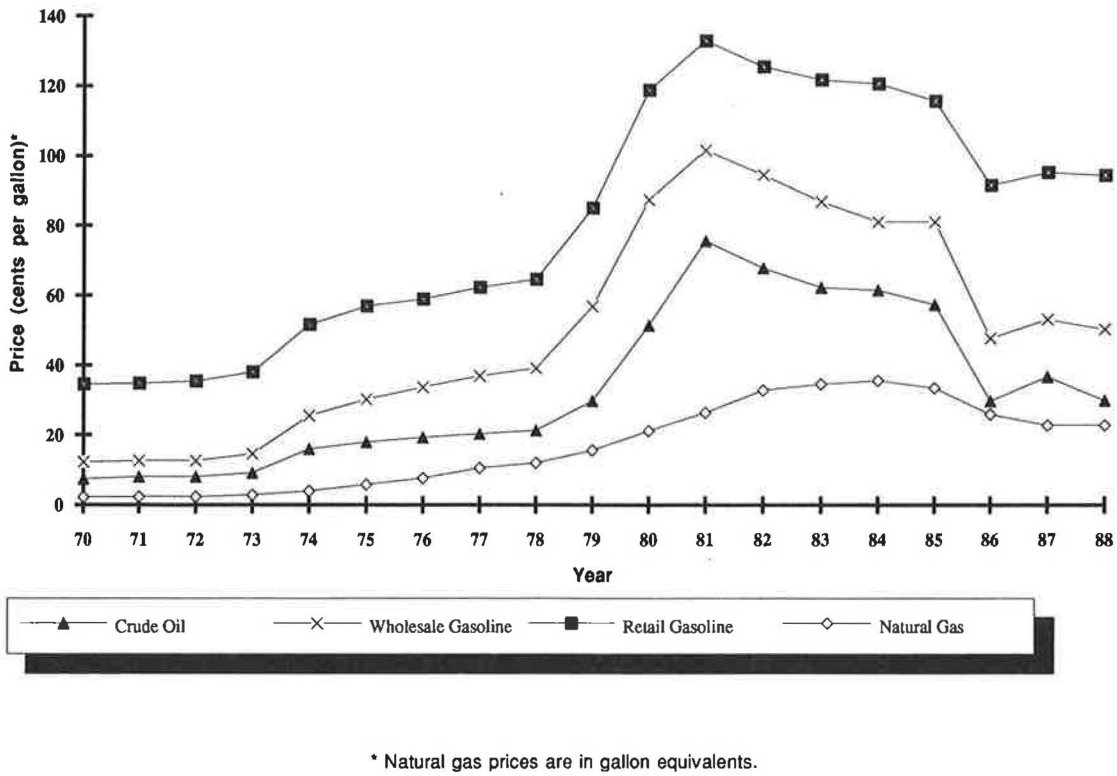

FIGURE 2 Fuel price comparison.

ular, values for the dispenser cost, dryer cost, switch time between vehicles, cycle time (i.e., session plus recharge time), number of dispenser hoses, station setup cost factor, usable storage, and average flow rate per dispenser hose over the whole session must be provided.

Fueling Labor Losses

The input data required for this calculation are very similar to those necessary to calculate the fueling session time for natural gas. In particular, values for gasoline and diesel flow rates, number of gasoline and diesel hoses, the gasoline/diesel switch time between vehicles, and the average hourly labor rate must be provided.

Miscellaneous Factors

Included here are the number of fleet work days per year, the cost of station maintenance per gasoline gallon equivalent, and the percentage of natural gas stored in a vehicle tank after the tank temperature stabilizes to around 70°F. During a fast-fill, increased tank temperatures effectively reduce the capacity of the tank (*9*). Compression factors allowing the calculation of the amount of natural gas in the vehicle when it is ready to be filled are also given, as are the volumes of natural gas in cubic feet at standard pressure and temperature (standard cubic feet, or scf) that have the energy equivalence of a gallon of gasoline or diesel.

The cost of electricity per kilowatthour is the price to the fleet under analysis. The national average is about $0.07/kWh (*13*). Also input is the number of days that tanks will be off a converted vehicle for DOT recertification. It is assumed that by the time OEM natural gas vehicles are widely available, tank recertification will be a part of ordinary state vehicle inspection and maintenance programs. Costs for this additional testing during inspection will be spread over all vehicle types, gasoline, diesel, natural gas, and others, so at that time there will be no incremental difference in cost for recertification. Finally, the discount rate or opportunity cost of capital, used to compute the present values of future monetary costs and benefits, is also an input.

