Fuel Cells for Auxiliary Power in Trucks: Requirements, Benefits, and Marketability

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Fuel Cells for Auxiliary Power in Trucks: Requirements, Benefits, and Marketability

By

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ABSTRACT

Public agencies and the trucking industry have recognized the idling of heavy-duty trucks as a considerable problem. Several potential technical solutions are in development, including the utilization of auxiliary power units (APUs). Using fuel cell APUs could be a promising alternative to idling with substantial fuel consumption, emissions, cost, and noise benefits, while serving as a niche for relatively early fuel cell technology market introduction. This paper, using a probabilistic Monte Carlo framework, reports on efforts to characterize existing data on idling trucks, develop an ADVISOR-based vehicle APU model that accurately depicts how utilizing fuel cell APUs to replace heavy-duty truck idling could be implemented, quantify energy consumption reductions, and analyze the economic benefits of the APU. The analysis shows that if fuel cell research targets for APUs are met over the next decade, a market in the tens of thousands of units may be possible in the line-haul trucking industry, and substantial diesel consumption reductions would result.

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ABBREVIATIONS AND ACRONYMS

AC: Alternating current
A/C: Air conditioning
ADVISOR: ADvanced VehIcle SimulatOR modeling software
APU: Auxiliary power unit
ARB-HDETL: California Air Resources Board's Heavy Duty Emissions Testing Laboratory
ATA: American Trucking Associations
ATL: Automotive Testing Laboratories, Inc
CARB: California Air Resources Board
CaTTS: California Truck Testing S****
CSM-CIFER: Colorado School of Mines – Colorado Institute for Fuel and Emissions Research
DC: Direct current
DOE: U.S. Department of Energy
EIA: Energy Information Administration
EnvCanada: Environment Canada, Inc
hp: horsepower
ITS-Davis: Institute of Transportation Studies, University of California, Davis
kW: kilowatt
NEDPG: National Energy Policy Development Group
NPV: Net present value
NREL: National Renewable Energy Laboratory
PEMFC: Proton exchange membrane (or polymer electrolyte membrane) fuel cell
RPM: Revolutions per minute
SAE: Society for Automotive Engineers
SOFC: Solid oxide fuel cell
SwRI: Southwest Research Institute
TAC: Texas Administrative Code
TMC: Technology & Maintenance Council
UC-Davis: University of California at Davis
WVURC: West Virginia University Research Corporation
WVU-THDVETL: West Virginia University- Transportable Heavy Duty Vehicle Emissions Testing Laboratory

INTRODUCTION

Context of the Problem

Heavy-duty trucks commonly haul freight over very long distances, with time and fuel as two key concerns. Drivers regularly sleep in their truck cabins, which are equipped similar to small mobile homes with beds, electrical appliances, heating, and cooling. Often in order to power cabin appliances and maintain cabin climate in seasonal weather, a truck's main propulsion engine is utilized. The net result is less than optimal, for the main engine, which has been developed and optimized to run at 300+ horsepower to haul a loaded 40-ton vehicle, can simply be powering an air conditioner and a light bulb.

The negative consequences of this practice of idling have been recognized and are now being targeted for change. At a truck or fleet level, this fuel inefficiency results in large fuel expenditure for an industry where profit margins are generally thin. Along with these direct fuel costs, indirect costs come from the increased maintenance and overhaul cost incurred by regularly idled engines (Stodolsky et al, 2000). Some neighborhoods restrict engine idling duration to minimize noise, smoke, and emissions, and at a regional level, diesel engine idling bans are promulgated in plans to attain national ambient air standards (Levinson, 2001; TAC, 2001). The resulting fuel consumption from the hundreds of thousands of idled engines has been targeted by a national program to reduce petroleum dependence (NEPDG, 2001).

Several technical solutions are in development to replace the operation of main propulsion engines for the roughly 400,000 line-haul tractor-trailers in the U.S. with sleeper cabs. To meet the demands of most drivers, the most widely successful solution must be able to efficiently provide heating, cooling, and electricity for vehicles while they are at truckstops, loading docks, and remote locations. Argonne National Laboratory published a broad survey of these alternatives, including a direct diesel-fired heater, a diesel powered APU, thermal storage, and electrification. Key conclusions of this study included highlighting the prohibitive disadvantages and limited market acceptance of these alternatives and supporting the exploration into fuel cell APUs (Stodolsky et al, 2000).

The use of fuel cell APUs could be a promising alternative to idling, with substantial fuel consumption, emissions, cost, and noise benefits. The use of solid oxide fuel cells in particular, could offer these potential benefits by still operating on the accustomed diesel fuel that is distributed through existing infrastructure. Utilizing fuel cells in this application, in addition to potentially providing cost-competitive solution to a recognized problem, could offer a niche market as a stepping-stone to larger fuel cell production scales (Lutsey et al, 2003).

Objectives

Although the deleterious effects of idling are understood, there has not yet been a comprehensive analysis on the integration of the fuel cell APU with the conventional vehicle electrical systems and the resulting expected fuel and emissions benefits. This report bridges this gap with the modeling of a heavy-duty truck and it stationary power needs. In addition, much of the work on idling line-haul trucks, in light of wide distributions in key variables, reports on average or typical trucks and estimates aggregate consequences and potential benefits. This report incorporates the widely dispersed data probabilistically, thereby including all types of driving behavior, in order to estimate potential benefits for fuel usage and cost savings on a disaggregate level. Doing so allows characterization of the potential market for fuel cell APUs in the line-haul truck application, including definition into variables of market size and fuel cell research targets.

Although the key objective of this paper is to assess the potential of a new market-unproven technology at solving a particular problem, there are also methodological goals. Along the way, the creation of a representative stationary duty cycle for line-haul trucks was a necessary objective. The procedure also includes the demonstration of the versatility of the ADVISOR vehicle model as a platform for more sophisticated and specific modeling questions and the quantification of potential benefits of this system probabilistically with the Monte Carlo method.

BACKGROUND

Currently the state of fuel cell technology as vehicle APUs is at a demonstration, or proof-of-concept, level of maturity. Several vehicle APU demonstrations have been made and are ongoing. For example, seeking to meet the high electrical demands of their luxury sedans, BMW has worked with International Fuel Cells (now UTC Fuel Cells) on a proton exchange membrane fuel cell (PEMFC), before working on solid oxide fuel cell (SOFC) systems with Delphi Automotive Systems and Global Thermoelectic Inc. (Tachtler, Dietsch, and Gotz, 2000; Zizelman, Shaffer, and Mukerjee, 2002). Freightliner LLC and XCELLSiS (now part of Ballard) demonstrated a hydrogen-fueled PEMFC APU in a Class 8 truck and are investigating liquid-fueled APUs (Brodrick et al, 2000; Venturi and Martin, 2001). Southwest Research Institute, SunLine Services Group, and the National Automotive Center have demonstrated a fuel cell APU system on a Class 8 truck (Montemayor, 2001). The Institute of Transportation Studies at the University of California at Davis (ITS-Davis) is engaged in a multi-year project that will demonstrate PEMFC and SOFC technologies as APUs.

More generally SOFC APU technology work is getting primed to meet the requirements of three key markets simultaneously. Initiated by the U.S. Department of Energy, the Solid State Energy Conversion Alliance aims to introduce a SOFC that delvers a peak power of 3-10 kW for a cost of $400/kW to satisfy the demands of 1) vehicle APUs, 2) residential electricity generation, and 3) military applications (Surdoval, Singhal, and McVay, 2001). With this multiple market approach, the Alliance aims to take advantage of larger production scales in the hundreds of thousands of units in the 2011 timeframe. Under SECA, multi-year, multimillion dollar contracts have been granted to groups including Cummins Power Generation, McDermott Technology, Inc., Delphi, Battelle, Honeywell, and Siemens Westinghouse Power Corporation (Surdoval, 2002). A large technical consulting report indicates that SECA's targets for cost and performance are achievable in the given timeframe (Arthur D. Little, Inc., 2001)

Some attempts have been made in assessing the viability of APUs as possible alternatives to idling vehicles. Argonne National Laboratory published a broad survey of the potential benefits of technology alternatives to idling truck engines, including options of a direct-fired heater, a diesel powered APU, and electrification. Key conclusions included highlighting the prohibitive disadvantages and limited market acceptance of these alternatives and supporting the exploration into fuel cell APUs (Stodolsky et al, 2000). An older study estimated the potential benefits specifically from truckstop electrification to power truck accessories (Van den Berg, 1996). Both used rough estimates for idling behavior and estimated nationwide benefits for typical drivers. The only attempt at evaluating the potential benefits of fuel cell APUs to supplant idling was done by Broderick et al, which included crude estimations and used sensitivity analysis to deal with the prevalent uncertainty (2002b). This study, citing the importance of fuel consumption at idle in its calculations, reported that PEM fuel cells in truck APU markets could have 2-5 year payback periods for average drivers (Brodrick et al, 2002b).

