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Potential Benefits of Utilizing Fuel Cell Auxiliary Power Units in Lieu of Heavy-Duty Truck Engine Idling

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Abstract. Truck manufacturers and vehicle component manufacturers are exploring using fuel cell auxiliary power units (APUs) in lieu of main engine idling. While fuel cell powertrains continue to face significant technical and economic barriers, the truck auxiliary power application may offer a viable near-term market for small (1 – 5 kW) fuel cells. The University of California, Davis Institute of Transportation Studies (ITS-Davis) has conducted a study to quantify the potential benefits of utilizing APUs in lieu of truck idling. ITS-Davis researchers estimated the potential reductions of (1) air pollutants and greenhouse gases and (2) heavy truck fuel and lubricant consumption through elimination of truck idling. For new tractors, idling is estimated to contribute 0.2 to 0.7 metric tons of nitrogen oxide emissions and 8 to 24 tons of carbon dioxide per vehicle per year. Thus, depending upon the emissions from fuel cell system production, fuel cell APUs in lieu of idling could substantially reduce pollution emissions and greenhouse gas emissions. The extent of cost saving that an APU could achieve depends upon the cost of diesel engine idling, the market cost of the APU, the APU fuel-type, and quantity of APU fuel consumed. Conservative estimates are that diesel engine idling uses 1818 gallons of fuel per year for an average late model truck that idles 6 hours per day, 303 days per year. The fuel cost per year is $3,127 (at a cost of $1.72 per gallon) in addition to preventative maintenance and engine overhaul costs. Potential costs of the fuel cell APU systems are speculative due to the early commercialization stage of the technologies and uncertainty with regard to architectures and production volumes. This paper concludes with a discussion of appropriate fuel cell architectures for truck auxiliary power applications and the costs considerations associated with each.

INTRODUCTION

Truck engine idling occurs to power climate control devices (e.g. heaters and air conditioners), to power sleeper compartment accessories (e.g. refrigerators, microwaves, and televisions), to avoid start-up problems in cold weather, and as general practice by truck drivers. Long-haul sleeper tractors in the U.S. often idle up to ten hours each day or 50% of total engine run time (1). Local ordinances limiting idling are common in the U.S., and over a dozen states also limit idling (1, 2). In most states, trucks and buses that are idling can be ticketed under state nuisance laws, but this is infrequent (2). In contrast to countries in Europe where truck engine idling is often severely restricted, there are no federal laws in the U.S. pertaining to truck idling. Many fleets, such as United Parcel Service, voluntarily restrict idling (2). However, despite the clear economic and environmental benefits of limiting idling, idling during delivery and overnight is prevalent. Argonne National Laboratory estimates that there are 458,000 trucks in the U.S. that idle between 3.3 and 16.5 hours per day (1).

In addition to excess fuel consumption, lubricant consumption, and engine wear, heavy-duty truck idling generates air pollutants, greenhouse gases, noise, and vibrations. Tractor vibration and noise are of special concern due to their potential impact on trucker sleeping and fatigue. Data on environmental and driver safety issues are scarce, but information on the estimated fuel consumption, lubricant consumption, and maintenance requirements associated with engine idling is widely distributed to the trucking industry by the Department of Energy (3). The Department of Energy Office of Heavy-Duty Technologies estimates that $1.17 billion is spent each year on fuel for idling, and an additional $1 billion is spent on engine wear and maintenance due to idling (3).

Little quantitative data are available on the amount of emissions and greenhouse gases emitted by heavy-duty vehicles during idle. In general, heavy-duty diesel vehicles produce low levels of hydrocarbons (HC) and carbon monoxide (CO) in comparison to gasoline engines. However, diesel trucks contribute relatively high amounts of nitrogen oxides (NOx) and particulate (PM). NOx is a precursor in the formation of ozone and is the primary pollutant that many Metropolitan Planning Agencies must reduce in order to attain the National Ambient Air Quality Standards set forth by the Clean Air Act. Diesel particulate matter has been associated with adverse health effects and in 1998 was declared a toxic air contaminant by the California Air Resources Board. In contrast, emissions of carbon dioxide (CO_2), a greenhouse gas, are lower for diesel engines than for comparable gasoline engines, but the emissions are still significant.

Of the alternative power sources available to reduce the need for idling (e.g. battery packs, auxiliary generators, direct-fired heaters, absorption coolers) all have economic and technical drawbacks that have limited their market acceptance. Truckers report that using battery power overnight puts too much stress on the vehicle’s batteries, and this leads to premature wear out. Auxiliary generator sets are reported to be heavy, expensive, and noisy. Direct-fired heaters and absorption coolers can be used to assist in climate control, but do not provide the power for other accessories such as televisions and refrigerators. Argonne National Laboratory provides a comprehensive comparison of alternative technologies to reduce idling (1). One alternative technology, fuel cell auxiliary power units, is a recent application that is being investigated by several truck and vehicle components manufacturers.

