Evaluation of Fuel Cell Auxiliary Power Units for Heavy–Duty Diesel Trucks

Evaluation of Fuel Cell Auxiliary Power Units for Heavy−Duty Diesel Trucks

Abstract

A large number of heavy−duty trucks idle a significant amount. Heavy−duty line−haul engines idle about 20−40% of the time the engine is running, depending on season and operation. Drivers idle engines to power climate control devices (e.g., heaters and air conditioners) and sleeper compartment accessories (e.g., refrigerators, microwave ovens, and televisions) and to avoid start−up problems in cold weather. Idling increases air pollution and energy use, as well as wear and tear on engines. Efforts to reduce truck idling in the US have been sporadic, in part because it is widely viewed in the trucking industry that further idling restriction would unduly compromise driver comfort and truck operations. The auxiliary power unites (APUs) available to replace the idling of the diesel traction engine all have had limited trucking industry acceptance. Fuel cells are a promising APU technology. Fuel cell APUs have the potential to greatly reduce emissions and energy use and save money. IN this paper, we estimate costs and benefits of fuel cell APUs. We calculate the payback period for fuel cell APUs to be about 2.6−4.5 years. This estimate is uncertain since future fuel cell costs are unknown and cost savings from idling vary greatly across the truck fleet. The payback period is particularly sensitive to diesel fuel consumption at idle. Given the large potential environmental and economic benefits of fuel cell APUs, the first major commercial application of fuel cells may be as truck APUs.

PERGAMON

Transportation Research Part D 7 (2002) 303–315

TRANSPORTATION RESEARCH PART D

www.elsevier.com/locate/trd

Evaluation of fuel cell auxiliary power units for heavy-duty diesel trucks

Christie-Joy Brodrick [a,*], Timothy E. Lipman [d], Mohammad Farshchi [a], Nicholas P. Lutsey [a], Harry A. Dwyer [a], Daniel Sperling [a], S. William Gouse, III [b], D. Bruce Harris [c], Foy G. King Jr. [c]

[a] *Institute of Transportation Studies, University of California-Davis, One Shields Avenue, Davis, CA 95616, USA*

[b] *Freightliner LLC, 4747 North Channel Avenue, Portland, OR 97217, USA*

[c] *National Risk Management Research Laboratory, US Environmental Protection Agency, Research Triangle Park, NC 27711, USA*

[d] *Energy and Resources Group, Renewable and Appropriate Energy Lab (RAEL), 4152 Etcheverry Hall, University of California-Berkeley, Berkeley, CA 94720, USA*

Abstract

A large number of heavy-duty trucks idle a significant amount. Heavy-duty line-haul truck engines idle about 20–40% of the time the engine is running, depending on season and operation. Drivers idle engines to power climate control devices (e.g., heaters and air conditioners) and sleeper compartment accessories (e.g., refrigerators, microwave ovens, and televisions) and to avoid start-up problems in cold weather. Idling increases air pollution and energy use, as well as wear and tear on engines. Efforts to reduce truck idling in the US have been sporadic, in part because it is widely viewed in the trucking industry that further idling restrictions would unduly compromise driver comfort and truck operations. The auxiliary power units (APUs) available to replace the idling of the diesel traction engine all have had limited trucking industry acceptance. Fuel cells are a promising APU technology. Fuel cell APUs have the potential to greatly reduce emissions and energy use and save money. In this paper, we estimate costs and benefits of fuel cell APUs. We calculate the payback period for fuel cell APUs to be about 2.6–4.5 years. This estimate is uncertain since future fuel cell costs are unknown and cost savings from idling vary greatly across the truck fleet. The payback period is particularly sensitive to diesel fuel consumption at idle. Given the large potential environmental and economic benefits of fuel cell APUs, the first major commercial application of fuel cells may be as truck APUs.

* Corresponding author. Tel.: +1-530-752-4122; fax: +1-530-752-6572.

E-mail addresses: cjbrodrick@ucdavis.edu (C.J. Brodrick), telipman@socrates.berkeley.edu (T.E. Lipman), mfarshchi@ucdavis.edu (M. Farshchi), nplutsey@ucdavis.edu (N.P. Lutsey), hadwyer@ucdavis.edu (H.A. Dwyer), dsperling@ucdavis.edu (D. Sperling), billgouse@freightliner.com (S.W. Gouse, III), harris.bruce@epa.gov (D.B. Harris), king.foy@epa.gov (F.G. King Jr.).

