A Comparative Cost Analysis of Biodiesel, Compressed Natural Gas,

Methanol, and Diesel for Transit Bus Systems

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Abstract

A comparison of operating costs for buses used in a transit system arc investigated considering four alternative fuels: biodiesel, compressed natural gas, methanol, and diesel. Rust's "nested fixed point" maximum likelihood estimation algorithm is used in this comparison. The algorithm considers both tangible costs such as fuel, maintenance, and infrastructure, and intangible costs associated with different levels of bus engine operating reliability under alternative fuels. Using data on actual monthly mileage and time of engine rebuilds under the four alternative fuels, the Rust algorithm is employed assuming an optimal maintenance strategy is adopted for each alternative fuel type. Results indicate that, although biodiesel and biodiesel blends have higher total costs than diesel fuel, they have the potential of competing with CNG and methanol as fuels for urban transit buses.

Key words: Biodiesel, Natural Gas, Methanol, Diesel, Buses, Alternative Fuels

JEL Classification: Q40, Q42, Q48

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Current regulatory policies place the alternative fuel industry at a critical junction. Emissions from alternative-fueled bus engines consistently indicate lower emissions of reactive hydrocarbons, carbon monoxide, and particulate matter than diesel engines. For example, the National Soybiesel Development Board reported that biodiesel used in a 20/80 blend with petroleum diesel, along with a catalytic converter, reduces diesel engine air pollution. Reductions include 3 1% in particulate matter, 2 1% in carbon monoxide, and 47% in total hydrocarbon emissions. Given this potential of improving air quality, as regulated by the Environmental Protection Agency (EPA), firms and governmental agencies promoting a particular alternative fuel for urban bus transit have an opportunity for significantly influencing its adoption. A small policy change by government or product promotion by industry may determine which alternative fuels will be widely adopted. However, such promotion requires a comprehensive analysis, including an economic evaluation on the relative comparative costs of operating an urban bus transit fleet on alternative fuels.

Fuel is a major cost, varying by type of fuel used; however, other tangible costs such as infrastructure, engine replacement, and maintenance costs, as well as intangible costs associated with bus reliability, also vary by fuel type. For a comprehensive comparison of these alternative fuels, estimates of the total costs are required (both tangible and intangible), based on the assumption that an optimal maintenance strategy is adopted for each type of alternatively fueled bus. With the addition of engine and fuel system modification costs for alternative-fueled buses, a cost comparison among the fuels may be determined by considering the present value of the total fleet operating cost over the fleet's life cycle.

In general, cost comparisons incorporating infrastructure, equipment replacement, and maintenance costs, along with reliability, are important factors in energy policy issues. A review of the literature found no previous empirical work that has examined the issue of economic competitiveness of alternative vehicle fuels based on total life-cycle costs. While the market for cleaner burning renewable fuels is becoming increasingly important, there is a significant gap in the literature comparing these alternative fuels. A comparison of just the fuel cost per mile-without consideration of infrastructure, engine replacement, and maintenance costs-can be misleading and can result in erroneous conclusions. Thus, the primary focus of this study is to provide a complete cost comparison for operating a transit bus fleet on compressed natural gas (CNG), methanol, biodiesel, and low-sulfur diesel fuel A specific objective is the development of a dynamic model of bus engine replacement for determining the present value of total fleet operating costs for these alternative fuels. Differences in maintenance costs among these alternative-fueled buses are estimated with Rust's nested fixed point maximum likelihood estimation algorithm. The Rust algorithm estimates bus maintenance costs, including unobservable intangible costs, for different fuel types. Comparing these maintenance cost estimates with actual observed costs reveals the sensitivity of total cost to changes in maintenance costs. This model identifies the potential competitiveness of biodiesel compared with CNG and methanol under alternative prices.

Alternative Fuels

Federal regulatory policies resulting from the implementation of the National Energy Policy Act (NEPA) will encourage the adoption and use of alternative-fueled vehicles and associated technologies. This is particularly true for the urban bus market. Recent EPA regulatory activities are aimed at reducing emissions of volatile organic compounds (VOC), nitrogen oxide (NOx), and particulate matter (PM-IO) as a means of controlling urban ozone. One alternative is biodiesel fuel; however, a number of other alternative fuels, including CNG and methanol, will be competing with biodiesel fuel.

