Compressed Natural Gas Vehicles

Financially Viable Option?

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Natural gas vehicles are being developed because of increasing concerns about energy dependence, air quality and emissions, and, more recently, climate change. The major advantage of natural gas vehicles is their lower fuel cost. Several economic and technical factors such as limited range and availability of relevant infrastructure prevent widespread adoption of natural gas vehicles. A model for the financial analysis of the possibility of compressed natural gas (CNG) vehicles being competitive with gasoline-powered vehicles is offered. The model evaluates the extent to which commuters find adoption of CNG vehicles to be economically viable in the United States. The results indicate that the percentage of commuters who would adopt CNG vehicles is small, even if fueling infrastructure were fully developed and CNG vehicles were widely available for purchase. A larger number of vehicle miles traveled and increased gasoline prices encourage commuters to adopt CNG vehicles, while higher fuel economy and purchase price differentials result in lower adoption rates. In some cases, which vary in accordance with the values of the model's parameters, commuters purchase a CNG vehicle as their second car and keep a gasoline-powered car as their first.

Natural gas could compete with gasoline in the automobile fuel market. One of the principal factors motivating governments to encourage the widespread adoption of compressed natural gas (CNG) vehicles is the reduction of local air pollution. Higher usage of CNG vehicles reduces the emission levels of nonmethane organic gases and reactive organic gases, oxides of nitrogen, carbon monoxide, and other air toxins. It also reduces cold-start emissions, off-cycle emissions, evaporation emissions, and running-loss emissions (*1, 2*). These benefits make CNG vehicles particularly attractive in areas where local urban air quality is poor and environmental issues are a concern.

Recently, improved drilling technology has increased natural gas production in the United States and effectively caused a significant price decrease (*3*). Natural gas prices in the United States have fallen more than 60% from their peak in 2008 (*3, 4*). Over the same period, prices for gasoline have increased, which means that natural gas has a growing cost advantage over gasoline. Accordingly, the Energy Information Administration expects natural gas to be the fastest-growing fossil fuel in the world through 2035 (*5*).

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Despite fuel cost advantages and reduced emissions, the use of natural gas in the transportation sector is not considerable (*3*). According to the Natural Gas Vehicle Association of America, there are approximately 120,000 natural gas vehicles (NGVs) in the United States and 15.2 million NGVs worldwide. The high initial price of NGVs, the lack of refueling infrastructure, and limited CNG power trains offered by automobile makers have historically suppressed the demand for CNG vehicles (*6*).

The disadvantages associated with CNG vehicles include reduced vehicle range, increased fueling frequency, increased vehicle weight due to heavy fuel tanks capable of storing compressed fuel safely, and reduced storage space inside the vehicle itself. In addition, CNG vehicles are typically less powerful due to the lower energy density of natural gas compared with gasoline (*7, 8*).

With regard to the attractions and limitations of NGVs, Deal (*9*) focused on the viability of heavy-duty CNG-powered trucks. He determined some factors that limit the growth of these vehicles. Among them are limited refueling infrastructure, the higher initial cost, the upgrading of maintenance shops to deal with CNG vehicles, limited trip range, and the weight of fuel tanks. Moniz (*10*) and the National Petroleum Council (*6*) both found that fuel price is the most attractive feature of a CNG vehicle. These studies also indicated that the high vehicle purchase price is a prohibitive factor even where CNG refueling infrastructure is widespread and even if automobile makers were to offer more CNG models. Whyatt (*8*) examined the incentives and barriers associated with adopting CNG as a fuel for light-duty passenger cars, heavy-duty combination trucks, and fleet vehicles of all types. In all these cases, the primary incentive to switch from gasoline or diesel to natural gas is the potential fuel cost savings.

Few CNG passenger vehicles are marketed in the United States. Thus, considerable uncertainty with regard to the premium price of a CNG vehicle can be observed. The limited information available suggests that the CNG premium price has not yet decreased over time. Furthermore, higher manufacturing volume may not result in lower costs (*11*). Therefore, for a CNG vehicle to make economic sense for consumers, the fuel cost savings must be large enough to compensate consumers for the higher up-front vehicle cost (or the costs of converting a vehicle to run on CNG).

In this paper, a formal model for analyzing CNG vehicle adoption is offered. The approach is based on the modeling of a consumer's financial decision, which depends on the cash flow associated with the capital and fueling costs. The model evaluates the percentage of commuters finding CNG vehicles financially beneficial in comparison with gasoline-powered vehicles. The model indicates what may be possible under conditions favorable to CNG adoption rather than what is probable under current or future conditions. To conduct the analysis, several simplifying assumptions were necessary: the existence of a broad range of choice in CNG vehicles and the wide availability of supporting infrastructure (fueling stations) to consumers. Currently, CNG vehicles have a shorter trip range than gasoline vehicles, and CNG fueling infrastructure is extremely limited in many areas of the United States. These concerns are serious constraints and render a CNG vehicle impracticable for many, if not most, consumers.

Many studies (*12, 13*) used a discrete choice–random utility approach to evaluate consumer preferences for vehicle attributes. They demonstrated that desirable vehicle attributes such as increased power, better fuel economy, and reliability are important factors affecting vehicle use. In contrast, the study described here simply calculates whether a gasoline or CNG fuel system would be more cost-effective on otherwise identical vehicles.