SAMPLE FLEET APPLICATION AND SENSITIVITY ANALYSIS

This section illustrates the use of the previously described net present value and sensitivity analyses. First, a hypothetical fleet with characteristics favorable to cost-effective operation on CNG is analyzed, as an illustration of the type of fleets that may be cost-effective. Such favorable characteristics include a large number of vehicles to share in the fixed fueling infrastructure costs and a high average annual mileage, generating great fuel price savings per year. Next, fleets more representative of TxDOT are analyzed and compared with the "favorable" fleet.

Sample Fleet

To facilitate comparison, characteristics of the favorable fleet are based on TxDOT fleets, with the main differences being higher average annual mileage and larger-than-average fleet size. The characteristics of this fleet are shown in Table 1.

TABLE 1 Characteristics of Favorable Fleet

Vehicle Type	Number of Vehicles	Average Fuel Efficiency	Average Annual Mileage
Automobile	10	19.0 mpg	22,500
Light Truck	120	14.0 mpg	22,500
Heavy-Duty Gasoline	10	5.5 mpg	22,500

Heavy-duty diesel vehicles are not considered, because their conversion is much less cost-effective than gasoline vehicles. This is due to higher vehicle costs, both conversion and OEM; reductions in fuel efficiencies for CNG over diesel (for dedicated CNG vehicles); the greater energy density of diesel relative to gasoline; and the lower price of diesel to TxDOT fleets relative to the price of gasoline ($0.04/gal less).

Vehicles are assumed to be used for 90,000 mi (i.e., 4 years for this fleet). For the first 10 years, OEM gasoline vehicles are purchased and converted to dual-fuel CNG operation. In Year 11, OEM-dedicated natural gas vehicles are assumed available for all vehicle types.

Other important input variables are fuel prices, conversion costs, and OEM vehicle price differentials. Fuel prices are obviously highly uncertain, and conversion and OEM costs are somewhat negotiable and subject to change owing to technological advances and economies available with mass production and market competition, among other things. In this example, constant fuel prices (1991 dollars) are used over the entire 30-year analysis period. A gasoline price of $0.89/gal (including tax) is assumed, based on the prices paid by TxDOT in 1991. Conversion costs and OEM cost differentials are drawn from several sources (*5,7,14*; Natural Gas Resources, Inc., unpublished data, 1991) and shown in Figure 3, along with all other major input data assumptions.

Conversion costs	
Automobile	$1,950
Light Truck	$2,200
Heavy-Duty Gasoline	$3,300
OEM vehicle cost differential	$900
Gasoline fuel price (cents/gallon) (constant over entire analysis period)	89.0
Station maintenance cost (cents/gallon)[a]	4.5
Electricity cost (cents/kWh)	6.3
Vehicle life (miles)	90,000
CNG in a gallon of gasoline (scf)	122.7
Vehicle tank pressure before fill (psig)	100
Year OEM vehicles available	11
Cylinder recertification cycle (years)	3
Analysis period (years)	30
Discount rate	10%
Fuel efficiency decrease for conversions	5%
Fuel efficiency increase for OEM	15%
Usable cascade storage	40%
Average flow rate per hose (scfm)	300
Number of dispenser hoses	2
Vehicle maintenance cost savings	$0
Land cost for fueling station	$0
Additional training cost	$0
Labor rate per hour	$15

[a] Values of this factor ranging from 3 to 10 cents have been reported (6, 7, 9–12).

FIGURE 3 Input data assumptions.

Figure 4 shows a summary of the analysis for the favorable fleet with a natural gas price of $1.65/mcf. Under the base assumptions of the model, this price is required for operation of this fleet to be cost-effective (i.e., for the 30-year NPV of savings minus costs to be non-negative). Because actual natural gas prices are quite variable for different fleet locations, the break-even price of natural gas (i.e., the price required for cost-effectiveness) is found by performing a sensitivity analysis. One can then compare the break-even price with the price to any particular location or—as done in these analyses—compare the break-even price with plausible natural gas prices. Herein, $2.50/mcf is considered to be the lowest plausible pipeline-delivered natural gas cost to TxDOT fleets (*15,16*). Thus, conversion of this hypothetical fleet is not cost-effective under the base model assumptions.