Although extensive research interest during the past decade centered upon ethanol and methanol processing technologies and policies, more recent research has emphasized the potential of plant oils as diesel fuel extenders or replacements (Gavett; McIntosh, Smith, and Withers). These nonpetroleum diesel fuel substitutes can be obtained from oilseed crops such as soybean, sunflower, and rapeseed. Methyl and ethyl esters derived from soybean and rapeseed have properties much closer to conventional diesel fuel (Ziejewski, Kaufman, and Pratt; Clark and Wagner). Fuels produced via chemical and thermal processes are referred to as biodiesel fuels. Biodiesel is a clean-burning, renewable, nontoxic, biodegradable, and domestically produced fuel that can be used neat or in blend with petroleum-derived diesel (Holmberg, Gavett, and Merrill). From an environmental standpoint, biodiesel blended with diesel can significantly reduce emissions of particulates, carbon monoxide, and unburned hydrocarbons. For economic and engine-compatibility reasons, biodiesel often is blended with diesel at a ratio of 20180.

CNG is another fuel with the potential of meeting tighter vehicle-emission requirements. Extracted from underground reservoirs, natural gas is a fossil fuel composed primarily of methane, along with other hydrocarbons including ethane, propane, and butane, and inert gas such as carbon dioxide, nitrogen, and helium. Interest in using natural gas as a transportation fuel has increased in recent years, particularly in urban areas, because it offers the potential for reducing exhaust emissions.

Methanol is yet another alternative fuel produced from both fossil and renewable domestic resources. It can be used in neat (100%) form as a diesel substitute or potentially blended with diesel. The majority of the methanol produced in the U.S. is from natural gas resources, Other sources for methanol production include coal, residual oil, and hiomass.

Petroleum-derived diesel is used as the base fuel in this study. In the past, petroleum refining was controlled primarily for gasoline yield and quality; thus, the quality of diesel fuel varied widely depending on the demand for gasoline (National Biodiesel Board). This has changed over the last few years. Diesel fuel now faces significant fuel-quality and engine-emissions requirements. Current EPA regulations set a maximum limit of 0.05% by weight on the sulfur content and a minimum cetane index of 40 for diesel fuel used in on-road vehicles.

An Optimal Maintenance Model for Bus Engines

Generally, the cost of engines is comparable among the alternative fuels considered in this analysis. However, fuel system costs and miles between rebuilds, along with engine rebuild costs, differ by fuel type. The differences in miles between rebuilds and rebuild costs across alternative-fueled buses suggest that the stream of maintenance costs varies by fuel type. For a determination of this maintenance cost, a bus engine can be regarded as a portfolio of individual components, each of which has its own stochastic failure as a function of accumulated use. If a particular component fails when a bus has relatively low mileage, then it may be optimal to replace or repair just this failed component. In contrast, for a bus with relatively high mileage, the optimal solution may be to rebuild the entire engine. Given an objective of minimizing unexpected engine failure, if a particular engine component fails when an engine has relatively high mileage, the probability of other parts failing increases, and so it might be optimal to rebuild the engine. Bus failures on the road are expensive in terms of both tangible costs such as towing, and intangible costs that include loss of time for the bus driver and passengers. Thus, a policy of preventive periodical engine rebuilding is cost effective, and the optimal preventive maintenance cost for each alternative-fueled bus will depend on the tradeoff between the value of unused life and the cost of failure.

Application of the Rust algorithm provides a consistent method for determining the differences in maintenance cost among these alternative-fueled buses. Basically, this method assumes that transit authorities have developed a procedure for optimally determining when a bus should be rebuilt. Given this optimal timing, the model estimates what the marginal maintenance cost per month must be to obtain this optimal timing.

Applying Rust's algorithm, the stochastic process is shown as $\{i_t, x_t\}$, where i, = 1 if rebuild occurs at time t, and i_t = 0 otherwise; x_t denotes mileage since the last rebuild at month t, and t = 1, ..., T. Unobserved state variables are incorporated by assuming that unobserved costs {E, (0), t,(l)} follow a specific stochastic process. Letting r denote the expected cost of a rebuilt bus engine and $c(x_t, 0,)$ the expected per period maintenance cost. where θ is a parameter to be estimated, the utility function is

$$(1) \qquad u(x_t, i_t, \theta_1) + \epsilon_t(i_t) = \begin{cases} -r - c(0, \theta_1) + \epsilon_t(1), & \text{if } i_t = 1, \\ -c(x_t, \theta_1) + \epsilon_t(0), & \text{if } i_t = 0. \end{cases}$$

Letting monthly mileage $(x_{t+1}\ x_t)$ have a subjective parametric density function, g, implies a transition density of the form

$$(2) \qquad p(x_{t+1} \mid x_t, i_t, \theta_2) = \begin{cases} g(x_{t+1}\ 0, \theta_2), & \text{if } i_t = 1, \\ g(x_{t+1}\ x_t, \theta_2), & \text{if } i_t = 0. \end{cases}$$