MODELING PROCEDURES

The theoretical model considers a consumer choosing between two otherwise identical cars or converting a gasoline-powered vehicle to run on CNG. Consumers who benefit financially by switching to CNG must save enough on fuel costs to cover the higher purchase price of CNG vehicles. Fuel cost is a function of fuel price, fuel efficiency, and vehicle miles traveled (VMT). VMT for the most part varies with a consumer's location and distance to work and to leisure and shopping destinations. To consider the effects of distance traveled on CNG vehicle adoption, a monocentric urban model was developed. It is based on the approach of Bilotkach and Mills (*14*).

The approach is centered on the notion of commuters who never walk or use transit. Thus, they use personal vehicles for all travel purposes. For the model of this paper, 100 commuters are assumed to be distributed uniformly along a linear path, and they are all assumed to work in the same location [i.e., a central business district (CBD)]. Each commuter is uniquely identified by location on the line and distance to the CBD, $x \in [0, 100]$. The distance of infrequent trip destinations (leisure or shopping) to the CBD is $\alpha < 100$. This model is shown in Figure 1.

Gasoline-powered vehicles and CNG vehicles are two options that differ in the single trip range (d). CNG vehicles' single trip range is limited to $200 < d < 2(100 + \alpha)$, which implies that all commuters are located within a CNG vehicle's range for their work trips, while for some commuters CNG is not a viable option for leisure or shopping trips. The point $k = (d/2) - \alpha$ is the location of the marginal commuter for whom the CNG vehicle is a feasible option for both types of trips. Commuters located between the CBD and $k = (d/2) - \alpha$ can use CNG for all their travel needs; commuters living between the k and 100 points need to use their regular vehicle, at least for shopping and leisure trips.

A rational commuter located at point x will choose the vehicle with lower cost, with cost being measured by the net present discount value of all cash flows associated with the choice. Expected maintenance costs, registration fees, and other costs associated with normal vehicle ownership are assumed to be the same for both vehicle types. The vehicles differ in the initial purchase price, depreciation costs (because of the purchase price differential), and fuel costs. The total cost associated with vehicle ownership can be expressed as follows (*15*):

$$\mathrm{TC}_i = V_{i0} + f_{i0} + f_{i1}(1+r)^{-1} + f_{i2}(1+r)^{-2} + \cdots + f_{iT}(1+r)^{-T} - V_{i0}(1+\delta)^{-T}(1+r)^{-T} \quad (1)$$

where

- TC_i = total present discounted value of all costs associated with the vehicle,
- V_{i0} = initial value or the vehicle's purchase price,
- f_{it} = fuel cost in time period t,
- r = individual's rate of discount,
- T = terminal time period at which the individual sells or disposes of the vehicle, and
- δ = parameter measuring the per period rate of depreciation (therefore, the last term in the expression captures the sale or scrap value of the vehicle at time T).

The subscript $i \in \{g, c\}$ indicates whether the vehicle is powered by gasoline (g) or CNG (c). If fuel costs are assumed to be similar in each time period ($f_{it} = f_i$ for all t), this expression can be simplified and written as follows:

$$\mathrm{TC}_i = \left\{V_{i0} - V_{i0}\left[(1+\delta)(1+r)\right]^{-T}\right\} + \sum_{t=0}^{T}(1+r)^{-t} f_i \quad (2)$$

The expression $V_{i0}^{*} = \{V_{i0} - V_{i0}\,[(1+\delta)(1+r)]^{-T}\}$ is the vehicle purchase cost minus the present discounted value of the terminal vehicle value (scrap or resale value). Therefore, it represents the cost of owning the vehicle for time period T, independent of fuel costs. Equation 2 can be rewritten as follows:

$$\mathrm{TC}_i = V_{i0}^{*} + \sum_{t=0}^{T}(1+r)^{-t} f_i \quad (3)$$

A commuter is assumed to make N trips to the CBD and one trip to a leisure or shopping destination within a given time period. Therefore, the commuter travels a distance of $2[(N+1)x + \alpha]$ in each time period. Fuel consumption is the ratio of distance traveled (VMT) to fuel efficiency [miles per gallon (MPG)]. Fuel cost f_i is the price of fuel, p_i, multiplied by fuel consumption. It is given by the following:

$$f_i = \frac{2\left[(N+1)x + \alpha\right]p_i}{\mathrm{MPG}_i} \quad (4)$$

where p_i is the price of fuel type i per gallon and MPG_i is fuel efficiency of vehicle type i. Thus, substitution of this formula for the total cost in Equation 3 yields the following:

$$\mathrm{TC}_i = V_{i0}^{*} + \sum_{t=0}^{T}(1+r)^{-t}\left\{\frac{2\left[(N+1)x + \alpha\right]p_i}{\mathrm{MPG}_i}\right\} \quad (5)$$

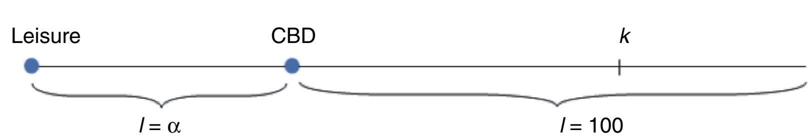


FIGURE 1 General model setup.