RESEARCH METHOD

Overview

This research entails the establishment of a representative line-haul duty cycle, the characterization of existing data on idling for incorporation into the model, the development of a model of a truck with a fuel cell APU, the probabilistic treatment of all input and output data for this model using the Monte Carlo method, and the resulting assessment of fuel cell APU market targets for line-haul trucks. A schematic representation of the research methods employed here is given as Figure 1.

In the absence of rigorous driver behavior data, a representative stationary duty cycle is estimated. This cycle utilizes survey data from previous work conducted in part by the author (published as Brodrick et al, 2001) and an original pilot survey conducted in summer 2002. In addition, input parameters to the model are based on researching empirical vehicle data, other available survey results, and industry estimates and will be described in turn. With the range of resources required to characterize fuel, emissions, and driver behavioral characteristics, it is clear that the analysis has considerable uncertainty and variability involved. To reflect this wide variety of input parameters, a probabilistic, instead of the more common deterministic, method was employed. Where deterministic analyses carry calculations for the average (or “base case” or “best guess”), the Monte Carlo method maintains the degree of uncertainty of individual inputs by propagating a proper range and distribution of values through the analysis, albeit with added computational complexity.

The ADVISOR-based vehicle APU model is used to depict how utilizing fuel cell APUs to replace heavy-duty truck idling is likely to be implemented. The modeling development strategy is a result of collaboration between the author and John Wallace, a colleague at ITS-Davis, who ultimately led the model programming in MATLAB/Simulink the computer platform. Our model is a modification of the 2002 edition of ADVISOR (or ADvanced VehIcle SimulatiOR software program), which was developed by the U.S. Department of Energy’s National Renewable Energy Laboratory and is publicly available (NREL, 2002). The flexibility of the model is a real asset, making it modification-friendly for users with specific modeling tasks. Taking advantage of the model versatility, a fuel cell APU module was added and integrated with the existing systems, engine maps were added and altered to better accommodate idling characteristics (low torque, low engine rpm), and the appropriate stationary cycle characteristics were introduced.

With appropriate distributions as inputs, the corresponding model results too are distributions of output values. Besides acknowledging more adequately the uncertainties of a model, probabilistic methods recognize and distinguish between typical and atypical drivers. This is especially important because the market for an innovative auxiliary power device is not all truck drivers or even necessarily "typical" drivers. Perhaps it is a much smaller subset of this population of truck owners that stands to benefit most and would therefore qualify as the potential market. Monte Carlo allows us to distinguish and quantify this market, and correspondingly formulate the desirable fuel cell market targets for these line-haul truck owners.

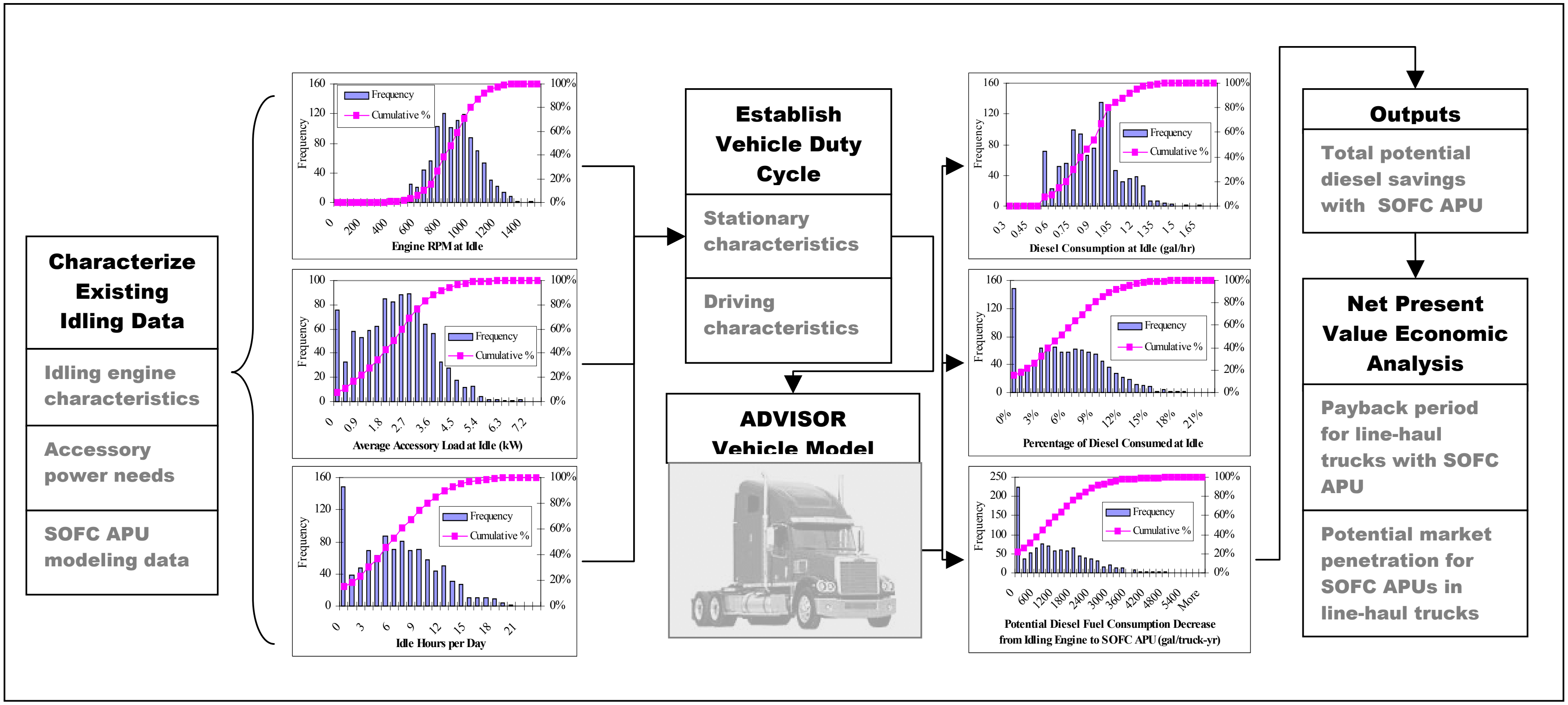


Figure 1 Schematic Representation of Overview of this Report

Establishment of Vehicle Duty Cycles

This modeling task requires an input of a range of duty cycles that reflect driver behavior for both driving and idling situations. Specifically, accurate information about driving (speed versus time) and accessory loading (power versus time) are desired for line-haul trucks. However, well-defined, statistical data on line-haul truck driver behavior are not available (Stodolsky et al, 2000, Brodrick et al, 2001). Several informal, non-rigorous studies and fleet surveys have been conducted and are applied to our analysis here. Input requires data on vehicle accessory power (devices and duration used) required and the proportion of time driving to that spent idling in order to accurately assess the potential benefits of installing an APU system. An original small pilot survey was conducted at a nearby truck rest area to complement a previous ITS-Davis survey (Brodrick et al, 2001) and the sparse research that is available in this area of characterizing driver behavior. This section reveals how all available research was utilized to characterize the driver behavior characteristics that are relevant to the modeling assessment. Distributions are created for variables that will be treated probabilistically in the analysis.

Pilot Survey

A literature search of available data left an incomplete picture of driver behavior. Specifically, the 1) duration and power of cabin accessories used during idling need further refinement and the 2) average hours of idling and driving per day. A smaller pilot survey was used to help examine these issues. The survey form is reproduced as Appendix A. Inquiring about the *last* 24 hours, instead of a “typical day,” was opted for to reduce potential problems associated with memory bias. Also, this choice ensured that the survey would capture those off-days that the driver was not on the road.

Two student researchers went to the nearby public rest area just off highway I-80, near Sacramento, to solicit information from Class 8 trucks drivers. The survey was verbally administered to the drivers, with driver responses filled in by researchers. The surveyors received an approximate response rate of 10-15% until 29 surveys were completed in full throughout one workday.

Potential problems with the data are numerous. The sample size is very small, introducing high variability as well as a higher chance for biases. The single geographic location for one day jeopardizes the generalizability of the data over the space and seasons, considering the importance of climate on driver behavior. Because the survey was only used for general guidance in association with all other available data and generous probabilistic ranges were applied later in the modeling stages, these problems are not thought to be substantial.