Data required consist of $\{ i_t^m, x_t^m \}$ $(t = 1, \ldots . T_m; m = 1, \ldots . M)$, where i_t^m is the engine rebuild decision in month t for bus m, and x_t^m is the mileage since the last rebuild of bus m in month t. The approach is to estimate the unknown parameters, $\theta = (\theta_1, r, \theta_2)$, with maximum likelihood using the nested fixed point algorithm. This involves discretizing the state variable x_t (mileage) into a certain number of intervals (say n) of a specified length,

Using the discretized mileage data, the distribution g reduces to a multinomial distribution corresponding to monthly mileage. A linear functional form for $c(x_t, 0,)$ is chosen because of its computational tractability, ease of interpretation, and its satisfactory fit with the data. The specification does not include a constant term because subtracting a constant term from the utility function (1) will not affect the choice probabilities. The most that can be identified is the value of change in maintenance costs as a function of mileage, so $c(x_t, \theta_1)$ can be normalized by setting $c(0, \theta_1) = 0$. It is hypothesized that the unobservable state variables $\{\epsilon_t(0), \epsilon_t(1)\}$ obey an independently and identically distributed bivariate process, with normalized mean and variance, because neither the location nor the scale of these observed costs are identifiable without further information. Notice that ϵ_t (0) should be interpreted as an unobserved component of maintenance costs for the bus in period t, and $\epsilon_t(1)$ should be interpreted as an unobserved component of cost associated with rebuilding the bus engine. Also, it is implicitly assumed that the stochastic process $\{x_t^i, \epsilon_t^i\}$ is independently distributed across buses.

The estimation procedure consists of three stages corresponding to each of the likelihood functions: L^1, L^2, and L^f. The full likelihood, L^f, is shown by equation (3):

$$(3) \qquad L^f(x_1, ..., x_T, i_1, ..., i_T \mid x_0, i_0, \theta) = \prod_{t=1}^{T} P(x_t \mid x_{t-1}, i_{t-1}, \theta_2) P(i_t \mid x_t, \theta)$$

L' and L^2 are partial likelihood functions, shown by equations (4) and (5):

$$(4) \qquad L^1(x_1, ..., x_T, i_1, ..., i_T \mid x_0, i_0, \theta) = \prod_{t=1}^{T} P(x_t \mid x_{t-1}, i_{t-1}, \theta_2);$$

$$(5) \qquad L^2(x_1, \ldots . x_T, i_1, \ldots . i_T \ \theta) = \prod_{t=1} P(i_t \mid x_t, \theta).$$

The first stage is to estimate the parameters θ_2 of the transition probability $P(x_{t+1}$ x„ i„ $\theta_2)$ using the likelihood function L^1. In Stage 2, the remaining structural parameters (θ_1, r) are calculated using L^2 and the estimates of θ_2 as initial starting values. The final estimation (Stage 3) employs the initial consistent estimate of θ computed in Stages 1 and 2 to produce efficient maximum estimates of θ using L^f.

Data

Unfortunately, data on monthly mileage and time of rebuilds for alternative-fueled buses is very limited. Most experiments on alternative fuels were conducted for demonstration purposes only, resulting in short time intervals and little if any data collection. One exception is an experiment by the Denver, Colorado, Regional Transportation District. That experiment, which lasted from June 1989 through December 1993, initially included five diesel buses which could use both diesel and biodiesel fuel, and five methanol buses. Five dual CNG/diesel buses (diesel buses converted so they can also use CNG) were added in 1991. The 15 buses (three fleets comprised of five buses each) resulted in 146 monthly observations for the analysis.

The three fleets of buses were exposed to similar operating conditions such as scheduled speeds, stops per mile, traffic conditions, and passenger loading. They were maintained under the same preventive maintenance program. The buses were fueled on site, This unique data set, combined with the application of Rust's algorithm, allows a cost comparison of alternative fuels based not only on fuel cost and usage, but also on maintenance, repair, engine-rebuild, and in-service failure costs for the total operational life of the transit buses.

Summary statistics indicate a large variation in mileage at time of engine rebuild, particularly for diesel and methanol buses. The coefficients of variation for mileage at rebuild are 0.522, 0.506, and 0.220 for diesel, methanol, and CNG/diesel, respectively. CNG/diesel buses are rebuilt at approximately half the time and mileage intervals of diesel and methanol buses, resulting in higher CNG/diesel maintenance costs. However, this higher cost is potentially offset by the considerably lower coefficient of variation for the CNGidiesel bus. This lower coefficient of variation implies less uncertainty regarding timing of rebuilds; thus, it is possible that CNG/diesel buses may have lower costs due to fewer unexpected required rebuilds.