1361-9209/02/$ - see front matter
PII: S1361-9209(01)00026-8

Keywords: Diesel trucks; Idling; Auxiliary power units; Fuel cells

1. Introduction

A large proportion of heavy-duty trucks idle a significant amount. Drivers idle truck engines to power climate control devices (e.g., heaters and air conditioners) and sleeper compartment accessories (e.g., refrigerators, microwave ovens, and televisions) and to avoid start-up problems in cold weather. The amount of idling is not well known, but appears to be significant. It is greatest for large line-haul heavy-duty diesel trucks (Classes 7 and 8). According to one study, many of the 458,000 long-haul trucks in the US that travel more than 500 miles from homebase each day could idle somewhere between 3.3 and 16.5 hours per day (Stodolsky et al., 2000). That study used a 6 hours per day annual average as the baseline case but noted that line-haul sleeper tractors may idle up to 10 hours each day or 40% of total engine run time depending on season and operation (Stodolsky et al., 2000). This amount of idling is not surprising since line-haul truckers often spend more than 300 days a year sleeping in the cab, and safety regulations limit their on-road driving hours. In this paper, we quantify the amount of idling by heavy-duty diesel truck traction engines that could be replaced by a fuel cell or other auxiliary power unit (APU).

The US has no federal laws limiting idling. A patchwork of idling rules has been adopted by local and state governments. Truck idling is now attracting increased attention from local and federal air quality regulators. New stringent rules are being explored. The eight-county Houston, TX, area and New York, NY, both have plans to limit truck idling (TNRCC, 2000).

Although heavy-duty diesel vehicles produce low levels of hydrocarbons (HCs) and carbon monoxide (CO) compared to gasoline engines, they produce relatively high amounts of oxides of nitrogen (NO_x) and particulate matter (PM). NO_x and PM are widely considered the two most serious air pollution threats. NO_x is a precursor in the formation of ozone and a primary target for many regions struggling to attain ambient air quality standards. PM is emerging as an even more serious health effect. In 1998, diesel PM was declared a toxic air contaminant by the California Air Resources Board.

There are also economic reasons to reduce idling. Idling engines operate very inefficiently – about 3% energy efficiency compared to 40% when operating on the highway – and suffer greater wear and tear (Gouse, 2000). The US Department of Energy (US DOE) estimates that $1 billion is spent each year on fuel for idling and an additional $1 billion on engine wear and maintenance due to idling (US DOE, 1999).

Trucking companies recognize the economic cost of idling. The American Trucking Associations, an industry trade group, and the US DOE both disseminate idling cost information to the trucking industry. Many of the large fleets in the US, including the large United Parcel Service fleet, voluntarily restrict idling (TMC, 1995a; Abrams, 2000). However, smaller fleets, those with less than 25 vehicles, are less likely to have these programs, and these fleets operate approximately 40% of the line-haul trucks in the US (Stodolsky et al., 2000). In the end, though, the prevailing opinion in the trucking industry seems to be that further restrictions on idling are not feasible. It is believed that further restrictions would unduly compromise driver comfort and safety and most companies are already having difficulty recruiting and retaining good drivers. The trucking industry is receptive to alternative technologies that would provide the necessary climate control and power for driver comfort.

To reduce idling by the large traction motor, several alternative technologies are available, including battery packs, auxiliary generators, direct-fired heaters, and a thermal storage system, but all have had limited their market acceptance (Brodrick et al., 2000). Truckers report that using battery power overnight puts too much stress on the vehicle's batteries, leading to shortened battery life and high replacement costs. Currently available auxiliary generator sets are reported to be heavy, expensive, and noisy. Direct-fired heaters and coolers can be used to assist in climate control, but do not provide the power for other accessories such as televisions and refrigerators. It is sometimes possible to access plug-in electricity at truck stops, but current electricity availability is limited, and it is uncertain how many trucks stop elsewhere for rests.

One alternative technology, fuel cell APUs, is a recent application that is being investigated by several truck manufacturers. Fuel cells have many attractions as APUs. Not only do they provide the potential to reduce pollution, energy use, and greenhouse gases, but they also provide: (1) the potential to reduce costs, (2) an increase in driver comfort, and (3) even an indirect improvement in safety. Benefits 2 and 3 result from reduced vibration and noise, thereby improving sleeping comfort and reducing driver fatigue.

In this paper, we analyze emissions, fuel consumption, and costs associated with diesel engine idling. We determine monetary savings likely to result from the use of fuel cell APUs, and then compare those savings to the cost of purchasing and operating fuel cell APU systems. We explore a range of fuel cell architectures for truck auxiliary power applications and the costs associated with each. Some of the data and much of the insight for this paper are drawn from an associated engineering project in which a hydrogen-fueled proton exchange membrane (PEM) fuel cell was installed in a Freightliner LLC demonstration vehicle (Brodrick et al., 2000).

2. Truck idling time

Data on truck idling are sparse (Stodolsky et al., 2000). To estimate the duration of idling, we utilized existing idling data from Argonne National Laboratory and supplemented this with information obtained from Freightliner LLC customer fleets.