Driving vs. Stationary Engine Run-time

The driving portion of the truck duty cycle is more straightforward to replicate in the model than are the stationary (idling) vehicle characteristics. The US Highway Federal Emissions Testing Cycle is the most apt candidate to represent the highway driving that commonly persists for line-haul trucks, short of a rigorous study to develop a more true cycle for line-haul Class 8 tractor-trailers. This being the case, this speed vs. time cycle (shown in Appendix B) was chosen to represent the driving section of the truck cycle. Data from an American Trucking Associations (ATA) survey of motor carrier members reported an average of 9.1 hours driving per day (ATA, 2000). Similarly, our pilot survey respondents reported an average of 9.3 hours driving per day.

Our survey revealed that truck use patterns are widely diverse. For example, 17% of drivers in our survey reported that they never idled their engines when resting, while another 17% idled their engines over 10 hours that day. The survey average was about 5 hours idling per truck per day. The reported average was in line with other estimates, as summarized in Table 1. The American Trucking Associations' Technology and Maintenance Council (TMC) used 6 hours per day for its daily idling duration for long-distance, freight-hauling, heavy duty trucks (TMC, 1995). Stodolsky et al, pointing out the seasonality of idling, use 10 hrs/day during winter (85 days) and 4.5 hours per day the rest of the working year (218 days); this equates to a base case of 6 hours per year (2000).

There are also some estimates that are presumed to be highly correlative. A California Air Resources Board-sponsored study logged total hours where trucks were at rest, as a percentage of total engine run time. With 84 trucks logged over a total of 1,600 hours, the average idling time was found to be about 42% of total engine-on time (Maldonado, 2002). This equates to approximately 7 hours of idling for every 9 – 10 hours day of driving; although no distinction is made regarding which stops were necessary, unavoidable stops (e.g., red lights) versus which ones were unnecessary, avoidable (e.g., idling while resting). Based on another source, the reported in-truck sleeping time is about 5 hours per day (Webasto, 2001). Based on these sources, a driver who idles 5 to 6 hours per day appears to be "typical," but a wide range of idling duration is applied to the model.

Table 1 Idling Estimates for Heavy Duty Trucks from Available Studies

Study	**Estimated average idling duration [a]**		**Comments**
	Hours per day	**Percent of engine run-time**	
TMC, 1995	**6**	**40**	**Estimation used in calculations**
Stodolsky et al, 2000 (basecase)	**6**	**40**	**Informal estimates from fleets (Given here is the "base case" for driver with 10 hrs/day in 85 winter days, 4.5 hours/day for 218 days)**
Webasto, 2001	**5**	**36**	**Based on average sleeping time in truck, *not* actual time with engine idling**
Maldonado, 2002	**6.5**	**42**	**Datalogs of 84 trucks over 1600 total hours in California fleets, without distinction between nondiscretionary and avoidable resting idling**
Pilot Survey	**5.0**	**35**	**Small sample (n=29) of Class 8 tractor-trailers in northern California**
"Typical"	**5.5**	**38**	**Assumed "typical" line-haul HD truck driver for this analysis**

[a] unless otherwise stated in study, 9 hours driving per day is assumed

For several reasons, a distribution of idling duration was applied. As briefly commented on in Table 1, none of the available studies offers a rigorous statistical collection of data that can inform conclusively about line-haul trucking in the US for this study. Some are based on industry estimates that may not be generalizable for different fleet sizes and independent owner-operators. Another is based on average time slept in truck cabins, regardless of how often engine is at idle or accessories are in use. The one study involving datalogging does not offer adequate distinction between when hotel loads, like climate control and accessories, are required.

In the absence of comprehensive data, a range of values must be applied. Using the pilot survey data in order to generate inputs, a distribution of behavior was created with a mean of 5.5 hours, taken from the Table 1 average of available idling estimates, and standard deviation of 5.1, taken from the 2002 pilot survey. Again this large distribution reflects the genuine diversity of driver behavior and/or the lack of rigorous statistical data. Figure 2 shows a histogram with the values randomly-generated from within this distribution to be used in model runs.

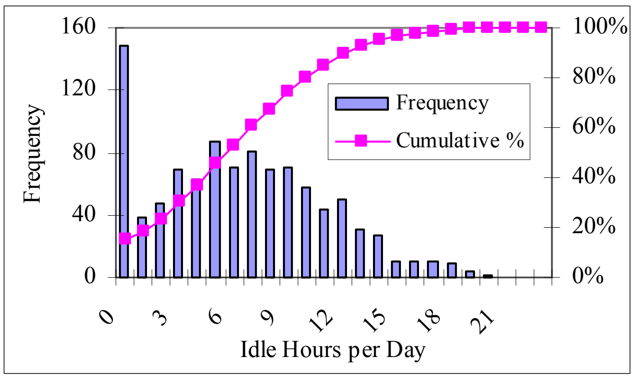


Figure 2 Distribution of Runs Generated for Monte Carlo Simulation for Daily Idling Duration (hrs/day)

Accessory Power Cycle for Stationary Truck

After estimating the fraction of time driving and idling, further understanding of energy flow aboard the vehicle is required. Although power is distinctly exchanged from vehicle subsystems in the forms of mechanical shaft power, voltage (DC and AC, with different voltages), and heating and cooling, these systems are currently modeled generically as power (W) with efficiencies addressed accordingly. The power characteristics for the electrical and climate control devices for the two systems of interest, 1) baseline main engine idling and 2) fuel cell auxiliary power in lieu of idling, vary slightly. The main objective in creating these two cycles was to maintain the same ability in both systems to provide the same services (electricity for appliances, cooling, and heating), shown schematically in Figure 3.

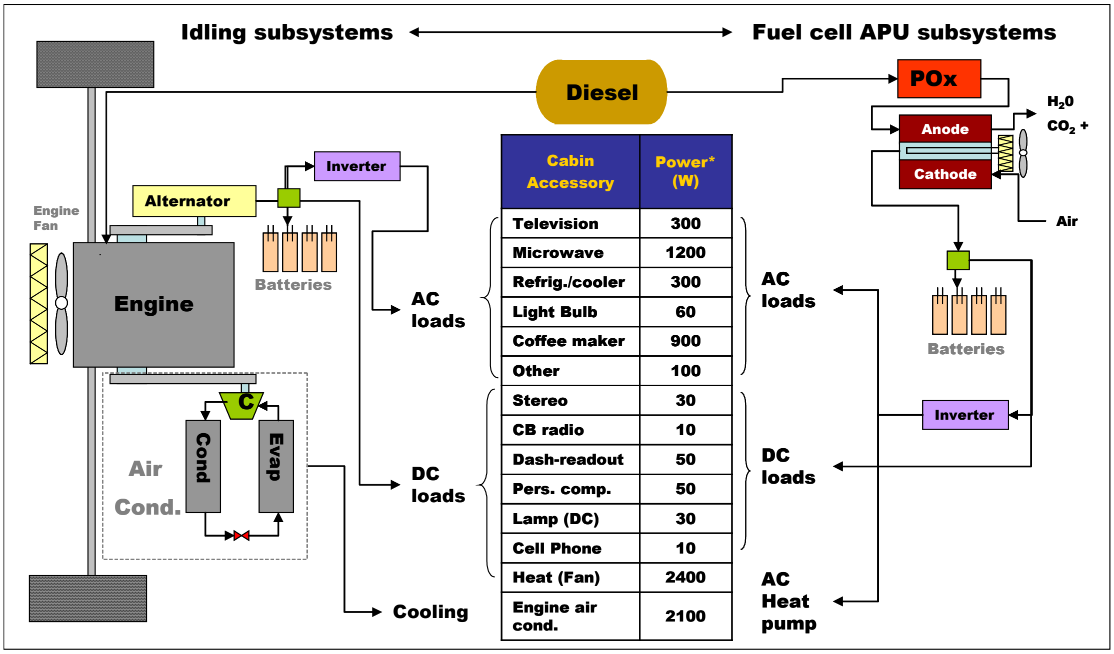


Figure 3 Systems Diagram for Idling and APU Subsystems Each Providing Same Cabin Services

Baseline Engine Idling Accessories. As a starting point, it is necessary to determine what appliances require power in truck cabins. Our survey results for the likelihood of drivers to have various accessories are shown in Table 2, along with our results from the previous survey (Brodrick et al, 2001). The way the surveys were crafted does not allow for a perfectly straightforward comparison; however, the results do show that the two driver samples appear to have similarly equipped cabins.