(Approximate location of tables l-3)

Total infrastructure cost per bus is only $1,46 1 for diesel and biodiesel (table 1) compared with approximately $10,000 per bus for both methanol and CNG/diesel buses (tables 2 and 3). Methanol buses require 2.5 times more fuel, resulting in larger tankage. Further, methanol tanks are over six times more expensive than those used for diesel fuels. The significantly higher infrastructure costs for CNGidiesel buses as compared to those for diesel are due to the requirement of eight refueling lanes instead of three, and to storing pressurized fuel. Annual refueling cost per bus is $21,102 for methanol buses, which is approximately twice the refueling cost for diesel buses. Again, the 2.5 factor increase in fuel consumption for methanol buses relative to diesel requires 4.5 additional laborers for bus refueling. The additional six refueling lanes for CNGidiesel buses primarily explain that alternative's 37% higher annual refueling cost per bus compared with diesel buses. However, the actual cost of fuel is lowest for CNG/diesel buses at $4,306, compared with $6,963 and $11,722 for diesel and methanol buses, respectively. Bus capital costs are the additional fuel system and engine conversion costs required for methanol and CNGidiesel bus conversion. The costs of alternative-fueled buses are based on the assumption that a regional transportation district already has diesel bus refueling and maintenance facilities. Therefore, fixed costs for alternative fuel facilities are incremental to diesel facility fixed costs.

Although this assumption may favor diesel and biodiesel, it is realistic given current transit operations.

Maximum Likelihood Results

(Approximate location of table 4)

Estimates of the unknown parameters (r, θ_1) associated with operating costs are computed by maximizing the full likelihood function, L^f [equation (3)], using the nested fixed point algorithm. Model results for diesel, methanol, and CNG/diesel alternative fuels are presented in table 4. All operating cost coefficients are significantly different from zero at the 1% significance level. The coefficients associated with rebuild costs are significantly different from zero at the 10%, 5%, and 30% significance level, respectively, for diesel, methanol, and CNG/diesel buses. Maintenance marginal cost is only $1.80 for CNG/diesel compared with $3 1.84 for methanol and $4.34 for diesel. These marginal cost estimates indicate that the Denver Regional Transportation District perceives average monthly maintenance costs to increase for every 5,000 accumulated miles on the buses. The large variation in marginal cost can be explained by the relatively large rebuild cost and variation in mileage at rebuild of methanol compared with CNG/diesel buses. This wide variation in mileage at rebuild implies higher marginal cost associated with determining optimal preventive maintenance.

Marginal cost is the incremental change in total monthly maintenance cost. This is the change from a base level of initial maintenance cost which is composed of routine maintenance, including such items as brake adjustment and replacement or repair of individual components. Assuming this base level of maintenance is the same for all alternative-fueled buses, then total monthly maintenance cost is incremented every 5,000 miles by the estimates in table 4, starting with zero as the base level. This results in an average monthly maintenance cost of $28.64, $128.62, and $5.40, respectively, for diesel and biodiesel, methanol, and CNG/diesel-fueled buses. These average costs are considerably lower than the data obtained from the Denver Regional Transportation District on explicit average maintenance costs per month of $41.90 for diesel and biodiesel, $419.38 for methanol, and $71.59 for CNG/diesel buses. Lacking information on the exact proportions of these explicit costs that represent some base level of maintenance, the proportion of this maintenance can be increased from zero-which will provide information on the sensitivity of the total cost of alternative fuels to changes in this base level of maintenance.

Present Value Analysis

A complete comparison of cost differentials among the alternative fuels requires consideration of all costs, including startup, rebuild, and operating costs. Startup costs, c_S, are $38,296 and $43,727 for methanol and CNG/diesel buses, respectively. These costs are comprised of incremental refueling infrastructure costs and incremental bus capital costs (tables l-3). For example, total infrastructure cost per bus for methanol ($9,858) minus infrastructure cost for diesel ($1,461) plus methanol's bus capital cost ($29,900) equals startup costs of $38,296 for methanol. Incremental bus capital costs, c_I, include fuel system costs and engine conversion costs. These additional costs above diesel base costs are accrued every ten years over the life of a bus. Rebuild costs (listed in table 4) represent a major component of the overall total, given that the engines are rebuilt on average every 20, 21, and 10 months for diesel, methanol, and CNG/diesel-fueled buses, respectively. The rebuild costs for CNG/diesel are equivalent to those for diesel; however, the interval between CNG/diesel rebuilds is only half of that for diesel. The interval between engine rebuilds for methanol is in close association with diesel, but the methanol's rebuild cost is approximately 46% higher than the rebuild cost for the diesel. Operating cost is composed of both maintenance and fuel costs. Monthly maintenance cost is based on mileage per month, considering cost changes every 5,000 miles (given estimates of marginal cost detailed in table 4). Fuel costs for diesel, methanol, and CNG/diesel buses are the mileage per month times the cost per mile (from tables 1-3).