It is interesting to note the relative magnitudes of the cost items. The 30-year NPV of fueling station infrastructure costs

SAVINGS	30 year NPV
Gasoline Price Diff.	$1,569,297
Automobiles	$75,664
Light Trucks	$1,232,247
Heavy Duty Trucks	$261,386
Diesel Price Diff.	$0
Maintenance	$0
Total Savings	**$1,569,297**
COSTS	
Infrastructure	
Land	$0
Station setup	($85,153)
Compressor	($65,829)
Storage Vessels	($240,395)
Dispenser	($24,857)
Dryer	($9,943)
Subtotal	($426,176)
Vehicle	
Conversion Kit	($89,889)
Tanks	($132,500)
Labor	($175,872)
OEM	($82,748)
Subtotal	($481,009)
Operating	
Station Maint.	($102,971)
Cylinder Recert.	($25,228)
Power	($127,855)
Labor - fuel time loss	($239,386)
NG Fuel Tax	($165,160)
Additional training	$0
Subtotal	($660,599)
Total Costs	($1,567,784)
Savings - Cost	$1,512

FIGURE 4 Favorable fleet analysis summary ($1.65/mcf natural gas price).

($426,176) and vehicle costs ($481,009) are of the highest magnitude, followed by labor-fuel time losses ($239,386), Texas state natural gas vehicle fuel tax ($165,160), power ($127,855), and station maintenance ($102,971). It should be noted that power and station maintenance costs accumulate on a per-gallon basis, and as such directly reduce the savings from the fuel price differential. There are no economies of scale for these costs, as more fuel is consumed through either annual mileage increases or changes in fuel economy. The sensitivity of the results to the assumptions used in computing the four highest cost items is examined next, along with the sensitivity to fleet size, average annual miles traveled per vehicle, and discount rate.

Sensitivity Analyses

For the sample fleet described, sensitivity to the following three relaxations of the base model assumptions are analyzed first:

- Relaxation 1—Eliminate Texas state natural gas vehicle fuel tax;
- Relaxation 2—Ignore labor-fuel time losses; and
- Relaxation 3—Reduce fueling station infrastructure costs by one-third.

Relaxation 1 is appropriate as a policy instrument for encouraging greater natural gas use. Relaxation 2 is important in order to highlight the value of both fueling station and on-board storage technology improvements. Finally, Relaxation 3 is used as an approximation of the maximum potential cost reductions associated with other fueling scenarios and technologies. The results are shown in Table 2 for the favorable fleet. Under relaxations 1 and 2 (jointly), this fleet's conversion becomes cost-effective at low—but plausible—natural gas prices.

Sensitivity to the price of natural gas can be examined by considering the base case above, where cost-effectiveness occurred at a price of $1.65/mcf ($0.20/gasoline-gal equivalent). As natural gas price increases to $7.25/mcf (equivalent to the gasoline price of $0.89/gal), fuel price savings approach zero (and become slightly negative owing to fuel efficiency losses with CNG), resulting in a very high cumulative NPV (−$1,567,784). Thus, cost-effectiveness is very sensitive to fuel price, since natural gas prices in the middle and at the high end of this range are quite plausible (*15,16*).

Vehicles in TxDOT fleets are driven in the range of 15,000 mi year. So, under the 90,000-mi vehicle life assumption used in this analysis, they are kept for 6 years. Because there are approximately 300 TxDOT locations at which vehicles fuel, and because TxDOT has about 6,000 gasoline vehicles statewide (mostly light trucks), the average fleet size is only about 20 vehicles, as opposed to 140 vehicles in the fleet analyzed earlier. Yet fleet variability is such that there are a few locations as large as 140 vehicles. Therefore, sensitivity analyses to average annual miles per vehicle and fleet size are performed. Fleet size is adjusted by changing the number of light trucks and leaving both the number of automobiles and the number of heavy-duty gasoline vehicles at 10. Three fleet sizes are analyzed. They contain 10, 60, and 120 light trucks, respectively, in addition to the 10 automobiles and 10 heavy-duty gasoline vehicles. The results for 15,000 mi/vehicle fleets are shown in Table 3.

The case with 120 light trucks differs from the one previously analyzed only in that the average annual mileage per vehicle is assumed to be 15,000 instead of 22,500 mi. The results are quite sensitive to this change. The break-even natural gas price is reduced by an amount ranging from $0.71 to $1.08/mcf. One must relax all three assumptions for the 15,000 mi/vehicle fleet to become cost-effective for a low—but plausible—natural gas price.