Table 2 Accessories in Truck Cabins, Reported in Two Pilot Surveys

Accessory	Percentage of trucks with the following accessories	
	2001 Pilot Survey[a]	2002 Mini-Pilot Survey
Stereo	96%	86%
TV	60%	21%
Computer	35%[b]	28%[c]
CB radio	90%	86%
Lamp (built-in)	84%	66%
AC light bulb	N/A	41%
Refrigerator	52%	48%
Coffee maker	14%	7%
Microwave	12%	10%
A/C powered by engine	92%	93%
Electric A/C	7%	0%
Heat from engine	94%	N/A
Heat from other source	2%	N/A
Stove using battery	9%	N/A
Stove using other source	3%	N/A
VCR	9%	N/A
Cell phones	N/A	28%
"Other"	5%	N/A
Power-take-off	13%	N/A

[a] from Brodrick et al., 2001
[b] no distinction between PC and dash-readout/company computer was made
[c] dash-readout/company computer percentage is given; 10.3% of trucks had personal computers

Modeling the baseline scenario, engine idling to power electronic and climate control devices, is not a trivial matter in an unmodified ADVISOR. Although the model does have some accessory power load information, it is lacking in some of the accessories that are crucially important for our analysis. For example, because the ADVISOR model is geared toward handling a driving vehicle, many standard auxiliaries like the engine cooling fan, the air brakes, and the alternator are included; however, many of the stationary aftermarket accessories (TV, microwave, etc.) for idling truck drivers are not included. Using our survey data on the frequency of use of the accessories and available data on their power demand, energy flows are modeled for the at-rest vehicle.

Modeling the loading of accessories with a constant average load would misrepresent the way electricity flows on-board the vehicle. Because the engine at idle and fuel cell have variable efficiencies for given power outputs, a more accurate cycle over time was created, based on the reported idling times, the reported accessory-use times (while the vehicle was at idle), and the estimated power demands of the accessories. These characteristics are shown in Table 3.

The main goal in creating two scenario cycles was to maintain the same ability in both systems to provide the same services (electricity for appliances, cooling, and heating). Estimates for accessory power draws were derived from several sources, including some field measurements of voltage and current from idling trucks at

Sacramento Select Trucks. Heating the cabin draws excess engine heat, while drawing up to 300 W of electrical energy to power fans to transport this heated air into the cabin. The cabin air conditioning requires variable shaft energy (from about 1.3 to 3.0 kW at 600 to 1200 rpm). Similarly, the engine cooling fan draws between 700 and 3 kW over idling speed ranges, and it is assumed to run 40% of the idling time. Electrical power for accessories shown in Table 3 are the loads "seen" at the accessory and do not account for the alternator efficiency losses.

Table 3 Estimations for Key Characteristics for Average Truck Idling

Accessory used during idle time	Fraction of idle time	Power for idling basecase (W)	Power for fuel cell APU case (W)
Stereo (stock, in dashboard)	0.31	30	30
CB radio	0.39	10	10
Television	0.05	300	300
Dash-read/company comp.	0.19	50	50
Personal computer	0.01	50	50
Microwave	0.01	1200	1200
Refrigerator/Electric Cooler	0.26	300	300
Overhead lamp (built-in DC)	0.15	30	30
Light Bulb (AC)	0.04	60	60
Coffee maker	0.01	900	900
Electric Blanket(Other)	0.06	100	100
Cell Phone(Other)	0.32	10	10
Cabin air conditioning	0.32	2100*	1700
Cabin heating	0.32	300	2400
Engine cooling fan	0.40	1800*	0

*These are taken from ADVISOR model, for an engine speed = 850 rpm. In reality and in the model these power magnitudes vary with idling rpm

Because the way engine systems are separated and the method that they interface with one another in ADVISOR, the electric accessories, whose electricity runs through the alternator and batteries, were separated from shaft-driven accessories (compressor for A/C and the engine fan). The "typical" driver at idle had an estimated average power draw of about 2.1 kW, and the standard deviation was a relatively high 1.4 kW. Figure 4 shows the distribution of values randomly-selected from within this distribution. The average power value, and the proportion each simulated driver (i.e. each Monte Carlo trial) is away from this value, was used to scale the entire electrical accessory profile.

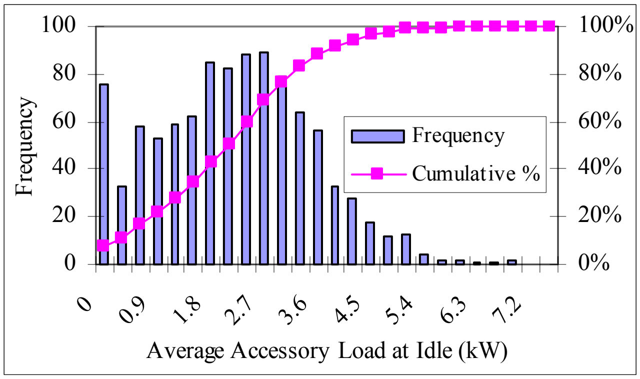


Figure 4 Distribution of Runs Generated for Monte Carlo Simulation for Average Accessory Power Load (kW)

Fuel Cell APU System Accessories. Several of the power loads for accessories in Table 3 are not equivalent for the baseline idling and fuel cell APU systems. For example, the fuel cell APU system does not have the opportunity to utilize excess engine heat for cab climate control. Although in the case of the SOFC, there may be usable excess heat, the model assumes that the fuel cell system can only provide electric power. This decision is conservative, but justified due to the current uncertainties regarding fuel cell technologies and the strong possibility for mismatch between available excess SOFC heat and desired cabin heating. Instead, we assume the specifications of off-the-shelf technology, powered by fuel cell electricity, to provide heating and cooling to the cabin. We used specifications provided by Cruisair® for a 115 V AC heat pump: 10,000 Btu/hr for cooling from 14.8 Amps (~1.7 kW) of electricity and 6,825 Btu/h for heating from 20.3 amps (~2.4 kW). An initial spike of about 4.4 kW is required at startup (Allen, 2002).

The procedure used to transform the characteristics of Table 3 into a power vs. time cycle is similar to that utilized by ADVISOR for other accessories, based on duty cycle estimations of SAE report J1343 on accessory power requirements (SAE, 2000). Accessories shift on and off, roughly according to how a user or control device in the real-world toggles them. The way they toggle must account for some loading situations with many appliances on at once. However, inconsistencies, such as running a heater and air conditioning simultaneously, are of course avoided.

Figure 5 shows estimations of the power-time traces applied to the ADVISOR model. Truly the traces are slightly different for each driver as a result of the engine speed (which determines power of air conditioning and engine cooling fan, as well as the alternator efficiency) and the variance in accessory use by driver, as shown above in Figure 3. ADVISOR's model accounted for engine speed (rpm)-dependent variables, and the differences in individual drivers' average accessories were accounted for by scaling the magnitude of the loads of Figure 4 with their difference from the average power of 2.1. For example, for a driver with an average accessory loading of 1 kW, the profiles of Figure 5 would remain similar in shape while decreasing by about a half. Developing the profile for the fuel cell APU, the heat pump values are all divided by 0.85, the assumed DC-AC inverter efficiency, in order to determine the amount of net power to be delivered by the fuel cell. The average for electric power over the fuel cell APU cycle is about 1.8 kW for the APU cycle shown in Figure 5.

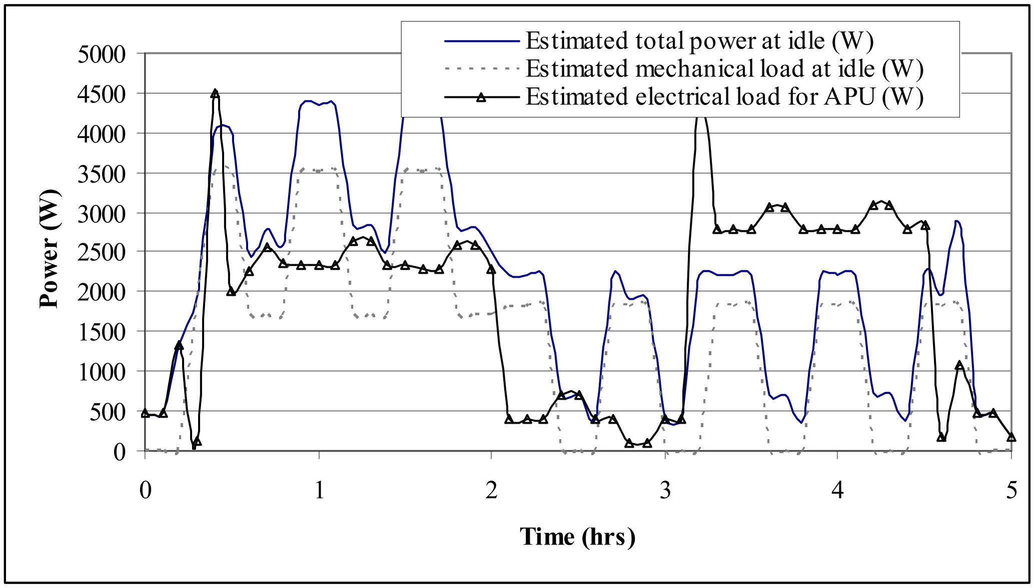


Figure 5 Estimated Accessory Power Profiles for Idling Scenario (Electrical and Mechanical) and APU Electric Load over Duration of Stationary Period

Engine Speed at Idle

Engine rpm varies substantially in the field (Brodrick et al, 2001). This adjustable engine setting has a profound effect on idling fuel consumption (Brodrick at al, 2002b; Irick et al. 2002). This parameter was initially tested for sensitivity in the model, and found to be important. As a result, the variable of rpm was applied probabilistically as shown in Figure 6, using values from the Brodrick et al (2001) pilot survey – mean of 850 rpm, standard deviation 170 rpm, and minimum 400 rpm.