Three alternative fuel prices ($0.1406, $0.2812, and $0.4218) per equivalent gallon for CNG/diesel were considered. An equivalent gallon is the number of BTUs in a gallon of diesel fuel. It is assumed that #2 diesel has a heat content value of 140,600 BTUs per gallon. Based on this gross heating value, the equivalent gallon of CNG in one million BTUs of CNG is 7.1123; thus, at a price of one dollar per million BTUs of CNG, an equivalent gallon costs $0.1406.

For biodiesel, the fuel costs are the same as for diesel; however, the fuel efficiency estimates of biodiesel blend fuels compared with diesel (as estimated by the Colorado Institute for Fuel and High Altitude Engine Research, Denver) are 0.9916, 0.9766, 0.9297, and 0.8887 for 20%, 35%, 60%, and 100% biodiesel blend, respectively. Three prices per gallon ($1.75, $2.50, and $3.00) for biodiesel were considered, as the current thin market for biodiesel may not reflect the long-run equilibrium price.

(Approximate location of table 5)

Considering only the fuel cost, CNG/diesel-fueled buses offer the lowest cost per mile, with diesel and methanol a distant second and third, respectively (table 5). Biodiesel at only a 20% blend is competitive with methanol; otherwise it is the highest priced fuel per mile. However, this fuel cost does not consider the differences in infrastructure, refueling, engine and fuel system, and maintenance costs associated with alternative-fueled bus transit systems. Results from accounting for these other costs in a present value analysis are listed in the last four columns of table 5. Present value is calculated over a 30-year (360 months) life cycle of the refueling infrastructure. At the end of 30 years, the infrastructure salvage value is assumed to be zero. The salvage value of the engine is implicit in the replacement parameter r. The parameter r estimates the difference between the scrap value and the cost of installing a new engine or rebuilding the existing one. Specifically, the present value of estimated total costs (PVC) is calculated as

$$(6) \qquad PVC = c_s + \sum_{i=1}^{M} \sum_{j=0}^{R} \frac{c_{ij}}{(1+\delta)^{i+jR}} + \sum_{i=RM+M+1}^{360} \frac{c_i}{(1+\delta)^{i}} + c_I \left[\frac{1}{(1+\delta)^{120}} + \frac{1}{(1+\delta)^{240}} \right],$$

where c,, denotes monthly operating cost in the ith month after rebuild for thejth rebuild. Variables M and R represent the number of months in an engine rebuild cycle and number of rebuilds, respectively. For diesel and biodiesel, methanol, and CNG/diesel, Mis 20, 21, and 10 months, and R is 17, 16, and 35 rebuilds, respectively. Monthly discount rate is denoted as 6. Note that the last rebuild month ($R \times M$) is 340, 357, and 350 for diesel and biodiesel, methanol, and CNG/diesel, respectively. Thus, at month 360, all alternative-fueled buses are at the relatively same point of requiring another rebuild. The term $RM+M+1$ represents the start of a trajectory off the rebuild cycle. For diesel and biodiesel, and CNG/diesel, this trajectory does not exist. Their rebuild cycles of 20 and 10 are factors of 360; however, methanol's rebuild cycle of 21 is not. Thus, the third term on the right-hand side of (6) represents the methanol trajectory off the rebuild cycle, starting at 358 $(RM+M+1)$ and ending at 360 months.

Based on equation (6), calculations of the present value per mile of estimated total costs with a 5% annual discount rate are presented in table 5. As an illustration of the sensitivity of operating costs, a comparison of baseline maintenance costs of zero and 50% of actual explicit maintenance costs is provided in columns three and four of table 5. Limited model sensitivity from this variation in maintenance costs is evident. When comparing these two levels of baseline maintenance cost, there is generally less than a 3% difference in per mile costs for all of the alternative-fueled buses. An exception is methanol-fueled buses, where the difference is approximately 7%. resulting from the relatively high level of explicit maintenance costs for methanol.

For comparison, the present value per mile of actual explicit operating costs (column five in table 5) is calculated and contrasted with the present value of total operating cost estimated solely on monthly mileage and time of rebuild. Again, limited model sensitivity is apparent when varying maintenance costs. Even in the case where estimated maintenance cost for CNG/diesel is less than 8% of its associated explicit cost, the difference in cost per mile (columns four and five in table 5) is only around 1%.