Since the gasoline and CNG vehicles are the only two alternatives, the commuter's choice is determined solely by the difference in total cost of the two vehicles. Commuters choose the alternative with the lesser total cost. In this study, the nominal fuel price and fuel efficiency are assumed to be the same for each type of vehicle in different time periods. However, fuel prices may fluctuate, and fuel efficiency may differ because of variations in vehicles' size, year, and make. The two types of vehicles are also assumed to depreciate at the same rate. This assumption may not be true in practice (*15*).

ANALYSIS

Location is a major factor affecting the decision to adopt a CNG vehicle. Two groups were analyzed. Group 1 consisted of commuters whose needs are met by the range of CNG vehicles ($x_1 < k$), and Group 2 consisted of commuters who are constrained by the range of CNG vehicles ($k < x_2 < 100$). Members of the first group decide to own a CNG or gasoline vehicle as their single car. Members of the second group, who have gasoline vehicles, decide to purchase a CNG vehicle as a second car for some of their needs. The point k from the CBD defines a boundary for commuters who can use CNG vehicles for both work and leisure trips. The magnitude of k is related to the single trip range of CNG vehicles and to the distance of leisure and shopping destinations from the CBD (α).

Group 1

On the basis of the difference in total ownership cost, a rational commuter will choose the CNG-powered vehicle if Equation 6 holds:

$$\Delta\text{TC} = \text{TC}_g - \text{TC}_c = \left(V^*_{g0} - V^*_{c0}\right) + 2\sum_{t=0}^{T}(1+r)^{-t}\left[(N+1)x_1 + \alpha\right]\left(\frac{p_g}{\text{MPG}_g} - \frac{p_c}{\text{MPG}_c}\right) > 0 \quad (6)$$

The minimum distance from the CBD for a rational consumer to select a CNG vehicle is defined by simplifying Equation 6:

$$x_1 \geq \frac{\left(V^*_{c0} - V^*_{g0}\right) - 2\sum_{t=0}^{T}\alpha\left(\frac{p_g}{\text{MPG}_g} - \frac{p_c}{\text{MPG}_c}\right)(1+r)^{-t}}{2\sum_{t=0}^{T}(N+1)\left(\frac{p_g}{\text{MPG}_g} - \frac{p_c}{\text{MPG}_c}\right)(1+r)^{-t}} \quad (7)$$

This expression indicates that rational commuters located closer than x_1 to the CBD would not buy a CNG vehicle. Commuters are indifferent between a CNG vehicle and a conventional vehicle on the boundary point x_1. These commuters can make up for the premium paid for a CNG vehicle by saving on fuel costs. However, commuters located at $x_1 > k$ still do not choose a CNG vehicle because of the range limitations.

Group 2

For commuters located farther away than k, a CNG vehicle is not practical because of range limitations. These commuters must retain their gasoline vehicle, but they can decide to buy a CNG vehicle and split their travel needs between the two vehicles. The CNG vehicle will be used for work trips, and the gasoline vehicle will be used for leisure trips. Therefore, the total cost of owning both types of vehicles is given by the following:

$$\text{TC}_{g+c} = V^*_{g0} + V^*_{c0} + 2\sum_{t=0}^{T}(1+r)^{-t}\left[\frac{(Nx_2)\,p_c}{\text{MPG}_c} + \frac{(x_2+\alpha)\,p_g}{\text{MPG}_g}\right] \quad (8)$$

An approach similar to that used for Group 1 indicates that the minimum distance of Group 2 to the CBD, x_2, to make the option of buying a CNG vehicle as a second vehicle financially beneficial is as follows:

$$x_2 \geq \frac{V^*_{c0}}{2\sum_{t=0}^{T}N\left(\frac{p_g}{\text{MPG}_g} - \frac{p_c}{\text{MPG}_c}\right)(1+r)^{-t}} \quad (9)$$

x_2 is the location of commuters who are indifferent between having a gasoline vehicle and purchasing a CNG vehicle as a second car. Thus, purchasing a CNG vehicle as a second car would be beneficial only for commuters whose distance to the CBD is more than x_2. If $x_2 \leq k$, all commuters living outside the CNG range in the interval $(k, 100]$ would purchase a CNG vehicle as their second car. If $x_2 > 100$, no one would buy a CNG vehicle as a second car. If $k \leq x_2 \leq 100$, commuters located between point k and x_2 will not adopt a CNG car, whereas those located between x_2 and 100 would. Distance to leisure destinations and the initial prices of gasoline vehicles do not affect Equation 9. This is because the choice to use a gasoline vehicle for leisure trips is predetermined.

Vehicle Ownership Patterns

On the basis of the model developed, the possibility of purchasing a CNG vehicle as the only car owned by commuters of Group 1 (P_1) and the possibility of buying a CNG vehicle as the second car owned by commuters of Group 2 (P_2) are calculated and shown below (*14*):

$$P_1 = \max\left[0, \min(k - x_1, k)\right] \quad (10)$$

$$P_2 = \max\left[0, \min(100 - k, 100 - x_2)\right] \quad (11)$$

Consideration of various values for the model's parameters results in the definition of six cases for CNG vehicle ownership. In each case, the adoption rate of CNG vehicles is determined as follows (*14*):

$$S_c = P_1 + P_2 \quad (12)$$

Case 1. $x_1 > k$; $x_2 > 100$. In this case, commuters fail to adopt a CNG vehicle. $P_1 = 0$, $P_2 = 0$, and $S_c = 0$ (Figure 2*a*).