Results are also fairly sensitive to fleet size. The break-even natural gas price increases as the fleet size increases, mainly because of economies of scale in the fueling infrastructure costs. The break-even natural gas price is about $0.20 less for the 60 light-truck fleet than for the 120 light-truck fleet and drops by about another $0.40 for the 10 light-truck fleet. Since most of the TxDOT locations are best represented by the 10 light-truck fleet, even relaxation of all three assumptions does not quite yield a plausibly low break-even price for natural gas. Any other combination of relaxations yields implausibly low break-even prices. One can therefore conclude that it will not be cost-effective to convert most TxDOT locations to natural gas, unless more of the base assumptions of this analysis can be relaxed or natural gas is available at prices less than $2.50/mcf.

Sensitivity to the discount rate is reported in Table 4 for the 10 light-truck fleet with 15,000 average annual miles per

TABLE 2 Sensitivity Analysis, Favorable Fleet

Relaxations	Break-Even NG Price (per mcf)
None	$1.65
1	$2.24
1 & 2	$3.09
1, 2, & 3	$3.60

Note: NG = natural gas.

TABLE 3 Sensitivity Analysis, 15,000-mi Fleet

	Break-Even NG Price (per mcf) for		
Relaxations	10 LTs	60 LTs	120 LTs
None	-$0.03	$0.37	$0.57
1	$0.75	$1.22	$1.46
1 & 2	$1.55	$2.06	$2.31
1, 2, & 3	$2.49	$2.75	$2.89

Note: NG = natural gas, LT = light truck.

TABLE 4 Sensitivity to Discount Rate, Fleet with 10 Light Trucks and Annual Mileage of 15,000 mi

Discount Rate	Break-Even NG Price (per mcf)
10 %	-$0.03
8 %	$0.68
6 %	$1.37
4 %	$2.04
2 %	$2.69
0 %	$3.30

Note: NG = natural gas.

TABLE 5 Analysis for Immediate Availability of OEM Vehicles, 15,000-mi Fleet

Fleet Size	Break-Even NG Price (per mcf)
10 LTs	$1.85
60 LTs	$2.37
120 LTs	$2.61

Note: NG = natural gas.

vehicle, assuming no other relaxations of the base assumptions. The appropriate discount rate would have to be very low (0 or 2 percent) for the majority of TxDOT fleets to be cost-effective, and then only with fairly low natural gas prices.

The final sensitivity analysis reported here is for conversion costs. Assumed conversion costs (see Figure 3), which include kit, tank(s), and installation labor, are about 30 percent less than TxDOT is currently paying, as our analysis assumed a more mature natural gas vehicle market in Texas. Nevertheless, because of claims that conversions can and will be performed even cheaper, the limiting case of immediate availability of dedicated CNG OEM vehicles was analyzed for the three fleet sizes for 15,000 average annual miles per vehicle. This is the best case possible for vehicle costs, because OEMs cost less than conversions, tank recertification is not necessary, and greater benefits accrue from the increased fuel efficiencies of OEM-dedicated CNG vehicles. The analysis results are reported in Table 5. As expected, the break-even natural gas prices are much higher than those when conversions are used for the first 10 years. This further confirms that the introduction of OEM vehicles is very important, as is the reduction of conversion costs until that time.

Sensitivity to other factors (e.g., maintenance savings, vehicle fuel efficiencies, labor costs, electricity costs, power costs, station maintenance costs, and cylinder recertification costs) can also be investigated using this model.

CONCLUSIONS

The analysis has illustrated the primary significance of fuel price differential, conversion cost, and fueling infrastructure cost in the trade-offs underlying CNG fleet operation decisions. This analysis confirms that the actions of the natural gas industry and others to push for OEM vehicles, improved and lower-cost on-board storage technologies, and improved and lower-cost fueling infrastructure represent a good near-term strategy for achieving greater market penetration of natural gas vehicles.

The analysis has shown that the Texas state natural gas fuel tax is a significant cost item. Its removal should be investigated as a possible policy measure for improving the effectiveness of the Texas alternative fuels legislation.

The model presented in this paper is a decision support tool that allows one to deal with uncertain energy and technological futures through alternative scenarios and sensitivity analyses. It allows the proper accounting for the costs and benefits to fleets versus society at large, which has implications for the budget-setting process. For example, Texas has recently approved legislation that mandates some fleet conversion to natural gas unless it is not cost-effective for the fleet to do so. From the analysis herein, it appears that it will not be cost-effective for most TxDOT fleets to convert to natural gas operation with fuel prices, conversion costs, fueling infrastructure costs, and such comparable to current prices. Yet, if the societal benefits are considered to be great enough, the required additional funds may be provided to these fleets to achieve those objectives. Public policy in this regard could be guided by the use of this approach to compute the valuation of societal benefits that would make fleet conversion cost-effective.

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