Idling differs by trip duration, season, geographic location, and trucking operation, making it difficult to quantify hours of truck idling for the truck population. Idling is classified as discretionary (non-essential, though desirable) or non-discretionary (i.e., essential). Discretionary idling includes overnight idling and delivery idling, and mainly serves to maintain driver comfort levels; it could be eliminated using a fuel cell. Non-discretionary idling includes intermittent idling in heavy traffic and during initial starting. It is neither practical nor desirable to turn a diesel engine off and on under these conditions. Other non-discretionary idling takes place during special applications, including using the engine to pump fuel into and out of tanker trailers. The power drawn for tanker trucks is larger than would be required to power in-cab accessories, and it is unlikely that a small fuel cell APU would be used. Since the objective of this study was to quantify the amount of idling that would be replaced by an APU, we focused only on discretionary idling.

Argonne National Laboratory's informal survey of truck fleets reports that most idling occurs in large Class 7 and 8 diesel trucks used for long-haul, overnight travel. The study found that idling time depends on season, and an average of 6 hours per day is a reasonable estimate of long-haul sleeper truck idling [1]. There is some evidence that the average idling time for long-haul trucks may be even higher. In Argonne's study, JB Hunt, a large truck fleet, indicated that average trucks idled 40% of the time, which is consistent with idling reported by fleets contacted by Freightliner LLC (Gouse, 2000). Freightliner LLC reported that a 90-truck fleet in Stockton, CA, idles 44% of the time, and a fleet in Tennessee idles nearly 50%.

Given the variation in idling time, a low and a high value were tested. We used a lower value of 1818 hours per year (303 days $\times$ 6 hours per day), consistent with the Argonne National Laboratory study as an average. A higher value of 2424 hours per year was calculated based on our discussions with fleets. These estimates were extrapolated by assuming that the trucks travel 10 hours per day 303 days per year, and idle 8 hours per operating day.

The 40% idling estimate was used, rather than 50%, since 10% of idling time was assumed to be non-discretionary and thus would not be eliminated by the fuel cell APU. The 10% factor was estimated based on discussions with three long-haul fleets. The actual percent of non-discretionary idling time will depend on factors that affect the truck driving cycle such as the type of truck, the truck route, traffic conditions, and the delivery location.

3. Emissions and fuel use

To quantify emissions and fuel use, idling data were compiled from four truck tractors tested by the US Environmental Protection Agency (US EPA). Emissions were measured at Research Triangle Park, NC, using the EPA's on-road emissions testing trailer. The emissions data were then compared with emissions rates from engine certification testing and the California Air Resources Board's (CARB) emissions inventory model (EMFAC2000).

Emissions test results are presented in Table 1. Emissions measured by EPA were determined to be reasonable based on comparison to emission estimates obtained from testing of a 1999 engine on an engine dynamometer at Southwest Research Institute (SwRI). Engine speed, accessory loading, and idling duration each had a significant effect as expected. For example, raising the engine speed from 600 to 1050 revolutions per minute (rpm) and turning on the air conditioning resulted in an increase in NO_x emissions of 2.5 times and an increase in CO emissions. HC emissions increases were unavailable due to analyzer failure (Brodrick et al., 2000).

As with idling duration, we elected to estimate a range of possible values for emissions levels. The emissions measured at 600 rpm without the air conditioner running were used as a conservative estimate. Idling emissions data from CARB's emissions inventory model, EMFAC2000, were used as the upper bound for emissions (CARB, 2000). The idling data from EMFAC2000 are shown in Table 2.

The above emissions and idling duration results were used to determine the potential emissions and greenhouse gas savings that could be achieved by eliminating idling in a tractor with a 1999 year model engine. Because emissions savings are highly dependent on idle time, accessory

[1] This estimate is based on 85 winter days at 10 hours per day and 218 nonwinter days at 4.5 hours per day.

Table 1
Emissions test results (in grams per hour) from EPA on-road testing

Mode	HCs	CO	NO_x	CO_2
1: idle after cruise	1.8	14.6	103	4034
2: idle after transient cycle	2.9	15.9	105	4472
3: idle at 600 rpm with a/c	1.4	15.3	166	4976
4: idle at 1050 rpm with a/c	N/A	86.0	254	9441
5: long idle at 1050 rpm with a/c	86.4	189.7	225	9743
6: cruise 55 mph, no a/c	5.6	65.1	713	60,590
7: cruise at 55 mph, with a/c	3.9	57.4	777	60,320

loading, and engine speed, several scenarios are presented in Table 3 with different combinations of these factors.

Each year the fuel cell APU could save between 0.2 and 1 ton NO_x at idle depending on idle time, accessories load, and engine speed. This quantity is a significant portion of total NO_x produced by late model year trucks. The Freightliner tested by EPA emitted an average of 12 grams per brake horsepower per hour (bhp-hr) over a variety of driving cycles. Assuming that the average Class 8 truck travels 100,000 miles per year and that the conversion factor for bhp-hr per miles is 2.6, this truck emits 3.4 tons NO_x on-road per year. Thus, the potential emissions reductions from fuel cell APUs are 6% (.2/3.4) to 29% (1/3.4) of NO_x emissions.