The truck fuel cell APU concept has the potential to (a) reduce heavy truck fuel and lubricant consumption and the related U.S. dependency on non-renewable foreign energy supplies, (b) reduce particulate and greenhouse gases emissions, (c) improve highway safety by greatly increasing the quality of driver rest periods; therefore, reducing fatigue, (d) decrease engine wear and tear, (e) reduce noise and heat signature levels while idling, (f) increase energy efficiency as well increased payload capacity, and (g) reduce the logistics support required for vehicles’ being operated in remote areas.

Since fuel cell APUs are in their infancy, the authors chose not to examine the cost and benefits of a specific system architecture. Instead, the authors assessed the emissions reduction and fuel savings that could be achieved by eliminating non-driving truck idling. Specifically, ITS-Davis quantified the potential reduction of (1) heavy truck fuel and lubricant consumption, (2) air pollutants and greenhouse gas, and (3) truck operator cost. The extent of these savings that an APU will achieve depends upon the market cost of the APU, as well as, the fuel-type and quantity of fuel consumed. The paper concludes with a discussion of appropriate fuel cell architectures for truck auxiliary power applications and the costs/benefits associated with each.

METHODOLOGY

A two phase approach was employed to estimate the potential impact of fuel cell APUs. The first step was to quantify truck idling and the second was to associate emissions and fuel use with this idling. Very little data exists on the characteristics of truck idling (1, 4). To estimate the duration of idling, the authors utilized the existing idling data from Argonne National Laboratory and supplemented this with information obtained by Freightliner customer fleets. Similarly, little data exists on emissions during idling. To quantify the emissions and fuel use associated with idling under various accessory loads, a Class 8 Freightliner Century Class tractor with 1999 engine was tested using the Environmental Protection Agency's on-road test facility based in Research Triangle Park, North Carolina. Emissions data are also presented from less extensive idling testing by EPA on three 1990 vintage tractors. The emissions estimates are then compared with emissions rates from engine certification testing, the Environmental Protection Agency's emissions model (MOBILE5b) and the California Air Resources Board emissions model (EMFAC2000).

Quantification of Truck Idling Time

Idling differs by trip duration, season, geographic location, and operation making it difficult to quantify hours of truck idling for the truck population. Idling can be classified as discretionary (i.e. non-essential, although possibly desirable) or non-discretionary (i.e. practically unavoidable). Examples of discretionary idling are overnight idling and delivery idling, which often take place to maintain driver comfort levels, and could be eliminated using a fuel cell. An example of non-discretionary idling is when a truck idles intermittently in heavy traffic. It is neither practical nor desirable to turn on and off the engine and run a fuel cell in this condition. Another example of non-discretionary idling is for special applications such as powering tanker fuel transfer. The power draw 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 on only discretionary idling.

To estimate the duration of idling, we utilized the existing idling data from Argonne National Laboratory and supplemented this with information obtained by Freightliner customer fleets. Argonne National Laboratory's informal survey of truck fleets found that trucks idle between 5 hours and 10 hours depending on season (1). The average, baseline truck idling estimated by Argonne is 6 hours per day for 303 days per year that a long-haul sleep truck operates (1). This equates to 1818 hours per year. There is limited evidence that the average time idling may be substantially higher. In Argonne's study, JB Hunt, a large truck fleet, indicated that their trucks idled 40% of the time (1). This is consistent with the idling reported by the fleets contacted by Freightliner LLC. A 90 truck fleet in Stockton, California idles 44% of the time (5). A third fleet based out of Tennessee idles 47% (5).

These higher idling times may be partially offset by idle reduction programs implemented by fleet owners. The Department of Energy sponsors a program to inform fleets of the fuel and lubricant cost during idle, and worksheets to assist truckers in calculating their idling cost are available on the American Trucking Association's (ATA) website as well as in their Fleet Manager's Guide to Fuel Economy (6). According to ATA's Truck Maintenance Council, 52% of their member fleets have a policy to reduce idling (6). However, smaller fleets, those with less than 25 vehicles, are less likely to have these programs, and these fleets make up 40% of the long-haul truck industry (1).

Given the variation in idling time, a range of possible idling times were used in this paper. The lower value used was the 1818 hours per year identified in the Argonne National Laboratory study as a baseline. The higher value of 2424 hour per year was calculated by ITS-Davis based on our discussions with the fleets that idle between 40-50% time. This figure is based on the assumption that a truck travels on the road 10 hours per day, idles 8 hours per day (40%) of the time, 303 days per year. 40% (as opposed to 50% idling time) was selected since 10% of idling time was assumed non-discretionary and thus would not be eliminated by the fuel cell. The 10% idle time spent in traffic was estimated based on discussions with three long-haul fleets that do intra-state deliveries of bulk products. The actual percent of non-discretionary idling time will depend on factors that affect the truck driving cycle such as truck, route, traffic conditions, and delivery location.