Case 2. $x_1 \leq 0$; $x_2 \leq k$. In this case, all the commuters adopt a CNG vehicle. All commuters located within the CNG range have a financial advantage in buying a CNG vehicle instead of a regular vehicle, whereas people living outside the CNG range have a financial advantage in buying a CNG vehicle as their second vehicle. Clearly, $P_1 = k$, $P_2 = 100 - k$, and $S_c = 100$ (Figure 2*b*).

Case 3. $x_1 > k$; $k \leq x_2 \leq 100$. In this case, none of the commuters living within the CNG vehicle's range have a financial advantage in adopting a CNG vehicle, whereas some or all of the consumers living outside the CNG vehicle's range have a financial advantage in purchasing a CNG vehicle as their second vehicle. $P_1 = 0$, $P_2 = 100 - x_2$, and $S_c = 100 - x_2$ (Figure 2*c*).

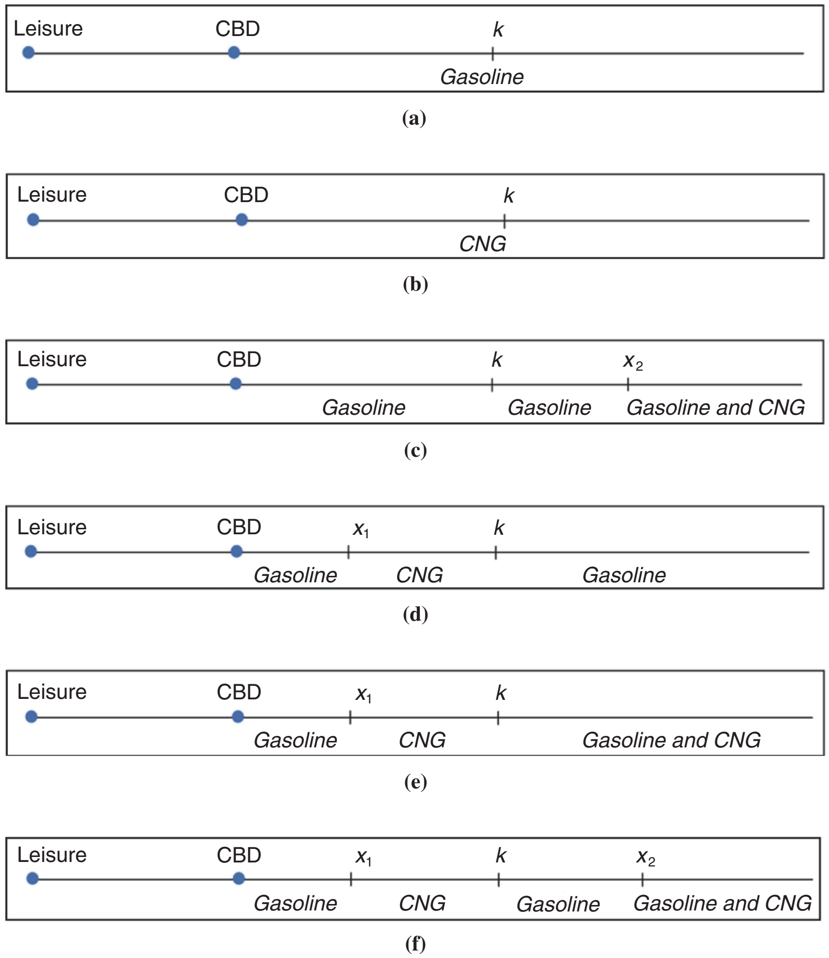


FIGURE 2 Car ownership pattern: (*a*) Case 1, (*b*) Case 2, (*c*) Case 3, (*d*) Case 4, (*e*) Case 5, and (*f*) Case 6.

Case 4. $0 < x_1 \leq k$; $100 < x_2$. In this case, some of the commuters living within the CNG vehicle's range have a financial advantage in adopting CNG vehicles instead of gasoline vehicles, but none of the commuters located outside the CNG vehicle's range have a financial advantage in adopting a CNG vehicle as a second vehicle. $P_1 = k - x_1$, $P_2 = 0$, and $S_c = k - x_1$ (Figure 2*d*).

Case 5. $0 < x_1 \leq k$; $x_2 \leq k$. In this case, all the commuters living outside the CNG vehicle's range have a financial advantage in adopting a CNG vehicle in addition to a gasoline vehicle. Commuters living within the CNG vehicle's range have a partial financial advantage in adopting CNG vehicles. $P_1 = k - x_1$, $P_2 = 100 - k$, and $S_c = 100 - x_1$. Therefore, only commuters living within $0 < x < x_1$ do not adopt a CNG vehicle (Figure 2*e*).

Case 6. $0 < x_1 \leq k$; $k < x_2 \leq 100$. In this case, commuters inside and outside the CNG vehicle's range have a partial financial advantage in adopting CNG vehicles. $P_1 = k - x_1$, $P_2 = 100 - x_2$, and $S_c = 100 + k - x_1 - x_2$ (Figure 2*f*).