The above analysis indicates the quantity of emissions that would be eliminated if the fuel cell APU generated zero emissions. It is a reasonable working assumption. Hydrogen-fueled PEM

Table 2
Idle emissions rates in EMFAC 2000

Weight class	Idle trips (%)	Idle emission rates (grams per hour)			
		HC	CO	NO_x	CO_2
Class 8 trucks	26	44	247	396	29687

Table 3
NO_x emissions and CO_2 greenhouse gas savings potential from eliminating truck idling

	Low emissions estimate		High emissions estimate	
	NO_x	CO_2	NO_x	CO_2
Scenario 1: average idle time (1818 hours per year)				
Baseline idle emissions (grams per hour)	104	4034	396	29687
Hours per day idle	6	6	6	6
Days per year idle	303	303	303	303
Emissions at idle (grams per year)	189,072	7,333,812	719,928	53,970,966
Tons per year per vehicle	0.208	8.08	0.793	59.5
Scenario 2: 40% idle time (2424 hours per year)				
Baseline idle NO_x emissions (grams per hour)	104	4034	396	29687
Hours per day idle	8	8	8	8
Days per year idle	303	303	303	303
Emissions at idle (grams per year)	252,096	9,778,415	959,904	71,961,288
Tons per year per vehicle	0.278	10.8	1.06	79.3

fuel cells do, indeed, have zero emissions of NO_x (and other pollutants). Other candidate fuels and fuel cells would generate some emissions, but the quantity would be very nearly zero as well. Methanol-fueled PEM fuel cells would be essentially zero emitting, and high-temperature solid oxide fuel cells, operating on a variety of possible fuels including diesel fuel, would also be very low emitting. If operating on petroleum fuels, fuel cells would produce CO_2, though substantially less than an idling diesel engine.

Another simplification in the analysis is the exclusive focus on vehicle emissions. A more sophisticated analysis would consider the entire energy and materials cycle, including emissions produced in the manufacturing of fuel cells and their fuels. In order to calculate actual emissions saving from a particular fuel cell APU, a full fuel cycle analysis should be conducted and emissions produced during these processes subtracted from the reduction potential. These additional emissions would be rather small, relative to the idling emissions calculated here.

4. Fuel cell APU architecture and costs

The cost savings of an APU depend upon the market cost of the APU, as well as the type and quantity of fuel consumed. A variety of fuel cells and fuels are candidate APUs. The likely candidates at present are PEM fuel cells and solid oxide fuel cells, operating on hydrogen, methanol, or a petroleum fuel. All of these combinations are plausible choices in the next 10 years. To date, however, only a few prototype truck APU designs are being tested. As part of the US Department of Transportation (US DOT) Advanced Vehicle Program, Freightliner LLC incorporated a 1.4-kW prototype hydrogen APU on one of their trucks; and Delphi, Sacramento Municipal Utility District, and XCELLSiS are in the early stages of APU applications. Several other APU development projects are planned.

PEM fuel cells are particularly attractive as truck APUs because they operate near ambient temperature, are easy to start and stop, can operate on a variety of fuels, and are the primary candidates for use in cars and buses. However, PEM fuel cell systems are intolerant of carbon monoxide (CO) and sulfur because their platinum catalysts can be easily poisoned by CO and sulfur-containing compounds, and thus PEM fuel cell systems that do not run on pure hydrogen will require gas cleanup systems and low- or zero-sulfur fuel (unless technical breakthroughs occur). If not operating on hydrogen, PEM fuel cells would require a device to reform the fuel into hydrogen; it would be less energy efficient and more complex and expensive (with the one possible exception being direct methanol fuel cells, but these are further from commercialization) (Zelenay et al., 1999).

A rather different fuel cell technology option would be a solid oxide fuel cell system. Unlike PEM cells, solid oxide cells operate at high temperatures (typically about 1000 °C, but recent research is focusing on lower temperature operation at 600–700 °C) and therefore require expensive heat-resistant materials such as yttria-stabilized zirconia for the ceramic electrolyte and doped lanthanum chromite for the cathode (Hirschenhofer et al., 1998). Due to their high-temperature operation, solid oxide fuel cells also have significant start-up times and requirements for thermal management, and would probably need to be operated continuously rather than intermittently. However, solid oxide fuel cells can "internally reform" natural gas, ethane, and some other fossil fuels for use in the fuel cell reactions, resulting in the production of electricity, water, and CO_2. Solid oxide fuel cells would make high-grade heat available for cabin, engine oil, and water heating (compared with the low-grade heat available from PEM systems), and this could at least partially offset the difficulties of high temperature operation and stringent thermal management requirements.