Quantification of Emissions and Fuel Consumption

Emissions measurements were made on a Freightliner Century Class tractor with 1999 engine. The tractor was tested at Research Triangle Park using the Environmental Protection Agency's (EPA) on-road emissions testing trailer. EPA's mobile facility was developed in 1994 by their Emissions Characterization and Prevention Branch for the purpose of quantifying gaseous emissions as a function of truck operating parameters. A majority of the facility's functional components are located inside the 45-

foot cargo van trailer that is towed by the truck being tested. The front 10 feet of the trailer is a laboratory space containing the continuous emissions monitoring (CEM) system, all the support equipment (pumps, heaters, compressed gases, etc.), and a computerized data acquisition system (DAS which records responses from the various operational sensors located throughout the facility. In the rear of the trailer, separated by an insulated partition, is space for 18 tons of removable concrete weights, which are used to simulate the effects of truck payload on emissions.

The CEM system consists of rack-mounted components that measure undiluted concentrations: Oxygen (O_2) by magneto-pneumatic detection, carbon dioxide (CO_2) and carbon monoxide (CO) by infrared absorption, nitrogen oxides (NOx) by chemiluminescence, and total hydrocarbon (THC) by flame ionization detection (FID). The sample delivery system (pump, filter, and sample lines) is heated to 365 F to prevent HCs from condensing out.

Using EPA's on-road emissions testing trailer, continuous hydrocarbon, carbon monoxide, carbon dioxide, and nitrogen oxide emissions were quantified at idle under a variety of accessory loadings and engine speeds. Four short-duration idle tests were run: 1) at standard idle (600 rpm) after running a 10 minute transient cycle, 2) at standard idle after cruising at 55 mph for 10 minutes, 3) a standard idle with the air conditioner on after running a 10 minute transient cycle, and 4) a high idle (1050 rpm) with the air conditioner running after a transient cycle. Additionally, a longer duration, 5 hour, idling test was conducted at 1050 rpm with air conditioning (mode 5).

The first two tests differ only in preconditioning, and were designed to test for any carry-over potential effects of vehicle operation prior to idling. In the first two tests, accessories in the cab were turned off. The second two tests were designed to quantify the effects of engine speed and accessory load. It is well documented that accessory load increases fuel consumption at idle (6), but the corresponding increase in emissions is uncertain. Different engine speeds were used because it is common practice for truckers to increase idle engine speed in order to prevent battery depletion while running accessories or to improve accessory (such as air conditioning) performance (5). Examination of engine emissions maps indicated that the different engine speeds would produce substantially different emissions results.

For reference, emissions were also measured during two other tests, mode 6, a 15 minute, 55 mph cruise at 45,000 lbs load with no accessories running and mode 7, a 15 minute, 55 mile per hour cruise with the air conditioner running. A minimum of three replications of each test were run, except for the high idle test with the air conditioner running. Due to time constraints, this test was not replicated.

Idle emissions testing was conducted in March of 2000. Each day the analyzers were calibrated before and after emissions testing. For the gaseous samples, the raw ppm data were later adjusted based on instrument drift and response time. Exhaust flow was calculated from the velocity head and static pressure measurements and used to convert the adjusted ppm measurements to grams/mile. The ambient temperature during emissions measurement ranged between 50 F to 70 F. Ambient temperature is likely to affect emissions, but the extent of this effect could not be determined due to the small range of ambient temperatures during testing.

RESULTS

Reduction in Air Pollutants and Greenhouse Gases

Emissions test results are presented in Table 1. To verify that the engine emissions were reasonable, the emissions measured by EPA were compared with emission estimates obtained from testing of a 1999 engine on engine dynamometer at Southwest Research Institute (SwRI). The engine was tested by SwRI and ITS-Davis in April of 2000.

Since the engine at SwRI did not have truck accessories attached, it is not possible to compare the effect of running accessories. Only the EPA standard idle emissions after cruise (mode 1) and transient (mode 2) driving are comparable to the SwRI engine tests. HC idle emissions measured at EPA on the standard idle after transient and cruise range from 1.8 g/hr to 2.9 g/hr, and this low, but reasonably consistent with the 7 g/hr emissions that were measured at SwRI. The CO idle emissions (14.6-15.9 g/hr) were also consistent with the 12 g/hr measured at SwRI. The NOx idle emissions (103-105 g/hr) were consistent with the 90 g/hr emissions measured at SwRI. CO_2 idle emissions as well as PM emissions are currently being analyzed and will be compared to the emissions estimates from the SwRI engine testing.

Examination of the EPA data reveals that increases in engine loading and accessory loading had significant effects as expected. Raising the engine speed from 600 to 1050 rpm and turning on the air conditioning resulted in an increase in NOx emissions of 2.5 times, and a 5 times increase in CO emissions. HC emissions increases were unavailable due to analyzer failure. With engine speed maintained at 600 rpm, and the air conditioner activated, hydrocarbon emissions decreased. The large increase in HC and CO emissions during long-duration idling at high engine speed warrants further study of long-duration idling that is typical of the type of idling that would be replaced by APUs.