These per mile cost figures can be misleading because they do not consider variation in the intensity of bus utilization. As indicated in tables 1-3, methanol and CNG/diesel-fueled buses have higher fixed costs relative to diesel buses, and thus their overall per mile costs should decline relative to diesel as the mileage per month increases. For example, consider doubling the average monthly mileage under the assumption of zero baseline maintenance costs. This results in per mile cost estimates listed in the last column of table 5. As expected, per mile costs for diesel and biodiesel-fueled buses experience relatively minimal reductions in per mile costs (less than a half percent difference). In contrast, methanol-fueled buses experience a reduction of approximately 9%, whereas CNG/diesel buses experience a more modest decline of approximately 3%. Especially for methanol, the higher fixed costs do result in a lower per mile cost as utilization increases.

In all of these scenarios, it is not surprising that diesel buses reflect the lowest cost per mile. As diesel is blended with biodiesel and the cost of biodiesel rises, the cost per mile increases to around $0.65, which is over three times the base diesel price. However, it is still within 7% of the cost per mile for a methanol-fueled bus. CNG/diesel has a significantly lower cost per mile compared with methanol; nevertheless, it is still over 70% more expensive than diesel. The threshold at which biodiesel is competitive with CNG/diesel on a cost-per-mile basis is between a 60–100% blend at $1.75 per gallon, a 35-60% blend at $2.50, and around a 35% blend at $3.00. Assummg a 35% blend, biodiesel fuel can comply with regulatory emission standards; biodiesel fuels at prices as high as $3.00 per gallon are competitive with the other alternative fuels. This competitiveness is underscored by the low infrastructure cost and lack of engine/fuel system cost of biodiesel relative to methanol and

CNG/diesel. As indicated in tables l-3, converting a fleet of buses to methanol or CNG fuel requires substantial investment costs relative to diesel and biodiesel. These higher costs are predominantly irreversible once incurred, potentially resulting in a large loss if the technology does not meet expectations. Conversely, biodiesel requires no additional infrastructure over current diesel facilities and only minor modifications in engine tuning. Thus, cost associated with the risk of technology failure is potentially minimized with biodiesel.

The results presented in table 5 would support a significantly broadened pilot project involving a larger number of buses over a longer time duration. Such an expanded project would diminish problems associated with a small sample. For example, in the sample of diesel bus engines, one of the engines required a rebuild at only 12,150 miles. This produced a lower than expected mean value of mileage at rebuild and months between rebuilds, thereby possibly inflating the cost per mile of diesel and biodiesel buses compared with the alternatives. However, the irreversible sunk cost associated with both CNG/diesel and methanol-fueled buses restricts the expansion of these fuel systems from relatively small pilot projects resembling the Colorado project used for this analysis. Biodiesel does not require additional infrastructure over current diesel facilities; thus, restrictions in undertaking a project with a larger number of buses would primarily be concerned with the fuel cost differential between petroleum diesel and biodiesel fuels. Such an expanded project would increase the accuracy in any comparative fuel cost differences.

Implications

The findings of this analysis show that biodiesel is competitive with CNG/diesel and methanol fuels. However, biodiesel is less competitive compared with petroleum diesel fuel, In the present situation of liquid fuel supply and at current crude oil prices, there is no great incentive to find replacements for liquid fossil fuels. Thus, compelling environmental or socioeconomic benefits must exist to warrant incentives for promoting alternative fuels. Incentives will be necessary for further industry development, leading to economies of size, and thus making any alternative fuel more competitive in the commercial marketplace.

Biodiesel represents one of the best alternatives as a renewable fuel for diesel engines from economic, energy, and environmental protection perspectives. Due to its structural nature, biodiesel is a fuel that does not contribute to the greenhouse effect. Biodiesel recycles carbon rather than pumping it from petroleum wells. As suggested by the results of this study, biodiesel may also be very cost competitive compared with the methanol and CNG alternative fuels.

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Table 1. Diesel Bus Cost Summary

Item	Unit cost ($)	Units	Total cost ($)
Annual Miles Driven (per bus)		36.578	
Infrastructure Cost/Lane:			
Building cost, $/1,000 sq. ft./lane [a]	92,000	3	276,000
Tankage, 20,000.gal. size [b]	40.600	4	162,400
Total infrastructure cost			438,400
Total infrastructure cost/bus		300	1,461
Refueling Cost:			
Labor costs/lane/day [c]			
Supervisor (per hr.) [d]	22.89	113	61.04
Labor (per hr.) [e]	19.95	3	478.80
Labor costs/day for 3 lanes	539.84	3	1,620
Overhead multiplier		2	3.240
Total labor costs/bus/year (365 days)		3,942	
Fuel usage/bus ($/gal., gal./mo.)	0.67	866	6,963
Annual refueling cost/bus			10,905
Cost/mile			0.298
Bus Capital Data			
Incremental first cost, bus engine plus fuel system [f]			**0.000**

Source: Colorado Institute for Fuel and High Altitude Engine Research.