With regard to the potential costs of fuel cell APU systems, estimates are necessarily speculative at this time due to the early commercialization stage of the technologies and uncertainty about what production volumes will be possible in what time frame. A few studies have been conducted on the potential manufacturing costs of automotive PEM fuel cell systems in high production volume, with estimates ranging from $40 to $200 per kW for 50-kW systems in production volumes of at least 300,000 units per year (Lomax et al., 1997; A.D. Little, 2000). These estimates include the fuel cell stack, auxiliary systems, and power and control electronics, but not the hydrogen storage system. Using a formula developed by Directed Technologies (DTI) for estimating the relative costs of different sizes of direct-hydrogen PEM fuel cell systems in high-volume production, a 5-kW system would have a manufacturing cost of about $240 per kW, and a 3-kW system would have a cost of about $435 per kW (Lomax et al., 1997). Costs per kW tend to be higher for smaller systems due to the higher burden of the ''balance of system'' components, but it should also be noted that the DTI estimates were developed primarily for systems in the 30–100 kW range and thus should be taken as illustrative only for smaller systems. In lower volume production conditions, which are likely to prevail for some time, manufacturing costs would be higher for small PEM systems, perhaps on the order of $1000–3000 per kW once the current phase of hand-built prototype production of PEM cells and stacks is surpassed by automated production.

Solid oxide fuel cell systems are also likely to be relatively expensive in the near term, although they can use relatively inexpensive nickel or copper-based catalysts rather than platinum or platinum/ruthenium. Westinghouse has targeted $1000 per kW for its complete solid oxide fuel cell cogeneration systems, based on tubular cell construction, while proponents of stacked planar cell configurations claim that costs could be as low as $400 per kW (Service, 2000). Raw material costs for these systems are relatively low, on the order of $7–15 per kW, but the need for high temperature ceramic material preparation, electrochemical vapor deposition for electrolyte materials, and other complex processing steps presently results in manufacturing costs of about $700 per kW for the basic solid oxide fuel cell stack and auxiliaries (Hirschenhofer et al., 1998).

The truck APU application for fuel cells could potentially combine with demand from other small and medium-sized fuel cell market segments, such as light-duty vehicles, buses and delivery vehicles, commercial and residential stand-alone and backup power systems, and so on, to gradually bring down manufacturing costs.

5. Economic analysis

A net present value economic analysis was applied to determine the payback period for the fuel cell APU. The costs associated with fuel cell APU system were compared against the savings offered by reducing diesel idling. The primary expenditures of the fuel cell option include the capital cost of the fuel cell system (including fuel cell stack, plumbing, inverter, fuel storage tank, and accessories), fuel cost, payload reduction costs, and maintenance costs. The savings due to the fuel cell APU include reduced diesel fuel consumption, lubricant changes, and engine overhauls.

The cost of fuel is by far the largest cost associated with idling. In order to calculate the cost of fuel consumption, it is necessary to assume a fuel consumption rate at idle. The US DOE estimates fuel consumption as a function of bhp demand of accessories and engine speed. The fuel consumption ranges from 0.6 gallons per hour for a truck idling at 800 rpm with no accessories to 2.25 gallons per hour for a truck idling at 1200 rpm with 30 bhp. The US DOE numbers are estimates used for the general truck population as opposed to the late model trucks that would be the target market for fuel cell APU application. The applicability of the numbers to tractors for 1995–2000 years model has not been determined. The general trends are similar to those observed for the late model Freightliner Century Class Tractor tested: fuel consumption will increase when truckers idle the truck at higher engine speeds and with higher accessory loads. One caution is that truckers increase the idle speed from its default setting in order to prevent battery drain and to improve accessory performance. The extent to which truckers increase the idle engine speed is unknown but could be determined using engine computer data.

For lack of better data, we chose to assume a 1.0 gallon per hour fuel consumption. 1.0 gallon per hour is a moderate estimate based on the range of fuel consumption estimates reported in the literature (US DOE, 1999; TMC, 1995a).

To estimate the cost of diesel fuel, we applied a range of values to reflect the volatility of the diesel market. The minimum US weekly average diesel cost over the past year, $1.35 per gallon, was used as our low value. Our middle estimate of $1.51 per gallon is the US average diesel cost over the past year. To reveal the difference in regional fuel costs and highlight a larger potential market for the fuel cell APUs, we applied California's average diesel cost of $1.70 per gallon as an upper bound (US EIA, 2001). Each of these values was multiplied by the idling fuel consumption and the hours of idling per year in order to obtain the annual fuel cost of idling.

Additional costs of engine idling included in this analysis are those resulting from engine wear and reduced payload capacity. The Maintenance Council (TMC) of the American Trucking Associations estimates that idling the engine for 1 hour is equivalent to driving the truck for 7 miles, assuming the truck averages 7 miles per gallon (TMC, 1995a,b). Using the TMC method, Argonne National Laboratory estimates that each hour of idling eliminated results in a savings of $0.07 in lubricant changes and $0.07 in engine overhauls (Stodolsky et al., 2000). However, use of an APU will mean the engine is started and stopped more frequently, and this will result in increased engine wear.