Table1: Emissions Test Results from EPA On-Road Testing

	HC	**CO**	**NOx**	**CO_2**
	g/hr	**g/hr**	**g/hr**	**g/hr**
Mode 1: idle after cruise	1.8	14.6	103	4034
Mode 2: idle after transient cycle	2.9	15.9	105	4472

Mode 3: idle at 600 rpm with a/c	1.4	15.3	166	4976
Mode 4: idle at 1050 rpm with a/c	-	86.0	254	9441
Mode 5: long idle at 1050 rpm with a/c	86.4	189.7	225	9743
Mode 6: cruise 55 mph, no a/c	5.6	65.1	713	60592
Mode 7: cruise at 55 mph, with a/c	3.9	57.4	777	60320

Emissions at 55 mph cruise are provided in Table 1 for comparison. High idle with air conditioning produces NOx emissions of about one third the emissions at 55 mph cruise with air conditioning. High idle with air conditioning raises CO levels above those of emissions at 55 mph cruise.

However, the average emissions levels above provide an incomplete picture of idling emissions. Close examination of the continuous emissions data reveals that the emissions at idle are not steady. Thus, simple averages may be misleading. Figures 1-3 below are examples of the emissions patterns observed over time under three of the test modes.

Figure 1 is an example of the patterns observed for idling after steady-state freeway driving at 55 mph. The emissions pattern illustrated is for NOx emissions at idle at 600 rpm with no accessory load. The figure illustrates that the idle emissions begin around the 100 g/hr level following the freeway driving. After several minutes, the idle emissions crept up and continued to creep up throughout the idle testing. This indicates that length of idle time over which emissions measurements are made may affect the NOx emissions levels. The observed pattern could partially explain the difference in emissions seen in replications of mode 1 and mode 2 tests. The longer tests had 10-15% higher average emissions because more data were taken after this increase in emissions. This indicates that the emissions numbers generated from the short idling tests are conservative, and actual emissions over longer durations, for example during overnight idling, are likely to be higher.

Figure 2 illustrates the trend in idle emissions following lower-speed transient modes that are typical of city driving. As with Figure 1, the emissions shown here are for a typical idling test at 600 rpm without accessories. In Figure 2, the NOx emissions immediately following the transient modes were at the 75 g/hr level. The emissions remained in the 75 g/hr region for several minutes. Then a sudden jump in emissions is observed. This is in sharp contrast to Figure 1 where emissions began at a higher level and crept upward. This pattern was observed to a lesser extent for one of the idle tests following 55 mph cruise. For an unexplained reason emissions started at the lower 75 g/hr level that is more typical of those from idle tests following transients than of the idle tests following 55 mph cruises.

Figure 3 shows yet another pattern. This figure is an excerpt from a 5 hour overnight idling test with air conditioning running and the engine speed at 1050 rpm. A distinctive pattern was observed for this long idling tests with accessories whereby a repetitive pattern occurred. This is likely due to the air compressor periodically loading the engine. The overall emissions level is clearly higher than in the shorter emissions tests at 600 rpm with no accessories. When idling emissions data is taken in the future, each of the tests will be held for a longer duration to capture and analyze these temporal patterns.

Based on these observations, it appears that in addition to accessory use and engine speed, the vehicle conditions prior to emissions testing as well as the duration of idle testing affects the idle emissions.

Figure 1: Idle Emissions vs. Time at 600 rpm with No Accessories Following 55 mph Cruising.

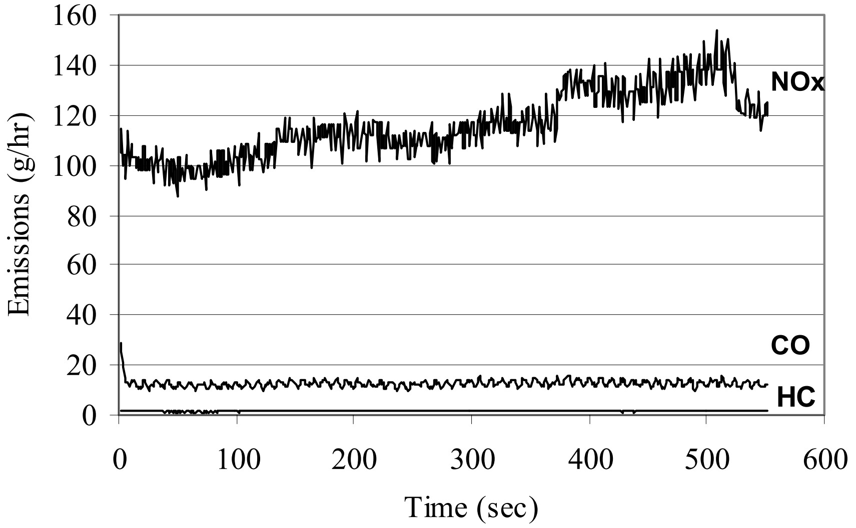


Figure 2: Idle Emissions vs. Time at 600 rpm with No Accessories Following Transient, City Operation.