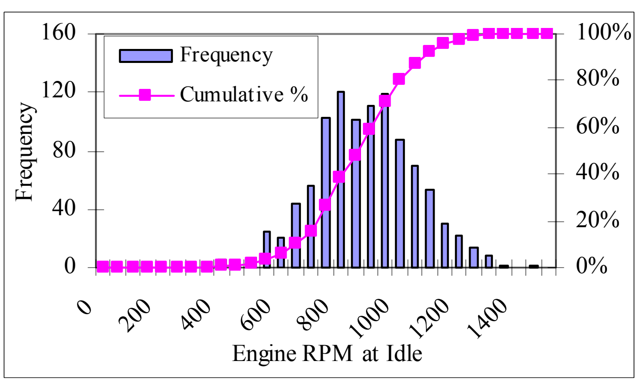


Figure 6 Distribution of Runs Generated for Monte Carlo Simulation for Engine Idle Speed (rpm)

The histograms of Figures 2, 4, and 6 show the distributions of the model input values. The Microsoft Excel random number generator was used to create these distributions. Because of practical real-world constraints, some filters were used to modify some of these inputs. Namely, negative values for idling duration and accessory power during idle were changed to zero, and engine speeds less than 400 rpm were changed to 400, which was the minimum value reported in our 2001 pilot survey (Brodrick et al, 2001). As a result of this filtering of the randomly generated trial inputs, the statistical variables (i.e., mean, median, standard deviation) are changed somewhat, as shown in Table 4.

Table 4 Summary of Statistical Characteristics for Model Inputs (n=1000)

	Engine Speed at Idle (rpm)	Daily Idling Duration (hrs/day)	Average Accessory Power During Idling Period (kW) *
mean	859.4	5.97	2.07
median	859.9	5.57	2.05
st. dev	167.4	4.51	1.31

*These loads are for the APU system. The magnitudes are different for the engine idling scenario, as discussed above.

Model Development

A prominent reason for modeling the fuel cell APU-equipped tractor-trailer system in ADVISOR is the model's flexibility in accepting different data types. The model, although it has much data for a wide variety of different vehicle subsystems, needed enhancements in several key areas for usefulness in addressing our problem. Figure 1 illustrates the conceptual framework of the model and our modifications to it. There were five key areas of modification: 1) Creation of a representative vehicle duty cycle, 2) inputting engine-specific emissions and fuel consumption maps, 3) addition and integration of the APU module with control strategy, 4) estimation of fuel cell performance data, and 5) appropriate sizing of the fuel cell APU. Fuel consumption and emissions estimates are the outputs of the vehicle simulation model.

Vehicle Duty Cycles

The power-time trace created for the idling portion of the drive cycle was shown above in Figure 5. The driving portion of the cycle (Figure 1) and the stationary cycle were concatenated, and then shrunk for the sake of the second-by-second model. The federal highway cycle is defined as 766 seconds; therefore a 9-hour drive cycle is decreased by a factor 42.3. Modeling a 5.5-hour stationary cycle requires similarly scaling to 468 seconds.

Generally, the default ADVISOR accessories cycle on (full-power) and off (zero power) according to a given frequency and duration. Several components are more dynamic. For example, the 2002 model has a look-up table to reflect the alternator operation for varying electric power delivered and engine power. Also, the air conditioning and engine cooling fan systems operate as functions of the engine speed (rpm). Pertinent characteristics of the ADVISOR electrical accessory system are tabulated in more detail in Appendix B.

Calibration of Engine Data Maps

Data that is perfectly applicable to the engine systems for our study were not available, and engine data maps (i.e., emissions and fuel consumption vs. torque and engine speed) are notoriously difficult to obtain. The ADVISOR heavy-duty truck model is equipped with a Detroit Diesel 330-kW engine component with a fuel consumption map, but excludes the accompanying emissions data. Since engine manufacturers of this power class declined to provide these emissions maps, total emission benefits were estimated by scaling up available engine emissions maps from a 1999 engine with a peak power of 209 kW that were already in our possession.

These emissions maps that are available are not fully comprehensive. As is normally the case, there are data gaps in the maps, particularly for low torque and rpm values of engine operation – those points that are especially relevant for our idling situations. As a result, a variety of methods was employed to approximate emissions and fuel rates in these areas, and calibration was done to ensure a baseline performance that is comparable to existing empirical data. The engine maps were ultimately approximated by linearly extrapolating the existing grams/second from the maps to lower torque values for given engine rpm. Other extrapolating techniques, including keeping grams/kWH and grams/second constant with engine rpm and grams/second linear with torque at constant rpm, were also explored. The engine maps for fuel consumption, before and after extrapolating, are shown in Figure 7.

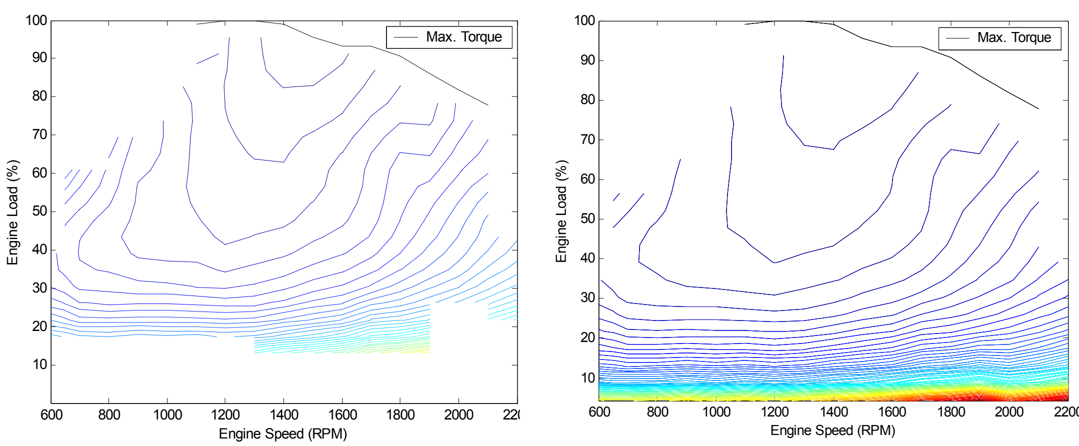


Figure 7 Engine Fuel Maps - Before and After Extrapolating for Missing Data

Baseline Fuel Consumption. Although there is not comprehensive statistical data on how line-haul trucks consume diesel fuel at idle, the key variables are known. Those key variables are engine speed (rpm) and accessory brake horsepower (bhp). The American Trucking Associations' Truck Maintenance Council estimates the relationship between rpm, bhp, and gallons of diesel per hour, shown in Figure 8. These curves are similar to existing trucks, but may be generally too high because they are based on pre-1995 truck data. As a result, available data on newer trucks was used to validate and calibrate the fuel consumption results of our model.