“Three lanes can service 360 buses at full capacity. The Denver Regional Transport District refuels approximately 280 buses per night in a three-lane refueling system. Service life for the building is 30 years.

[b] Tank is $10,600 plus 1.5 times the tank size. A tank capacity off 26,666 gallons is required per lane. Diesel tank is an FTP-3, 20,000-gallon tank with dimensions of 11’ diameter by 28’ tall.

‘Refueling labor includes one supervisor per three lanes and three laborers per one lane. Two laborers drive the buses to the lane, and a third laborer refuels the buses.

[d] Hourly rate is $16 plus benefits of 29%. Five-day work week, eight hours per day yields 2,080 hours per year. Fifteen days of paid vacation (120 hours), nine paid holidays (72 hours), and eight paid sick leave days (64 hours) yields an annual loss of 256 hours. Actual hourly rate is then $16[(2,080/1,824) + 0.29] = $22.89.

“Hourly rate is $13.95, which results in $19.95 actual hourly labor cost based on the same formula used for supervisor’s rate.

‘The diesel engine and fuel system are the base, so the incremental cost is the additional cost of methanol or CNG fuel engine and fuel system.

Table 2. Methanol Bus Cost Summary

Item	Unit Cost ($)	Units	Total Cost ($)
Annual Miles Driven (per bus)		29,801	
Infrastructure Cost/Lane:			
Building cost, $/1,000 sq. ft./lane”	92,000	3	276,000
Tankage, 20,000-gal. size [b]	268,148	10	2,681,480
Total infrastructure cost			2,957,480
Total infrastructure cost/bus		300	9.858
Refueling Cost:			
Labor costs/lane/day [c]			
Supervisor (per hr.) [d]	22.89	1/3	61.04
Labor (per hr.) [e]	19.95	7.5	1,197.20
Labor costs/day for 3 lanes	1,258.24	3	3,775
Overhead multiplier		2	7,550
Total labor costs/bus/year (365 days)		9,185	
Fuel usage/bus ($/gal., gal./yr.)	0.59	19,867	11,722
Lubrizol ($/gal., gal./yr.) [f]	15.69	12.42	195
Annual refueling cost/bus			21,102
Cost/mile			0.708
Bus Capital Data:			
Incremental first cost. bus engine plus fuel system [g]			29,900

Source: Colorado Institute for Fuel and High Altitude Engine Research.

“Three lanes can service 360 buses at full capacity. The Denver Regional Transport District refuels approximately 280 buses per night in a three-lane refueling system. Service life for the building is 30 years.

[b] Tankage is based on 2.5 times diesel tankage, given that methanol buses require on average 2.5 times as much fuel.

‘Refueling labor includes one supervisor per three lanes and 7.5 laborers per one lane. Summary assumes 2.5 additional labor hours for fueling based on 2.5 times more fuel than diesel.

[d] Hourly rate is $16 plus benefits of 29%. Five-day work week, eight hours per day yields 2,080 hours per year. Fifteen days of paid vacation (120 hours), nine paid holidays (72 hours), and eight paid sick leave days (64 hours) yields an annual loss of 256 hours. Actual hourly rate is then $16[(2,080/1,824) + 0.29] = $22.89.

‘Hourly rate is $13.95, which results in $19.95 actual hourly labor cost based on the same formula used for supervisor’s rate.

‘Lubrizol is added at 6.25 gallons per 10,000 gallons of methanol.

[g] The diesel engine and fuel system are the base, so the incremental cost is the additional cost of methanol fuel engine and fuel system.

Table 3. CNG/Diesel Dual Bus Cost Summary

Item	Unit Cost ($)	Units	Total Cost ($)
Annual Miles Driven (per bus)		34,691	
Infrastructure Cost/Lane:			
Building cost, $/1,000 sq. ft./lane [a]	92,000	8	736,000
Fueling facility [b]			2,320,500
Total infrastructure cost			3,056,500
Total infrastructure cost/bus		300	10,188
Refueling Cost:			
Labor costs/lane/day [c]			
Supervisor (per hr.) [d]	22.89	1/8	22.89
Labor (per hr.) [e]	19.95	3	478.80
Labor costs/day for 8 lanes	501.77	8	4,014
Overhead multiplier		2	8,028
Total labor costs/bus/year (365 days)		9,767	
Fuel usage/bus ($/gal., gal./yr.) [f]	0.40	10,764	4,306
Maintenance costs/bus/year			400
Energy cost of compressors/bus/year	1.28	365	467
Annual refueling cost/bus			14,940
Cost/mile			0.43 1
Bus Capital Data:			
Incremental first cost, bus engine plus fuel system [g]			35,000