Annual costs for the fuel cell APU include fuel, maintenance, and lost payload capacity. The cost of hydrogen depends upon the production method, scale economies, the facility location, and the distribution cost. Ogden et al. (1999) have examined production of hydrogen via steam reforming of natural gas at both service stations and centralized facilities, across a range of production scales. The cost estimates were $20–30 per gigajoule higher heating value (GJ HHV) for liquid hydrogen delivered by truck (over a range of production of from 0.1 to 2.0 million SCF per day), $18–27 per GJ (HHV) for gaseous hydrogen delivered by pipeline, $12–40 per GJ (HHV) for on-site production with conventional reformers, and about $11–25 per GJ (HHV) for on-site production with advances reformers (Ogden et al., 1999). Hence, a range from $11–40 per GJ was applied to the model, with $25 per GJ as a conservative middle estimate, for the cost of fuel for the APU. Based on the 0.013 GJ per hour of hydrogen consumption, we calculate the fuel cost to be $0.14–0.52 per hour of APU power.

A possible additional cost is the revenue loss due to reduction in payload capacity. For trucks that travel at maximum weight ("grossed-out"), the weight of the fuel cell would displace an equivalent weight of payload. The cost associated with this displaced weight would vary greatly and is not included in this analysis. Additionally, there will be costs associated with the maintenance of the fuel cell system, as well as additional maintenance costs of the diesel engine due to increased number stops and starts. The maintenance costs associated with the APU are roughly estimated to be $0.05 per hour of APU power (Gouse, 2000).

Potential capital costs of the fuel cell APU systems are necessarily speculative due to the early commercialization stage of the technologies and uncertainty with regard to what production volumes will be possible in what timeframe. Manufacturer estimates solicited for this paper are $1000–3000 per unit.

Freightliner LLC provided estimates of additional capital costs required for the Freightliner fuel cell APU prototype. These include the cost of the Wabasto auxiliary heater and Coleman air conditioner ($1800), plumbing and wiring ($250), and the Trace inverter ($1300). The prototype utilizes a specially designed hydrogen fuel storage tank. Service (2000) estimates that hydrogen tanks for fuel cell cars will range from $700 to $1800. This range, with a figure of $1100 as the middle estimate, was used in the economic model. As an aftermarket addition, the APU system installation time is estimated to be 20 hours at a cost of $75 per hour ($1500 total). This initial capital cost is between $6950 and $8950.

Additional assumptions were made for the economic analysis. The net present value analysis required correcting future costs by the inflation rate. Prices of labor, engine overhaul, and hydrogen fuel were assumed to follow a general inflation rate of 3%. Due to volatility in the cost of diesel in the past decade, picking a constant average inflation rate would be less appropriate, therefore payback periods were calculated with three scenarios, with −5%, 5%, and 15% annual diesel inflation. These were within the range of annual diesel inflation of the past several years (US EIA, 2001).

Also, the costs and savings in future years had to be adjusted to present terms by the real discount rate (or time value of money). The real discount rate accounts for risk of the investment, depreciation, interest rate, inflation, and the lifetime of the investment to estimate the relative value of a unit of money today versus one in a future year. The commonly accepted nominal discount rate for comparing investment alternatives is 7% (US OMB, 1992). Compensating for inflation to make this the real discount rate, the value used here was 10%.

Table 4 provides a summary of the parameters and assumptions that were used in the analysis. Values that were varied according to their higher uncertainty are shown as ranges, whereas more certain values were held constant. We note which variables the payback period was most sensitive to. With the middle estimates of each parameter taken as our reference case, one parameter was varied at a time in order to both check sensitivity as well as bound our uncertainty with varying scenarios. The net present value methodology is explained in detail in the Appendix A.

Nearly all scenarios revealed payback periods between 2.6 and 4.5 years. The one exception to this general trend was with varying idling diesel consumption. As mentioned above, idling diesel fuel consumption can vary between 0.6 and 2.25 gallons per hour. Such a large variance in this parameter results in a wide range in payback periods for the fuel call APU systems – from 1.3 years for 2.25 gallons per hour, to 6.5 years for 0.6 gallons per hour. The plot of this is shown as Fig. 1. Clearly, in order to accurately estimate the payback period, it is imperative to gain a better understanding of real-world fuel consumption.

The American Trucking Associations reports that truckers desire a 2-year payback time on equipment purchases. Given the large pollution and greenhouse gas benefits, it is plausible that

Table 4
Summary of parameters for net present value analysis, with resulting payback periods