SIMULATION

Many factors affect a commuter's vehicle ownership pattern. To predict vehicle type choice for a given consumer, the model requires estimation of V_{g0}, V_{c0}, p_g, p_c, MPG_g, MPG_c, T, r, and δ. If a commuter knows the value of these parameters, calculation of the total cost for either type of vehicle and the making of an appropriate decision are straightforward. On the basis of the present value of total cost, this model simulates the minimum distance to the CBD for both commuters located inside (x_1) and outside (x_2) the CNG vehicle's range, and it calculates the adoption rate.

Simulation results are based on assumptions of commuters' total cost minimization (as discussed above) and, more important, on similarity of fuel efficiency for both vehicles' fuel systems and availability of vehicle supply and infrastructure.

Baseline parameter values assumed in this study are as follows: depreciation rate = 15%, discount rate = 6%, expected length of vehicle ownership = 60 months (current average of Kelley Blue Book), $N = 30$, $\alpha = 40$, $d = 200$, $k = 60$, and MPG = 25. The simulation was done on the basis of changing the purchase price and the fuel price differentials (the fuel price differential is the difference between the gallon-equivalent price of CNG and of gasoline).

Table 1 shows how the minimum distance to the CBD for commuters of Group 1 (x_1) varies with the fuel price differential and the vehicle price differential (baseline values were used for other parameters). As Table 1 indicates, the minimum distance to the CBD increases with increasing purchase price differential and with decreasing fuel price differential. The results demonstrate that consumers located farther from the CBD are more likely to adopt a CNG vehicle even when the

TABLE 1 Minimum Distance to CBD for Group 1 Commuters (x_1)

Fuel Price Differential	Purchase Price Differential								
	$2,000	$3,000	$4,000	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000
$1.50	28.95	44.06	59.18	74.30	89.42	104.54	119.65	134.77	149.89
$1.60	27.06	41.23	55.40	69.58	83.75	97.92	112.09	126.27	140.44
$1.70	25.39	38.73	52.07	65.41	78.75	92.09	105.42	118.76	132.10
$1.80	23.91	36.50	49.10	61.70	74.30	86.90	99.50	112.09	124.69
$1.90	22.58	34.52	46.45	58.39	70.32	82.26	94.19	106.13	118.06
$2.00	21.39	32.73	44.06	55.40	66.74	78.08	89.42	100.76	112.09
$2.10	20.31	31.11	41.90	52.70	63.50	74.30	85.10	95.90	106.70
$2.20	19.33	29.63	39.94	50.25	60.56	70.86	81.17	91.48	101.79
$2.30	18.43	28.29	38.15	48.01	57.87	67.73	77.59	87.45	97.31
$2.40	17.61	27.06	36.50	45.95	55.40	64.85	74.30	83.75	93.20
$2.50	16.85	25.92	34.99	44.06	53.13	62.21	71.28	80.35	89.42
$2.60	16.15	24.88	33.60	42.32	51.04	59.76	68.48	77.21	85.93
$2.70	15.51	23.91	32.31	40.70	49.10	57.50	65.90	74.30	82.70
$2.80	14.91	23.01	31.11	39.20	47.30	55.40	63.50	71.60	79.70
$2.90	14.35	22.17	29.99	37.81	45.63	53.45	61.27	69.09	76.91
$3.00	13.83	21.39	28.95	36.50	44.06	51.62	59.18	66.74	74.30

vehicle price differential is large and the fuel price differential is small. These consumers can recover the high purchase price differential with savings on fuel costs.

If x_1 is less than $k = 60$, commuters of Group 1 located between x_1 and k have a financial advantage in adopting a CNG vehicle (Cases 4, 5, and 6). If x_1 is farther than $k = 60$, the adoption rate is zero (Cases 1 and 3). For example, for a fuel price differential of $2.00 and a purchase price differential of $4,000, the consumers between points 44.06 and 60 would have a financial advantage in adopting a CNG vehicle instead of a gasoline vehicle for all purposes. These data imply that a 15.94% primary vehicle adoption rate is possible on the basis of financial decision making.

Table 2 shows the variation of adoption rates with respect to fuel price differential and vehicle price differential for Group 1. Increasing the fuel price differential and decreasing the purchase price differential result in a higher primary adoption rate. However, the purchase price has a much stronger impact on adoption rate than does fuel price. For example, if the purchase price differential is $6,000 and the