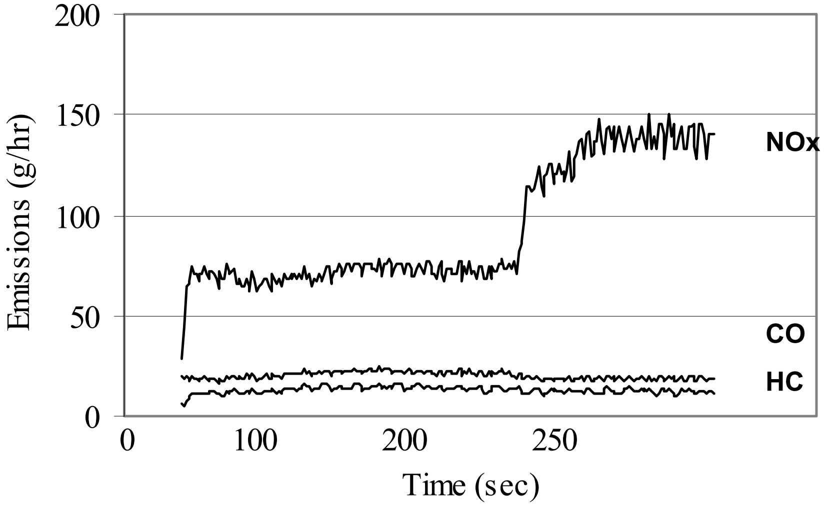
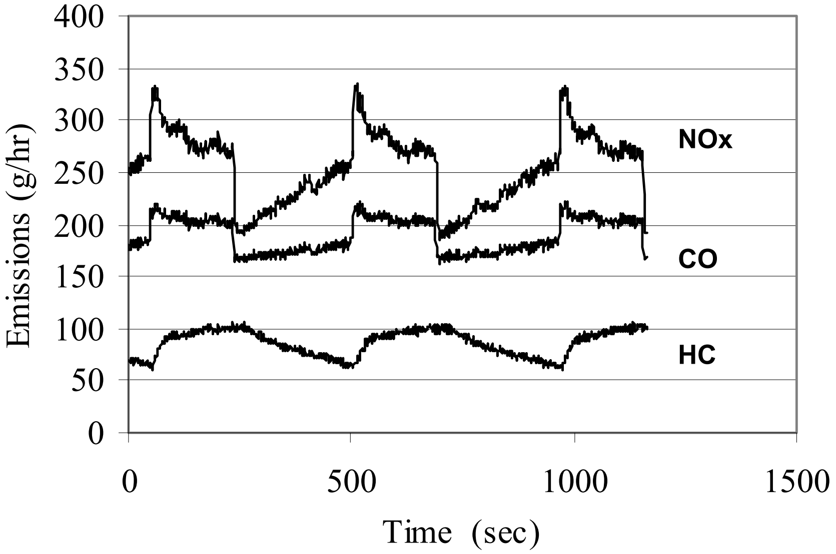


Figure 3: Idle Emissions vs. Time at 1050 rpm with Air Conditioning on During a Long Idling Period.



Theoretically, idle emission behavior of the heavy-duty truck and its dependence on the conditions prior to the idling could be attributed to the engine's complex nonlinear response. It appears that depending on the initial conditions leading to the idling activity, there is a bifurcation in the engine response. This is well within plausible mathematical solutions for such highly nonlinear systems. However, the detected emission level changes and the repeatability of the results within a given mode indicate that the observed behavior may be an integral part of the engine design, made possible by the advanced electronic controls. It appears from this limited data that fuel rich operation provides lower emissions level for the first few minutes of idling, after a transient operation. This ensures low emission in congested high way traffic and in cities with many red lights and stop signs. Prolonged idling requires a more fuel-efficient strategy and lean burning, resulting in higher NOx production.

Comparison to Previous Findings

In 1996-1998, EPA conducted idling tests of three older heavy-duty diesel trucks: a 1989 Ford CL-9000 with mechanical Cummins NTC-315 engine, a 1990 Freightliner with electronic Caterpillar 3176 engine, and a 1990 Kenworth with Detroit Diesel Series 60 electronic engine. The emissions test results are presented in Table 2 for reference. The 1990 Freightliner and 1990 Kenworth tests were run at standard idle with air conditioning, and the Ford was run without air conditioning. The emissions test results for these trucks as well as the modern Freightliner are shown in Table 2. For the 1989 truck, the results represent the average of 8, four-minute idle tests after transient driving with no accessory load. For the 1990 trucks, EPA conducted 12, four-minute tests after transient driving with accessory load. The emission figures from the 1999 Freightliner Century Class with 1999 engine are provided in the last row for reference. The data for the Freightliner are the average of three idling tests at 600 rpm with the air conditioning on.