		Parameter			Payback periods for varied parameters (years)		
	(unit)	Low	Middle	High	Low	Middle	High
Annual vehicle idling	(hours)	1818	2121	2424	2.8	3.2	3.8
Diesel							
Idling diesel consumption	(gallons per hour)	0.6	1	2.25	1.3	3.2	6.5
Diesel fuel cost	($ per gallon)	1.35	1.51	1.7	2.8	3.2	3.7
Lubricant cost	($ per hour idled)	–	0.07	–	–	3.2	–
Engine overhaul cost	($ per hour idled)	–	0.07	–	–	3.2	–
Fuel cell							
Fuel cell capital cost	($ per kW)	1000	2000	3000	2.8	3.2	3.7
H_2 fuel tank cost	($)	700	1100	1800	3.0	3.2	3.5
H_2 fuel cost	($ per GJ (HHV))	11	25	40	2.8	3.2	3.8
Idling H_2 consumption	(GJ per hour)	–	0.013	–	–	3.2	–
Fuel cell installation cost	($)	–	1500	–	–	3.2	–
Fuel cell O & M cost	($ per hour idled)	–	0.05	–	–	3.2	–
Heater and air conditioner cost	($)	–	1800	–	–	3.2	–
Plumbing and wiring cost	($)	–	250	–	–	3.2	–
Trace inverter	($)	–	1300	–	–	3.2	–
Market							
Inflation (labor, overhaul)		–	3%	–	–	3.2	–
Inflation (diesel)		−5%	5%	15%	2.6	3.2	4.5
Inflation (H_2)		–	3%	–	–	3.2	–
Discount rate		–	10%	–	–	3.2	–

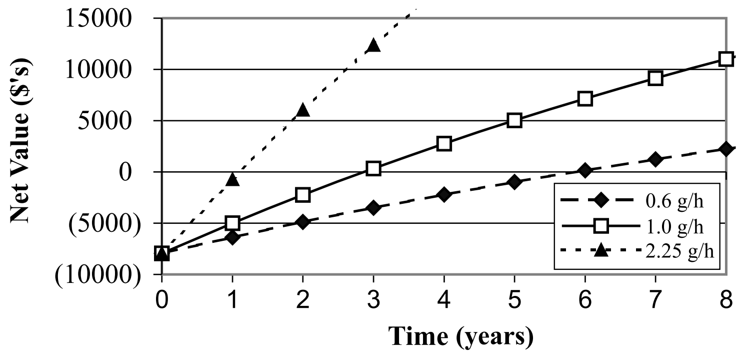

Fig. 1. Net present value of fuel cell APU installation on heavy-duty truck, with varying diesel fuel consumption at idle.

government incentives would be made available for fuel cell APUs, especially in the early years. For instance, the California Air Resource Board's Low Emissions Incentive Program offers $1500 toward the purchase of a fuel cell APU. This could reduce the payback period to the desirable 2-year timeframe.

6. Conclusions

Using fuel cell APUs in lieu of engine idling could substantially reduce truck fuel consumption, pollution emissions, and greenhouse gas emissions – and perhaps offer potentially attractive payback periods. The extent of these savings and the length of the payback period will depend on the market cost of the APU, the type and quantity of fuel consumed, the nature and quantity of idling, and characteristics of the baseline diesel engine. Our analysis is based on fuel cell APU cost estimates of $6950–8950, and a variety of other assumptions and calculations.

In our analysis, we find that the payback period for a truck operator would likely be 2.6–4.5 years for a hydrogen-fueled PEM fuel cell. However, the payback period is very sensitive to the amount of fuel consumed at idle. The payback period ranges from 1.3 years for diesel consumption of 2.25 gallons per hour, to 6.5 years for diesel consumption of 0.6 gallons per hour.

Other fuels and fuel cells are also APU candidates. The actual payback period would be higher initially (unless government incentives were available), but the eventual payback period could prove to be more or less, though it would be more initially. In the end, a variety of factors, beyond simple financial analyses, will play a large role in determining the general attractiveness of fuel cell APUs, and their market success. If they greatly enhance driver comfort, then that factor could dominate. If certain regions aggressively oppose the use of diesel engines because of emissions, as is possible in Los Angeles, then fuel cell APUs would gain an advantage. However, wider spread of truck stop electrification would be a competitor that could affect the adoption of APUs.

Acknowledgements

Special thanks goes to Jenny Tang and Ling Li of ITS-Davis, and Ed Brown and Matt Clayton of ARCADIS, Geraghty, and Miller for their valuable assistance with data collection and analysis. Portions of this work were funded by the California Air Resources Board and the Federal Highway Administration's Dwight D. Eisenhower Fellowship Program. This research was also funded in part under the US Department of Transportation, Research and Special Programs Administration's Advanced Vehicle Program. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Research and Special Programs Administration or the US Government.

Appendix A

The net present value (NPV) predicts what an investment today, with costs and benefits in the future, is worth, as compared with other alternatives. The NPV of an initial capital investment (K_0) today is worth

$$NPV_0 = K_0,$$

where K_0 is the cost of the fuel cell stack, fuel storage tank, installation, and other accessories. Whereas the value, today, of this investment one year from now can be calculated as:

$$NPV_1 = NPV_0 + \frac{\sum(\text{Benefits, year 1}) - \sum(\text{Costs, year 1})}{(1+d)^1}.$$

Or, more generally,

$$NPV_x = NPV_{x-1} + \frac{\sum(\text{Benefits, year } x) - \sum(\text{Costs, year } x)}{(1+d)^x}.$$