TABLE 2 Proportion of Commuters with CNG Vehicle as Their Single Vehicle

Fuel Price Differential	Purchase Price Differential (%)								
	$2,000	$3,000	$4,000	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000
$1.50	31.05	15.94	0.82	0.00	0.00	0.00	0.00	0.00	0.00
$1.60	32.94	18.77	4.60	0.00	0.00	0.00	0.00	0.00	0.00
$1.70	34.61	21.27	7.93	0.00	0.00	0.00	0.00	0.00	0.00
$1.80	36.09	23.50	10.90	0.00	0.00	0.00	0.00	0.00	0.00
$1.90	37.42	25.48	13.55	1.61	0.00	0.00	0.00	0.00	0.00
$2.00	38.61	27.27	15.94	4.60	0.00	0.00	0.00	0.00	0.00
$2.10	39.69	28.89	18.10	7.30	0.00	0.00	0.00	0.00	0.00
$2.20	40.67	30.37	20.06	9.75	0.00	0.00	0.00	0.00	0.00
$2.30	41.57	31.71	21.85	11.99	2.13	0.00	0.00	0.00	0.00
$2.40	42.39	32.94	23.50	14.05	4.60	0.00	0.00	0.00	0.00
$2.50	43.15	34.08	25.01	15.94	6.87	0.00	0.00	0.00	0.00
$2.60	43.85	35.12	26.40	17.68	8.96	0.24	0.00	0.00	0.00
$2.70	44.49	36.09	27.69	19.30	10.90	2.50	0.00	0.00	0.00
$2.80	45.09	36.99	28.89	20.80	12.70	4.60	0.00	0.00	0.00
$2.90	45.65	37.83	30.01	22.19	14.37	6.55	0.00	0.00	0.00
$3.00	46.17	38.61	31.05	23.50	15.94	8.38	0.82	0.00	0.00

TABLE 3 Minimum Distance to CBD for Group 2 Commuters (x_2)

Fuel Price Differential	CNG Vehicle Purchase Price								
	$10,000	$12,000	$14,000	$16,000	$18,000	$20,000	$22,000	$24,000	$26,000
$1.50	156.22	187.46	218.71	249.95	281.19	312.44	343.68	374.93	406.17
$1.60	146.46	175.75	205.04	234.33	263.62	292.91	322.20	351.49	380.78
$1.70	137.84	165.41	192.98	220.54	248.11	275.68	303.25	330.82	358.38
$1.80	130.18	156.22	182.26	208.29	234.33	260.36	286.40	312.44	338.47
$1.90	123.33	148.00	172.66	197.33	222.00	246.66	271.33	295.99	320.66
$2.00	117.16	140.60	164.03	187.46	210.90	234.33	257.76	281.19	304.63
$2.10	111.58	133.90	156.22	178.54	200.85	223.17	245.49	267.80	290.12
$2.20	106.51	127.82	149.12	170.42	191.72	213.03	234.33	255.63	276.93
$2.30	101.88	122.26	142.63	163.01	183.39	203.76	224.14	244.52	264.89
$2.40	97.64	117.16	136.69	156.22	175.75	195.27	214.80	234.33	253.86
$2.50	93.73	112.48	131.22	149.97	168.72	187.46	206.21	224.96	243.70
$2.60	90.13	108.15	126.18	144.20	162.23	180.25	198.28	216.30	234.33
$2.70	86.79	104.15	121.50	138.86	156.22	173.58	190.93	208.29	225.65
$2.80	83.69	100.43	117.16	133.90	150.64	167.38	184.12	200.85	217.59
$2.90	80.80	96.96	113.12	129.28	145.45	161.61	177.77	193.93	210.09
$3.00	78.11	93.73	109.35	124.98	140.60	156.22	171.84	187.46	203.08

fuel price differential is $2.20, increasing the fuel price differential to $2.30 would raise the rate of possible adoption to 2.13%. In contrast, decreasing the purchase price differential to $5,000 would raise the rate of possible adoption to 9.75%.

As mentioned earlier, the minimum distance of Group 2 commuters who live outside the CNG vehicle's range does not depend on the gasoline vehicle's price. Table 3 shows the predicted distance (x_2) with respect to the fuel price differential and the CNG vehicle purchase price. On the basis of the definition of x_2, commuters living between this point and point 100, there is a financial advantage in adopting a CNG vehicle in addition to a gasoline vehicle. Clearly, the minimum distance of commuters to the CBD, for beneficial adoption of CNG as a second vehicle, increases as the vehicle price increases. It decreases as the fuel price differential increases.

The secondary vehicle adoption rates calculated for various CNG vehicle purchase prices and fuel price differentials are shown in Table 4. For CNG vehicle purchase prices greater than $12,000, no consumers would find a secondary CNG vehicle financially

TABLE 4 Proportion of Commuters with CNG Vehicle as Their Second Vehicle

Fuel Price Differential	CNG Vehicle Purchase Price (%)								
	$10,000	$12,000	$14,000	$16,000	$18,000	$20,000	$22,000	$24,000	$26,000
$1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.40	2.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.50	6.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.60	9.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.70	13.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.80	16.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$2.90	19.20	3.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$3.00	21.89	6.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00

advantageous under the baseline parameters. A high secondary vehicle adoption rate only occurs under the baseline assumptions when the CNG vehicle purchase price is $10,000 and the fuel price differential is at least $2.50.

SENSITIVITY ANALYSIS

A sensitivity analysis in combination with analytical methods is an effective way of assessing the effects of various components of the system. Many factors affect a commuter's decision concerning adoption of a CNG vehicle.

CNG fueling is extremely limited in many areas of the United States. Accordingly, the single trip range affects whether commuters living in different locations consider adopting a CNG vehicle. Figure 3*a* shows estimated adoption rates for Group 1 for various single trip ranges (k) and fuel price differentials. The CNG vehicle adoption rate increases when the single trip range is improved. This increase results in more trips and more savings on fuel costs. Fuel price differential also has a positive effect on CNG adoption rates; increasing the gasoline price and decreasing the overall price encourage adoption of CNG vehicles. The slope of CNG vehicle adoption rate over fuel price differential is increased with a higher CNG trip range. This implies that the magnitude of the fuel price effect on CNG adoption rate increases as the single trip range improves.