Table 2: Emissions Test Results from EPA Testing of Older Tractors

	HC		**CO**		**NOx**		**CO_2**	
	g/hr	**st. dev.**	**g/hr**	**st. dev.**	**g/hr**	**st. dev.**	**g/hr**	**st. dev.**
1989 Ford	12.4	1.0	21.6	2.3	65.7	6.8	NA	NA
1990 Freightliner	2.6	0.4	44.6	41.1	149.3	22.3	NA	NA
1990 Kenworth	4.9	1.3	79.3	24.8	134.6	36.2	NA	NA
1999 Freightliner	1.4	0.2	15.3	0.6	166	5	4976	73

In Table 2, the NOx emissions from the 1999 Freightliner truck at standard idle with air conditioning is only slightly more than those of the 1990 Freightliner and Kenworth trucks. HC emissions from the 1999 Freightliner are the significantly lower and the CO emissions are much lower.

Comparison of Findings to Those in Emissions Models

As a baseline against which to compare the EPA emissions measurements, we examined the emissions factors used in EPA's and ARB's emissions models. Emissions estimates from EPA's MOBILE5b model vary based on environmental factors such as temperature and pressure, as well as, truck fleet characteristics, such as truck model year. Assuming an ambient temperature of 75°F, 9.0 pounds per square inch Reid vapor pressure, and the U.S. fleet characteristics noted by EPA in 1998, average idling emissions for the U.S. fleet, were 55 g/hr of NOx (7). The average NOx emissions of 55 g/hr are approximately half of that measured for the 1999 model year Freightliner at standard idle with no accessories. At standard idle with accessories, the NOx emissions from the 1999 Freightliner are nearly 3 times higher than the EPA values estimated for fleet average. This indicates that emissions from idle may be underestimated by MOBILE5b.

ARB's model EMFAC2000 incorporates idling factors for the first time (8). The idling factors are presented in Table 3. They were derived from testing on a set of light-heavy duty diesel trucks. Because this was the only data available, emissions rates for the light-heavy trucks are applied to the other two classes of heavier vehicles. The emissions factors are the same for all model years. The emissions factors are significantly higher than those measured from the Freightliner that EPA tested. The highest emissions measured on the Freightliner tractor were 254 g/hr NOx at 1050 rpm with the air conditioning on. The NOx emissions used in EMFAC2000 are 396 g/hr. This NOx emissions factor is likewise much higher than those measured by EPA on the 1990 vehicles at 600 rpm idle with the air conditioning on. We suggest that prior to finalizing the EMFAC2000 model, idling data be collected for a variety of model year vehicles under a variety of accessory loadings and engine speeds to determine if in fact these emissions factors are too high.

Table 3: Idle Emissions Rates in EMFAC2000

Weight Class	Idle Trips	Idle Emission Rates (grams per hour)			
	(Percent)	HC	CO	NOx	CO2
LHD	5%	44	247	396	29687
MHD	5%	44	247	396	29687
HHD	26%	44	247	396	29687

Cost of Fuel and Lubricant Consumption

In order to calculate the cost of fuel consumption, it is necessary to assume a fuel consumption rate at idle. The Department of Energy (DOE) publishes a table that estimates fuel consumption as a function of brake horsepower (bhp) demand of accessories and engine speed. The numbers suggested by the DOE are shown in Table 4 (2). The fuel consumption ranges from 0.6 gallons/hour for a truck idling at 800 rpm with no accessories to 2.25 gallons/hour for a truck idling at 1200 rpm with 30 bhp of accessories.

Table 4: Fuel Consumption (gallons per hour) as a Function of Accessory Horsepower Demand and Engine Speed (2)

RPM	Brake Horse Power of Accessories				
	0	5	10	20	30
800	0.6	0.7	1.0	1.4	1.7
1000	0.75	1.0	1.2	1.55	2.0
1200	1.0	1.2	1.5	1.8	2.25

However, the DOE numbers are estimates used for the general truck population, as opposed to late model trucks that would be the target market for the fuel cell APU application. Thus the applicability of these estimates for tractors from model year 1995-2000 has not been determined. The general trends are similar to those observed for the 1999 model year Century Class Tractors tested: fuel consumption will increase when truckers idle the truck at higher engine speeds and with higher accessory loads. Truckers increase the idle speed from its default setting in order to prevent battery drain and to improve accessory performance, but the extent to which truckers increase the idle engine speed is unknown.

We wanted to generate a conservative estimate of fuel cost at idling, so we chose to assume a fuel consumption of 1.0 gallon per hour. This is the fuel consumption rate we observed for the 2000 model year Argosy Tractors at idle with no accessories running. A fuel consumption rate of up to 1.4 gallons per hour was observed for idling at 1050 rpm with the air conditioner running. This is consistent with what we measured on the Freightliner tractor tested by EPA, but there was very little fuel consumption data on that tractor due to a communications problem with the engine.

The cost of fuel was calculated for the range of idling hours discussed in the previous section. At a cost of $1.72 per gallon of diesel fuel for 1818 hours of idling per year at 1.0 gallons fuel per hour, this amounts to $3127 per year spend on fuel during idling. Using the same assumptions for 2424 hours of idling per year, the annual cost of fuel for idling is $4169.