A year from the present, the costs and benefits are summed, and this value is discounted by the time value of money, as mentioned above. This discount compounds yearly. Substituting specific variables for yearly savings and costs results in the following:

$$\begin{aligned}\text{Benefits, year } x &= (\text{Diesel O \& M savings}) + (\text{Diesel fuel savings}) \\ &= (D_{\text{oil}} + D_{\text{overhaul}})(\text{Idle}_{\text{hours}})(1+i)^x + (D_{\text{fuel}})(D_{\text{cons}})(\text{Idle}_{\text{hours}})(1+i_{\text{d}})^x,\end{aligned}$$

$$\begin{aligned}\text{Costs, year } x &= (\text{Fuel cell O \& M costs}) + (\text{Fuel cell fuel costs}) \\ &= (FC_{\text{O\&M}})(\text{Idle}_{\text{hours}})(1+i)^x + (FC_{\text{fuel}})(FC_{\text{cons}})(\text{Idle}_{\text{hours}})(1+i)^x,\end{aligned}$$

where $\text{Idle}_{\text{hours}}$ is annual vehicle idling (h); i is the general inflation rate (%); i_{d} is the diesel inflation rate (%); d is real discount rate, or time value of money (%); D_{oil} is lubricant cost for diesel idling ($ per hour idled); D_{overhaul} is overhaul cost for diesel idling ($ per hour idled); D_{fuel} is diesel fuel cost ($ per gallon); D_{cons} is diesel fuel consumption (gallons per hour idled); $FC_{\text{O\&M}}$ is operating and maintenance cost of fuel cell ($ per hour idled); FC_{fuel} is hydrogen fuel cost for fuel cell operation ($ per GJ); FC_{cons} is hydrogen consumption of fuel cell (GJ per hour idled).

The NPV is simply calculated in this way, with the net benefit of the investment each year gradually offsetting the initial capital investment cost of the fuel cell system. When, or if, the NPV for a given year is greater than zero, the investment pays for itself, or it is said to "break even". The first year in which an investment breaks even is its payback period.

References

Abrams, F., 2000. Fuel for thought. American Trucking Associations, Alexandria, VA. Fleet Owner Magazine, May.

Arthur D. Little Inc., 2000. Cost analysis of fuel cell system for transportation: baseline system cost estimate. SFAA No. DE-SCO2-98EE50526, Final Report to US Department of Energy.

Brodrick, C.J., Farshchi, M., Dwyer, H.A., Gouse, S.W., Mayenburg, M., Martin, J., 2000. Demonstration of a proton exchange membrane fuel cell as an auxiliary power source for heavy trucks. Society of Automotive Engineers. Paper 2000-01-3488.

California Air Resources Board, 2000. Public meeting to consider approval of state's on-road motor vehicle emissions inventory. Technical Support Document. Sacramento, CA.

Gouse, S.W., 2000. Personal communication. Executive Engineer Technology Planning, Freightliner LLC, Portland, OR.

Hirschenhofer, J.H., Stauffer, D.B., Engelman, R.R., Klett, M.G., 1998. Fuel Cell Handbook. Fourth ed. US Department of Energy Federal Energy Technology Center, Business Technology Books, Morgantown, WV.

Lomax, F.D., James, B.D., Baum, G.N., Thomas, C.E., 1997. Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles. Directed Technologies Inc, Arlington, VA.

Ogden, J., Steinbugler, M., Kreutz, T., 1999. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles. Journal of Power Sources 79, 142–168.

Service, R.F., 2000. New tigers in the fuel cell tank. Science 288 (5473), 1955–1957.

Stodolsky, F., Gaines, L., Vyas, A. 2000. Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks, ANL/ESD-43. Argonne National Laboratory, Argonne, IL.

Texas Natural Resource Conservation Commission (TNRCC) DieselNet Update, 2000. Website, http://www.dieselnet.com/news/0012tnrcc.html. Texas Natural Resource Conservation Commission, Austin, TX. Visited December 7, 2001.

The Maintenance Council (TMC), 1995a. Fleet Managers Guide to Fuel Economy. American Trucking Associations, Alexandria, VA.

The Maintenance Council (TMC), 1995b. Analysis of Costs from Idling and Parasitic Devices for Heavy Duty Trucks, Recommended Procedure 1108. American Trucking Associations, Alexandria, VA.

United States Department of Energy (US DOE), 1999. Don't Idle Your Profits Away, Brochure. Office of Heavy Vehicle Technologies, Washington, DC.

United States Energy Information Administration (US EIA), Department of Energy, 2001. Historical Data on US Retail Sales of Diesel. Website, http://tonto.eia.doe.gov/oog/ftparea/wogirs/xls/psw18vwall.xls. Visited August 10, 2001.

United States Office of Management and Budget (US OMB), 1992. Circular A-94. Website, http://www.whitehouse.gov/omb/circulars/a094/a094.html. Visited August 10, 2001.

Zelenay, P., Ren, X., Thomas, S., Dinh, H., Davey, J., Gottesfeld, S., 1999. Direct methanol fuel cells. Fuel cells for transportation. 1999 Annual Progress Report. US Department of Energy, Washington, DC.