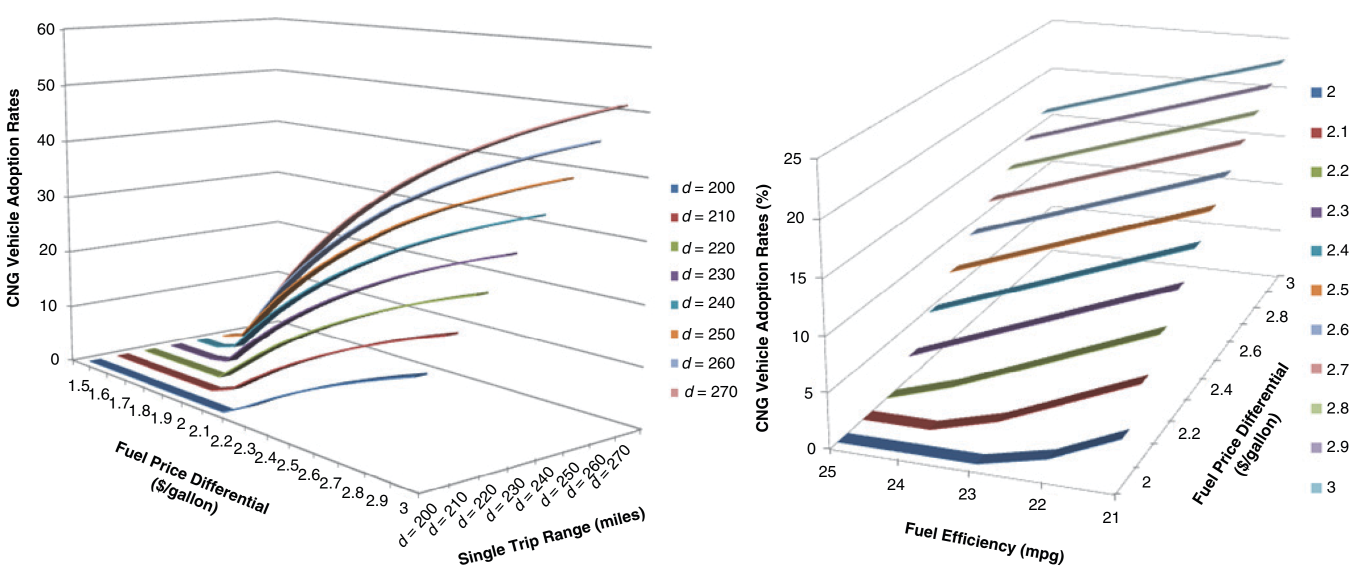
Fuel efficiency is assumed to be constant across vehicle types. However, this assumption is not realistic. Interestingly, a rebound effect is documented in the literature. It indicates that reduction of fuel consumption by improvement in fuel efficiency is relatively small and declines over time (*16–21*). Sensitivity analysis of the CNG vehicle adoption rate with respect to fuel efficiency, as presented in Figure 3*b,* demonstrates that higher fuel efficiency leads to lower adoption rates. This is explained by the reduction in the expected fuel cost savings associated with CNG as consumers use less fuel. On the contrary, improved fuel efficiency increases the single trip range and the adoption rate of CNG vehicles.

A sensitivity analysis of adoption rates with respect to single trip range at various levels of fuel price differential is presented for the commuters of Group 2 in Figure 4*a.* Improving the single trip range shifts the boundary point k farther from the CBD. Generally, this decreases the percentage of people adopting a CNG vehicle as their second car, because some commuters of Group 2 become part of Group 1 and can adopt a CNG vehicle for all their needs.

Changes in fuel efficiency have the same effect on CNG adoption by commuters of the two groups. Fuel efficiency reduction results in greater fuel consumption, which magnifies fuel costs. In addition, Figures 3*b* and 4*b* show that the effect of fuel efficiency on CNG vehicle adoption rates is negligible at low levels of fuel price differential. Overall, in view of the results of the sensitivity analysis on CNG vehicle adoption rate, the fuel price differential magnifies the effect of other factors. This means that the CNG vehicle adoption rate is more sensitive to single trip range and fuel efficiency at higher levels of fuel price differential.

DISCUSSION OF RESULTS AND CONCLUSIONS

A framework was developed for modeling CNG vehicle adoption rates by considering (*a*) adoption of a CNG car as the single vehicle of commuters located inside the CNG vehicle's trip range and (*b*) adoption of CNG vehicles as a second car for commuters outside that range. To conduct the research, several simplifying assumptions were necessary: availability of a broad range of choices of CNG vehicles and fueling infrastructure and equivalency of CNG- and gasoline-powered vehicles. However, as noted earlier, CNG vehicles are inferior to gasoline vehicles in terms of weight and power output, and they are less convenient to own and operate because of reduced storage space and more frequent refueling. Another assumption is that, at least for passenger vehicles, fuel efficiency will be unaffected by a switch to CNG. This may be approximately accurate for these vehicles, but not necessarily for other types of vehicles. Finally, fuel cost was considered fixed in each period. However, fuel price and



(a) (b)

FIGURE 3 Group 1 CNG vehicle ownership varies by (*a*) single trip range and fuel price differential and (*b*) fuel price differential and fuel efficiency.