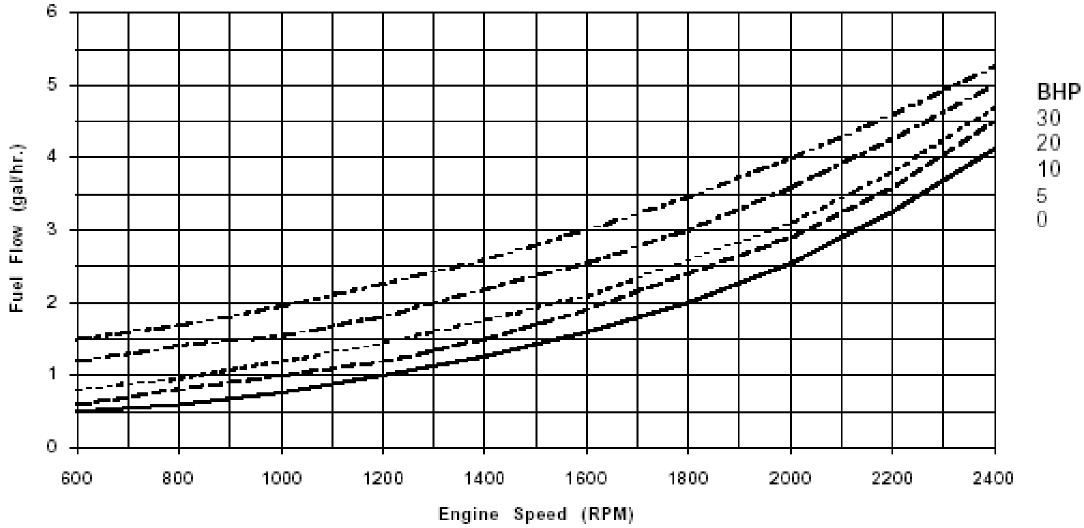


Figure 8 Estimated Fuel Consumption with Varying Engine Speed (rpm) and Accessory Loading (bhp) (TMC, 1995)

Much of the testing done on idling engines intentionally involves disengaging all nonessential accessories for reasons of replicablility and consistency. There are only two known sources that specifically tested idling engines over a range of engine speeds and accessory loadings (including "hotel loads"). Previous ITS-Davis work investigated the effects of accessory loading and engine rpm on fuel and emissions. The study concluded that both of these factors had substantial effects (Brodrick et al, 2002). Another group has found similar effects for fuel consumption (Irick et al, 2002). Plotting data from the Irick et al (2002) and Brodrick et al (2002), strong positive correlations emerge between idling fuel consumption (in gallons of diesel per hour) and engine rpm and accessory loading. As seen in Figure 8, there are near linear increases (R^2 values of 0.72 to 0.98 for each accessory loading line) of fuel consumption with rpm, with higher trendlines for increased accessory loading.

Along with empirical data points, ADVISOR outputs for idling fuel consumption are shown on Figure 9. These points appeared to validate that our baseline model for fuel consumption is accurate in capturing the correct relationship for fuel consumption rate with respect to engine speed. The model was than calibrated by adjusting the points in the engine data maps in the extrapolated regions for low torques. In a previous survey, respondents reported engine speed during idling for accessory use (Brodrick et al, 2001). The middle range from the survey of 700 to 1000 rpm corresponds to 0.7 to 1.05 gallons of diesel per hour, equivalent to the industry cited average values.

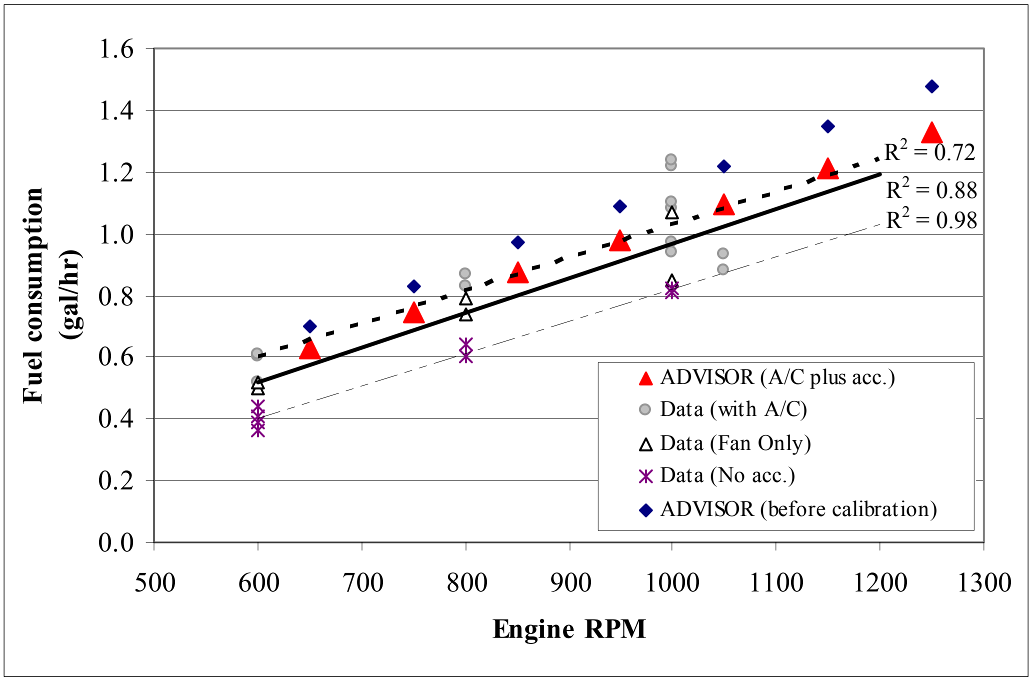


Figure 9 Fuel Consumption at Idle: ADVISOR Results with Empirical Data (fitted to linear regression lines)

Emissions maps. Several impediments lie in the way of developing an accurate, interactive emissions modeling capability for varying idling situations. Steady-state engine emissions maps, and especially ones that are well-defined at very low torque and engine speed points (where idling occurs) are very difficult to obtain. Furthermore, because of the inherently transient nature of emissions, empirical data is crucial to calibrate the model and validate the results. There are some small studies that suggest that engine speed and accessory loading may play a large role in emissions as for fuel consumption (Brodrick et al, 2002b, Irick et al, 2002, WVURC, 2002). However, the bulk of the rest of idle emissions testing (McCormick et al., 2000; Traver, 2002; WVURC, 2002) has been conducted without these conditions and ample data were not available to show well defined relationships such as those in Figure 9 above. EPA work in this area is ongoing. January 2, 2003, EPA released a report from testing of a variety of heavy-duty vehicles for long periods under various load conditions (Lim, 2002). The EPA report is the most comprehensive in its inclusion of different idling conditions, truck model years, and testing modes, but the study only includes the emissions of carbon dioxide (CO_2) and oxides of nitrogen (NO_x). Table 5 highlights the idle emissions tests that have been done with brief comments on procedural differences.

Table 5 Idling Emissions Testing

Study	Trucks	Modes or tests	Comments on testing procedure
McCormick et al., 2000	10	1	Class 8 trucks 1990-1997 model year. 36K-443K mi. Tested hot, within 20 min. of chassis dyno driving cycle. Measured over 20 min period. Ambient 20C. Elev. 1609 m above sea level. Without testing for effects of accessory loading.
Traver, 2002			Ford L-9000 tractor, 106K mi. Cummins M11-280E+, 280 hp diesel engine. Tested at 6 facilities, data from one was later omitted: (ARB-HDETL in LA, CA; CaTTS in Richmond, CA; CSM-CIFER in Golden, CO; EnvCanada in Ottawa, Ontario; SwRI in San Antonio, TX; WVU-THDVETL in Riverside, CA). No Accessory loading.
Lab A	1	2	
Lab B	1	3	
Lab D	1	3	
Lab E	1	3	
Lab F	1	9	
WVURC, 2002	1	8	1995 Mack CH 613 tractor, Mack E7-400 engine 728 in^3, 400 hp @ 1800 rpm; 10 minutes per idling mode; at WVU-THDVETL. Reported emission values for collections were with the lights, air conditioning, and other accessories were off. Engine cooling fan, alternator, air brake compressor, and AC compressor varied throughout.
Brodrick et al, 2002	1	5	1999 Freightliner Century Class 450-hp tested over 5 modes (with several tests per mode) with varying rpm (600 and 1050), with varying accessory loading, and following several types of driving cycles.
Lim, 2002	9	42	Over 30 unique tests at engine speeds from 600 to 1200 rpm, with variable accessory loadings (heat, air conditioning), with span of extreme ambient conditions. Truck model years from 1980s to 2001.

Due to the limitations of idling emissions data (e.g., lack of emissions rates that are dynamically related to accessory loading and rpm variance), further calculations on truck emissions would be questionable. For this reason and because of the secondary importance of emissions (as compared with fuel and cost benefits) in this analysis, presentation of model results for annual truck emissions is forgone at this point. Data from the idling emissions testing are shown in Appendix C.

Creation of APU module and control strategy

ADVISOR was originally constructed with some ability to model the idling of the main diesel engine. ADVISOR's engine/accessory control strategy was modified to accommodate engine-off APU operation. The APU block contains a fuel cell system performance relationship discussed in the following section.

The APU block checks the state of the engine (on/off), takes the stationary accessory load as an input, uses both the TIAX fuel cell performance data and subroutine (described later), and outputs the power achieved, fuel consumed, and emissions produced during the process. This model has been created to be flexible enough to use several different types of APUs, including a fuel cell, diesel generator, or large battery pack, as well as predict their performance over any combined driving/idling cycle. A key issue is how the APU and the existing electrical system (primarily the battery) interact, or when each one supplies power to the accessories. Characteristics of the strategy include–

- APU is off when driving, APU turns on when vehicle is at rest.
- When vehicle is at rest, the APU-battery system acts out the following subroutine:
  - APU delivers all accessory power up to its peak power.
  - When APU cannot deliver all required power, the battery delivers the difference.
  - If the battery state-of-charge (SOC) is below its initial state of charge, and the accessory loading is below the APU peak power, the APU increases its output to charge the battery. The excess power from the APU is proportional the difference of initial SOC and current SOC.