In addition to fuel costs, engine idling results in increased maintenance costs associated with substantial wear to the engine. The Truck Maintenance Council (TMC) estimates that idling for only one hour per day for a year results in the equivalent of 6,400 miles of engine wear (9). On a monetary basis, the TMC estimates that idling the engine for one hour is equivalent to driving the truck for 7 miles, assuming the truck averages 7 mi/gal. 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 (1). The development of these correction factors and appropriateness of them for application to fuel cell APU applications in late model vehicles is being evaluated.

Use of an APU will result in the engine being started and stopped more frequently and this will result in wear on the engine. The maintenance cost savings by the APU will be the difference in cost savings due to reduced idling and the cost of excess wear caused by increased stops and starts. At present, there are inadequate data on these costs to estimate the net impact on operating costs from this factor. The cost of maintenance and wear is being studied currently, and a detailed report on idling costs is being prepared.

DISCUSSION

The above results were used to determine the potential emissions and greenhouse gas savings that could be achieved by eliminating discretionary idling in a 1999 model year truck. NOx emissions were examined, since they are the focus of the regulators, and CO_2 emissions were examined because they are a general concern to regulators, environmental groups, and the public. Because emissions savings are highly dependent on idle time, accessory loading, and engine speed, several scenarios are presented below (Table 5) with different combinations of these factors.

Table 5: NOx Emissions and CO_2 Greenhouse Gas Savings Potential from Eliminating Truck Idling

Scenario 1: Average idle time (1818 hours per year)				
	standard idle, <u>no accessories</u>		**high idle <u>with air conditioning</u>**	
	NOx	**CO_2**	**NOx**	**CO_2**
baseline idle emissions (g/hr)	100	4350	275	10000
hours/day idle	6	6	6	6
days/yr idle	303	303	303	303
g/yr emissions at idle	181,800	7,908,300	499,950	18,180,000
metric tons/yr/vehicle	0.18	7.9	0.5	18.0
Scenario 2: 40% idle time (2400 hours per year)				
	standard idle, <u>no accessories</u>		**high idle <u>with air conditioning</u>**	
	NOx	**CO_2**	**NOx**	**CO_2**
baseline idle NOx emissions (g/hr)	100	4350	275	10000
hours/day idle	8	8	8	8
days/yr idle	303	303	303	303
g/yr emissions at idle	242,400	10,544,400	666,600	2,424,000
metric tons/yr/vehicle	0.24	10.5	0.67	24.2

Each year, the a fuel cell auxiliary power unit could save between 0.18 and 0.66 short tons NOx at idle depending on idle time, accessories load, and engine speed. This is a significant portion of total NOx produced by late model year trucks. The 1999 long-haul truck engine is estimated to produce 6 g/bhp-hr NOx based on engine dynamometer emissions testing conducted by ITS-Davis in cooperation with Southwest Research Institute. Assuming the average Class 8 truck travels 100K mi/yr and the conversion factor for bhp-hr/mi is 2.6, this truck emits 1.72 tons NOx on-road per year. Thus, for late model trucks that idle average to high amounts, the potential emissions reductions from fuel cell APUs are 10 (0.2/1.72) to 39% (0.67/1.72) of these emissions. A more realistic estimate of on-road NOx emissions (12 g/bhp-hr) was obtained during EPA on-road emissions testing of the 1999 model year Freightliner. Based on this emissions estimate, the fuel APU could provide an emissions reduction equivalent to 5-19% of on-road running emissions.

The above numbers reflect the potential of fuel cell APUs to reduce emissions. The emissions levels presented assume that fuel cells do not produce additional emissions, and they do not account for full fuel cycle emissions (e.g. emissions produced in the manufacturing of fuel cells and the production of their fuels). In order to calculate actual emissions saving from a particular fuel cell APUs, a full fuel cycle analysis should be done and the emissions produced during these processes subtracted from the reduction potential. There is currently no published empirical data on the emissions during fuel cell manufacturing, but data are available on emissions during fuel processing and delivery.

The assumption of no emissions production by the fuel cell itself is true of the hydrogen and methanol fueled fuel cells being considered in the near-term, but it does not hold true for solid oxide fuel cells or PEM fuel cells fueled with gasoline or diesel fuel. Solid oxide fuel cells as well as fuel cells that accept gasoline or diesel are years away from commercialization for transportation applications, and emissions data on these are speculative at best. Solid oxide fuel cells would produce CO_2 emissions and diesel or gasoline fueled fuel cells would produce many of the same pollutants seen in conventional vehicle operation, although likely at much lower levels.

APU ARCHITECTURE AND COSTS

The extent of the savings that an APU will achieve depends upon the market cost of the APU, as well as, the fuel-type and quantity of fuel consumed. As part of the Department of Energy Advanced Vehicle Program, Freightliner LLC has completed development of a 1.44-kW (1.9 hp) prototype hydrogen proton-exchange membrane (PEM) fuel cell auxiliary power unit (APU). Other potential architectures that will be investigated include direct-methanol PEM and solid oxide fuel cells. A discussion of the characteristics of each is provided below.