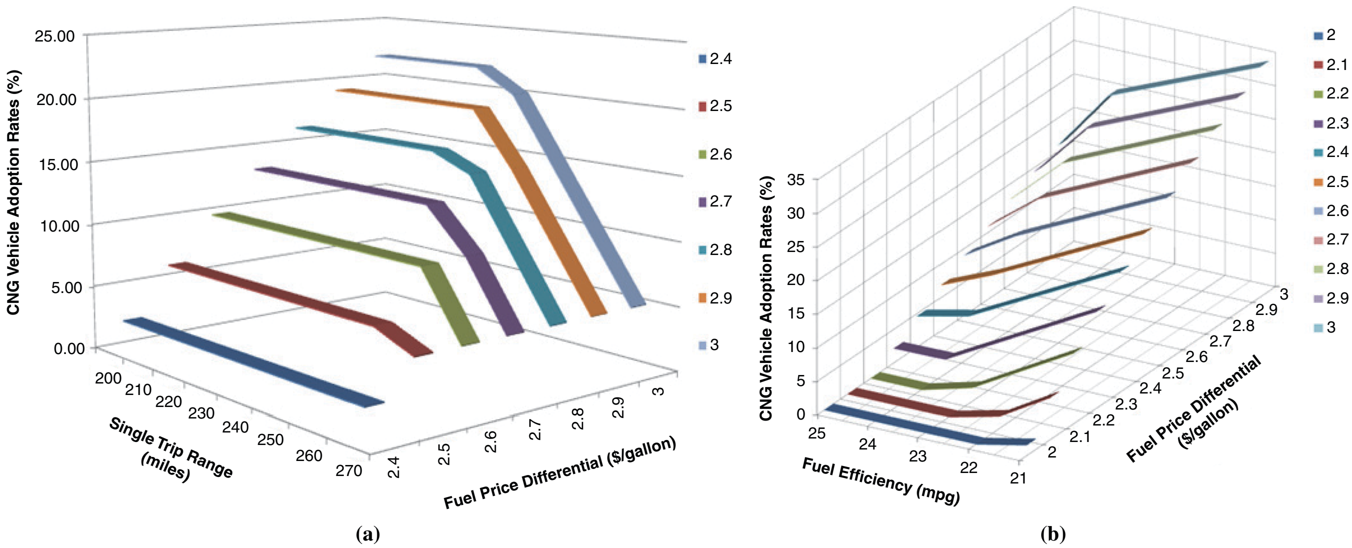


FIGURE 4 Group 2 CNG vehicle ownership varies by (*a*) single trip range and fuel price differential and (*b*) fuel efficiency and fuel price differential.

fuel consumption may vary. This assumption may be approximately true on average and aids in developing a model, but the actual effect will depend on many factors such as consumer expectations with regard to future fuel prices. Overall, the assumptions mentioned are generally favorable toward CNG adoption. Thus, the CNG vehicle adoption rate estimated in this study can probably best be viewed as an upper bound of the CNG ownership rate that can be expected. The percentage of commuters with a financial advantage in switching to a CNG vehicle was estimated in this study. However, in reality several other factors affect vehicle ownership behavior. The presumption behind this calculation is that an alternative fuel type is unlikely to achieve widespread adoption unless it can compete economically with gasoline.

The results indicate that the proportion of the vehicle fleet that would find a CNG vehicle economically advantageous is small, though knowledge and utilization of CNG vehicles are increasing. This prediction reflects the current market share. Simulations suggest that a substantial decrease in CNG vehicle prices will be necessary to induce significant CNG vehicle adoption. The model predicts that a higher effective range of CNG vehicles, increased fuel infrastructure, and technology improvement to lower production costs are factors that will lead to more CNG vehicle adoption. In addition, provision of various incentives similar to those offered for electric vehicles is effective in increasing the adoption of CNG vehicles (*22*).

Changes in vehicle fleet composition and driving habits can affect this analysis. However, as consumers respond to gasoline price increases by driving less and purchasing more fuel-efficient vehicles, the gains from CNG vehicle adoption will be diminished. In summary, the model suggests that CNG is most likely to be cost-effective for high-mileage users, for low-MPG vehicles, at high gasoline prices (especially relative to natural gas), and with the existence of adequate fuel infrastructure.

The methodology developed in this study was a simplified framework for modeling adoption of a CNG vehicle. Several issues remained outside the scope of this analysis that can be examined in future studies. In this study, commuters were identified with their location at different distances from the CBD. That is certainly not the only feature that affects their decision. Socioeconomic characteristics such as income, family size, and level of education remained outside of the model's consideration. In addition, commuters' location was considered fixed. Another limitation of this model is that travel demand is not exogenous or fixed; vehicle miles driven vary by fuel efficiency and by fuel price (*23*). There is a simultaneous endogenous relationship between CNG vehicle adoption and VMT. While an increase in VMT leads to more CNG vehicle adoption, use of more CNG vehicles with a lower fuel price may also increase VMT (*24*).

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