Source: Colorado Institute for Fuel and High Altitude Engine Research.
“Eight lanes can service 300 buses at full capacity. Service life for the building is 30 years,
‘Estimated installed cost is $1,700,000 plus 10% for contractor’s markup, 10% for engineering, 5% for development and permitting, and 10% installed cost, engineering plus development and permitting for contingency.
“Refueling labor includes one supervisor per three lanes and three laborers per one lane. Two laborers drive the buses to the lane, and a third laborer refuels the buses.
[d] Hourly rate is $16 plus benefits of 29%. Five-day work week, eight hours per day yields 2,080 hours per year. Fifteen days of paid vacation (120 hours), nine paid holidays (72 hours), and eight paid sick leave days (64 hours) yields a loss of 256 hours. Actual hourly rate is then $\$16[(2,080/1,824) + 0.29] = \$22.89$.
[e] Hourly rate is $13.95, which results in $19.95 actual hourly labor cost based on the same formula used for supervisor’s rate.
[f] Fuel usage is in equivalent gallons,
[g] The CNG/diesel bus engine is the same as the diesel bus, so the incremental cost is the conversion cost of a diesel bus to CNG and additional cost of the fuel system.

Table 4. Marginal Cost Estimation Results for Diesel and Biodiesel, Methanol, and CNG/Diesel Buses

Summary Statistics	Diesel and Biodiesel	Methanol	CNG/Diesel
Structural Coefficients:			
Operating Costs,” θ_1	3.38 (2.32)***	15.55 (7.32)***	0.89 (1.40)***
Rebuild Costs, *r*	5.06 (1.16)*	4.64 (0.94)**	3.21 (0.80)
Log Likelihood	-29.28	-45.49	-22.74
Rebuild Costs, *RC*	6,500	9,500	6,500
Scale Parameter,[b] σ	1,284	2,047	2,025
Marginal Cost (per 5,000 miles)’	4.34	31.84	1.80

Notes: Numbers in parentheses are standard errors of estimates. Single, double, and triple asterisks (*) denote significance at the 0.10, 0.05, and 0.01 levels, respectively.

[a] Operating costs include maintenance costs, insurance costs, and loss of ridership and goodwill costs due to unexpected breakdowns.

[b] Scale parameter is the actual rebuild cost (*RC*) divided by the rebuild cost coefficient (Y).

[c] Marginal cost = $0.001\theta_1\sigma$

Table 5. Fuel Cost and Present Value per Mile of Estimated Total Costs and Actual Explicit Operating Costs over a 30-Year Life Cycle with an Annual 5% Discount Rate [a]

Alternative Fuel	Fuel Cost	Estimated Cost [b]		Explicit cost	Double Mileage
		Zero	50%		
Diesel	0.200	0.214	0.217	0.216	0.213
Methanol	0.393	0.562	0.603	0.606	0.513
CNG/Diesel					
$0.1406/gal.	0.044	0.383	0.390	0.396	0.372
$0.2812/gal.	0.087	0.406	0.413	0.418	0.394
$0.4218/gal.	0.131	0.429	0.435	0.441	0.417
Biodiesel					
$1.75/gal.					
Blend =					
20%	0.267	0.289	0.297	0.292	0.288
35%	0.321	0.316	0.323	0.318	0.315
60%	0.423	0.366	0.374	0.369	0.365
100%	0.588	0.447	0.454	0.449	0.446
$2.50/gal.					
Blend =					
20%	0.312	0.312	0.319	0.314	0.310
35%	0.401	0.355	0.365	0.357	0.354
60%	0.568	0.437	0.445	0.439	0.436
100%	0.841	0.571	9.578	0.573	0.569
$3.00/gal.					
Blend =					
20%	0.342	0.326	0.334	0.329	0.325
35%	0.454	0.381	0.389	0.384	0.380
60%	0.664	0.484	0.492	0.487	0.483
100%	1.008	0.653	0.660	0.655	0.652

“Explicit operating cost is the sum of maintenance and fuel costs. Estimated total cost is fuel cost plus an estimate of maintenance and opportunity costs. Opportunity costs are lost ridership and goodwill due to unexpected breakdowns.

[b] Estimated cost is based on baseline maintenance costs of zero and 50% of actual explicit maintenance costs.