Truck APUs based on PEM fuel cells are particularly attractive due to the near ambient temperature operation of this fuel cell type, the ease of starting and stopping the system, and the flexibility of fuel supply, as well as the general interest in commercializing PEM fuel cells for other transportation applications (e.g., cars and buses). PEM fuel cells can be operated on a range of fuel input mixtures, including pure hydrogen, impure hydrogen “reformate” gas streams, and even gaseous or liquid methanol (in a direct-methanol system). However, PEM fuel cell systems are intolerant of CO and sulfur because their platinum catalysts can be easily poisoned by CO and sulfur-containing compounds. PEM fuel cell systems that do not run on pure hydrogen therefore require gas cleanup systems along with the use of an initially low or zero-sulfur fuel. At present, reforming methanol into hydrogen appears practical because methanol can be reformed at relatively low temperatures (about 300 °C), while reforming gasoline or diesel is much more difficult due to the more complex processes involved, the higher reformer temperatures (600-700 °C), and the higher concentrations of CO, oxides of sulfur, and other waste gases in the reformate streams.

PEM fuel cell systems that use methanol directly, rather than first reforming it into a hydrogen-rich gas stream, are known as direct-methanol fuel cell systems. These systems are at an earlier stage of development than hydrogen PEM systems, with commercialization still several years off. Direct-methanol fuel cells are widely perceived to have low efficiencies, partly because of fuel lost due to the problem of methanol crossover. This occurs when some fuel is lost due to physical crossover of methanol through the fuel cell electrolyte membrane, but recent progress has been made in solving this problem. Los Alamos National Laboratory reports that with a small five-cell "short stack" it has demonstrated a power density of over 1 kW per liter of active stack volume, with methanol fuel utilization rates as high as 82% with 1.0 M methanol and 99% with 0.75 M methanol (11). These achievements are particularly noteworthy in that they are due to improvements in the structure of the cell electrodes, rather than to a novel electrolyte membrane type or treatment. Of course, only small (under 1 kW) systems have yet been constructed, and precious-metal catalyst loading levels remain about 2.5 times as to high as for indirect-methanol PEM systems (12).

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 at about 1000 °C), but recent research is focusing on lower temperature operation (600-700 °C) and therefore requires expensive heat-resistant materials such as yttria-stabilized zirconia for the ceramic electrolyte and doped lanthanum chromite for the cathode (12). Due to their high-temperature operation, solid oxide fuel cells also have significant startup 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 (which are somewhat different than the proton-exchange mechanism in PEM cells), resulting in the production of electricity, water, and carbon dioxide. Solid oxide fuel cells would make high-grade heat available for cabin 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 these fuel cell APU systems, estimates are necessarily speculative at this time due to the early commercialization stage of the technologies and uncertainty with regard to what production volumes will be possible in what timeframe. 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 per kW to ($200 per kW for 50-kW systems in production volumes of at 300,000 units per year (13,14). 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 Inc. (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 (13). 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 $1,000 to $3,000 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 $1,000 per kW for its complete solid-oxide fuel cell cogeneration systems, based on tubular cell construction, while proponents of stacked planar cell configurations argue that costs could be as low as $400 per kW (15). Raw material costs for these systems are relatively low, on the order of $7 to $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 (13).

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. Fortunately, due to the significant fuel cost savings, the heavy-duty truck APU application has the potential of being economically feasible at higher per-kW fuel cell costs than many other applications. This suggests that fuel cell APUs may be a particularly good early market for fuel cell introduction in the transportation sector.

CONCLUSIONS

Fuel cell APUs in lieu of idling could substantially reduce truck fuel consumption, pollution, greenhouse gas emissions, and trucking costs associated with truck idle. The extent of these savings will depend on the market cost of the APU, as well as, the fuel-type and quantity consumed. This paper quantified the potential benefits of fuel cell APUs and discussed the projected costs of several promising APU architectures. A review of the findings is presented below.

- Emissions and fuel consumption during truck idling vary based on engine model year, accessory loading, and engine speed. Limited evidence also suggests that emissions at idle may be affected by idle duration and vehicle operation prior to idling.

- For modern long-haul tractors, idling is estimated to contribute 0.18 to 0.67 metric tons of nitrogen oxide emissions and 8 to 24 tons of carbon dioxide over a year period depending upon the engine model year, engine speed, accessory loading, idle time, and fuel consumption rate.

- Differences in continuous emissions patterns and emissions levels in long-duration idling warrants further study of long-duration idling typical of the type of idling that would be replaced by APUs.

- Each year (assuming 6 hours and 303 days per year used in the emissions calculations and assuming a 1 gallon per hour fuel consumption at idle) 1818 gallons of diesel fuel are consumed at idle per truck. Under the same assumptions, this results $3,127 in fuel (at a cost of $1.72 per gallon) per truck per year.

- One potential fuel cell APU architecture would be based on PEM fuel cells, which can be operated on a range of fuel input mixtures, including pure hydrogen, impure hydrogen "reformate" gas streams, and even gaseous or liquid methanol. A second potential architecture would be based on solid-oxide fuel cells.

- Potential costs of these 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 presented in this paper are in the range of $1,000-$3,000 per kW for production in the near term.

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