The characteristics, particularly with respect to start-up time, of the SOFC system may require modification from this strategy. Even if there is a long start-up, it may be a relatively small problem for this application. It may be reasonable to assume drivers, knowing roughly when they will take their rest press the "warm-up" button a half-hour in advance. For this start-up period, a certain minimum power draw would be required. In light of uncertainties about the still developing SOFC technology and how such issues will ultimately be resolved, the strategy above was retained. The chosen control strategy has the ability to utilize the battery to "peak-shave" on brief occasions where the APU can not supply power to the demanded load (e.g., when the air conditioner first turns on).

Fuel cell performance map

The ADVISOR APU model inputs fuel cell performance data from TIAX, LLC (formerly Arthur D. Little) for a diesel-fueled solid oxide fuel cell (SOFC) system with a reformer. Although a more rigorous fuel cell model would include transient effects on the reformer, the air supply subsystem, fuel flow and utilization rates, and any other supporting and parasitic loads, this study does not. Doing so is beyond the scope of this work. Instead the model relies on the work of TIAX for fuel cell performance characteristics.

The fuel cell system was modeled with efficiency vs. load relationships. As shown in Figure 10, these relationships differ slightly for systems of different fuel cell peak power. These curves reflect the improved balance-of-plant efficiency with larger systems – as peak power increases, the power required for parasitics, heat loss, and auxiliary subsystems (reformer, air compressor, etc.) increases more gradually. More discussion on the SOFC system and model is given in Appendix D.

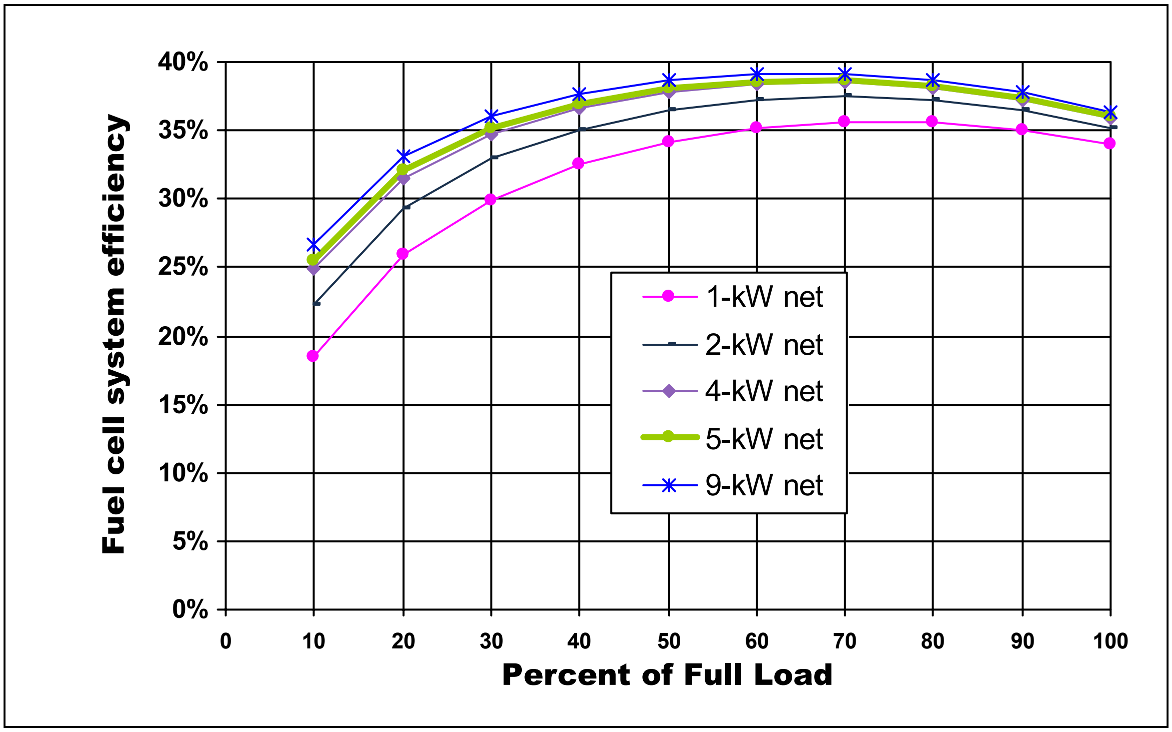


Figure 10 Fuel Efficiency Curves for SOFC Systems of 1 -9 kW Peak Power (Stratanova, 2002)

APU Sizing

In determining the most appropriate fuel cell APU size, many competing criteria must be considered. To be a marketable product, the fuel cell size would have to satisfy a majority of conditions for a majority of truck drivers. At the same time the peak power that is chosen requires consideration of the discharge and cycling of the battery and the overall cost of the fuel cell system.

As shown above, the fuel cell APU power-time trace has an average value of 1.8 kW and a peak of 4.4 kW. Therefore, an absolute minimum for the APU is the average accessory power for the "typical" driver of 1.8 kW, to avoid a net battery discharge from the beginning to the end of the stationary APU cycle. However, in order to size the APU with some security about its ability to operate in more difficult environments (e.g., summer in Phoenix, winter in Green Bay), larger power requirements need to be met. Holding the types of devices (and therefore their power magnitudes) constant, the accessory time durations were changed to the maximum amount that a driver would feasibly turn on devices. The biggest change was to leave the heating and cooling units on at full capacity for nearly the entire cycle in the summer and winter, respectively. The durations that the other accessories were turned on were also elongated with less effect. The average power demands for these climate extremes were approximately 2.3 kW for winter and 3.1 kW for summer. These atypical values serve as rough minimum safety factors for peak size.

An average or typical driver in demanding situation requires about 3.1 kW, but another approach involves estimating most drivers in typical situations. Our survey allowed us to roughly approximate all drivers' average power demanded over 24 hours. Using the mean 1.8 kW and standard dev of 1.2 (from the survey), we can get a distribution of average power demand. For such a distribution, the 90th percentile is 3.3 kW and the 95th percentile is about 4 kW. Considering coverage of difficult climate situations for typical drivers and this "most drivers" approach, 4.0 kW is a reasonable choice for the peak power size.

The control strategy described above to some extent introduced the two potential competing concerns of battery cycling and APU size (and therefore cost). For example, the smallest and least expensive fuel cell that could provide the average power requirement (1.8 kW) would subject the battery to frequent battery discharge and recharging. If instead the fuel cell is sized to peak follow perfectly (up to 4.4 kW), the battery is never discharged but the fuel cell stack purchase increases as a result. Because batteries too are expensive and their lifetimes are based on number of charge-discharge cycles, this topic requires more study than is allowed here to assess whether the chosen fuel cell size of 4.0 kW does not put undue stress on the battery for some drivers. Truly examining this issue would require more extensive data on consumer real-world accessory loading, as well as manufacturing and cost tradeoffs between batteries, control systems, and APU integration complexity.

Net Present Value

The distribution of the potential diesel savings on a per truck basis is the foundation for this analysis of the potential monetary savings. Applying assumptions for pertinent economic variables such as the price of diesel and the time value of money, estimations of the potential market size and the desirable R & D targets for fuel cell APUs for the application of line-haul sleeper cabs are quantified using a net present value (NPV) framework. At its most basic, an NPV analysis involves an assessment of a current capital investment with costs and benefits in the future, and the first time at which the investment breaks even, or the sum of future benefits outweigh the initial and final costs, is called the payback period. In this case, the fuel cell APU, its ancillary components, and its installation costs make up the capital investment, K_0.

$$NPV_0 = -K_0$$

Future benefits and costs are discounted by the discount rate, or time value of money, *d,* to correct for the difference in the value of money in hand today versus money in the future (based on the depreciation, interest rate, inflation, and other factors). The NPV of the investment one year from now (in current dollars) is calculated,

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

Or, more generally in any year *x*,

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

Although there are other potential benefits, direct and indirect, that require inclusion in a complete benefit-cost comparison, fuel-related cost savings are the only ones considered here. This decision was made for several reasons. The estimates on other idle-related private costs are highly uncertain. Operating and maintenance cost (e.g., oil and lubricant changes) estimates in the literature vary widely and are much less likely to influence investment decisions. Relevant indirect benefits, such as those related to pollutants and noise, are less-easily translated to monetary benefits. Those pollutants that do possess monetary equivalents, such as emissions of oxides of nitrogen (NO_x), do not have an existing regulatory framework to give due credit for reductions specifically from idling tractors. Also, because the actual distribution of line-haul truck emissions is not yet well defined (as discussed above), any calculation done here would be cursory without more-defined emissions data.

Key economic variables chosen here for the NPV analysis are summarized in Table 6. Because distributions of these variables are not known, nor are they known to be normally distributed, the key assumptions made here are applied with high and low estimates. For example, the choice of the real discount rate, or time value of money, of 5% is chosen with low and high estimates of 3 and 7 percent, respectively. Similarly, the cost of a gallon of diesel at truck stops is varied to recognize its relatively volatile nature. Using DOE data, the estimates used were a low of $1.25/gal (lowest annual U.S. average in last four years); a middle of $1.38/gal (4-yr U.S. weekly average); and a high of $1.50/gal (highest annual U.S. average in last four years) (EIA, 2003).

Along with the capital cost of the 4-kW net SOFC system, many ancillary costs must be included. Any fuel cell system delivering direct current power will require power conditioning to convert to desirable alternating current with an inverter to power the heat pump and various accessories. As a side note, this inverter is likely to offer an input of electric grid power to offer the possibility of "shore power" when possible for trucks, as some such devices already do, but any such benefits are ignored here. Estimates taken here are based on ITS-Davis' previous assessment of hydrogen fuel cell APUs (Brodrick et al, 2001), as well as insights from our ongoing work retrofitting a Class 8 truck with and auxiliary power system.

Table 6 Summary of Key Variables for NPV Analysis

Variable	Lower market limit	Middle estimate	Upper market limit
Diesel price	$1.25/gal	$1.38/gal	$1.50/gal
Discount rate (real)	7%	5%	3%
Inverter		$1400	
Heat pump		$1800	
Installation		$1500	
Misc. (housing, conduit, etc.)		$500	

RESULTS

Baseline Scenario

After 1000 runs for the engine idling scenario, the mean and median values were both about 0.9 gallons of diesel per hour. This distribution, shown as Figure 11, is skewed upward as a result of the imposed minimum engine speed of 400 rpm that eliminated lower values from the distribution, thereby eliminating the some lower fuel consumption values. Moreover, the relatively jagged appearance of the histogram is likely due to the strong dependence of fuel consumption on rpm; any non-gradual shift in frequency in the randomly generated rpm distribution (Figure 6) results in an exacerbated effect in fuel consumption. Interestingly, the highest frequency for the baseline was for values near 1 gallon diesel per hour, the often-assumed and reported industry average for idling fuel consumption. Ninety percent of the values lie between 0.52 and 1.20 gallons/hour.

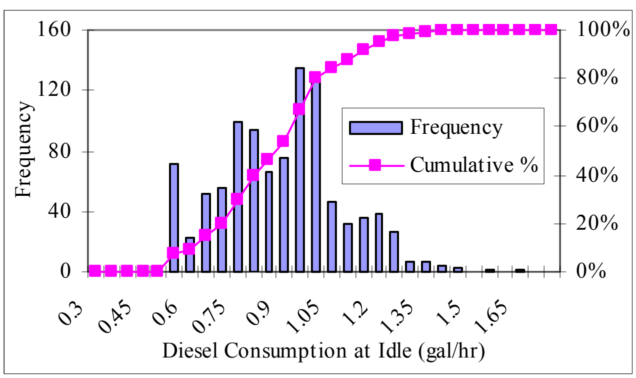


Figure 11 Distribution of Idling Fuel Consumption from ADVISOR Output

Multiplying the output of diesel consumption rate at idle (gal/hr), the daily idling duration (hr/day), and the estimated average of truck operation (day/truck-yr) for each of the 1000 runs yields the histogram of Figure 12. In estimating the percentage of fuel consumed at idle compared to the total consumed diesel (including driving), I assume 9.1 hour/day and 300 days/yr driving on the U.S. highway cycle. This equates to about 110,000 miles driven per year on the highway driving cycle, roughly in line with US Department of Commerce statistics (VIUS, 1997). Using this approximation of the driving cycle, the percent of fuel consumed at idle is estimated. Also shown in Figure 12, the typical driver could use about 5-8 percent of total fuel at idle.

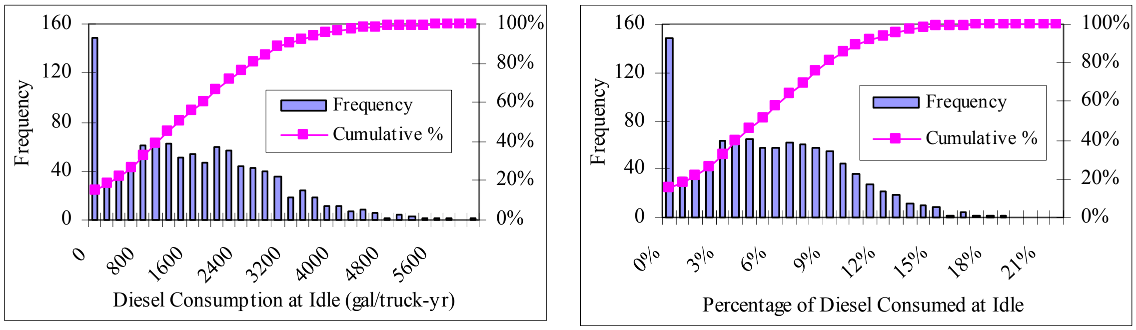


Figure 12 Distributions of Diesel Consumption at Idle, in Annual Gallons per Truck and as Percentage of Total Fuel

Note that 149 of the 1000 trials have no annual diesel consumed while at idle. These runs correspond to the roughly 15% of survey respondents who reportedly do not or did not idle their main engines during non-driving periods. Because it is unclear whether or not these are non-sleeper-cab tractors, local haul tractors, or simply voluntary non-idlers, statistical characteristics are calculated for all 1000 trials as well as for the subset of 851 trials of those drivers with non-zero idling duration, as shown in Table 7.

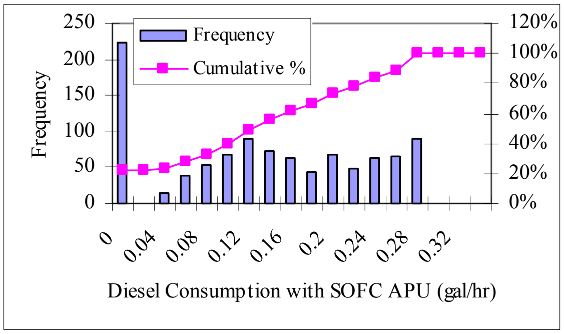
Table 7 Summary of Baseline Idling Characteristics

	Diesel fuel consumption rate at idle (gal/hr)	All trials		Excluding Non-Idlers [a]	
		Annual diesel consumption at idle (gal/yr)	Percent of total diesel consumed [b] (fuel consumed at idle/ total fuel consumed)	Annual diesel consumption at idle (gal/yr)	Percent of total diesel consumed [b] (fuel consumed at idle/ total fuel consumed)
mean	0.86	1535	5.3%	1803	6.2%
median	0.87	1396	5.0%	1682	6.0%
st. dev	0.19	1219	4.0%	1123	3.6%

[a] excludes the 14.9% of trials with 0 hours idled per day
[b] assumes 9.1 hrs/day driving, 300 days/yr on U.S. federal highway cycle

Fuel Cell APU Scenario

The outputs for the SOFC, shown in Figure 13, reveal a noticeably more flat distribution of fuel consumption values in gallons of diesel per hour yet very small variation in SOFC system efficiency. The main reason for this result is the very flat performance curve for the SOFC system (Figure 10), allowing the SOFC system to often operate within its ideal operating zone between 30 and 70 percent of the peak load of 4 kW. However, the combination of the highly transient accessory load profile (Figure 5) with the one-size-fits-all approach of choosing the 4-kW SOFC for all drivers assured enough variation among drivers and cycles outside this optimal range to make the average fuel consumption rates more variably distributed.



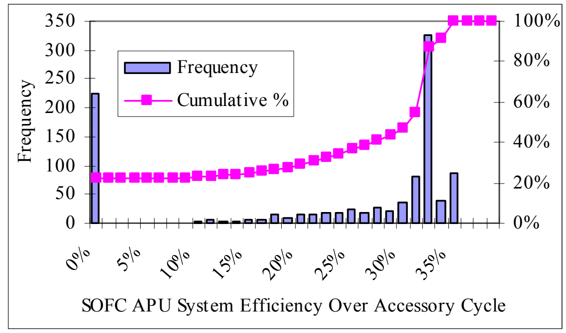


Figure 13 Distributions of FC APU Fuel Consumption and Stack Efficiency Over Transient Accessory Cycle from ADVISOR Output

Along with the 149 (14.9%) of non-idling trials, another 74 trials had near zero accessory load while still having non-zero idling durations. This 7.4% could represent those trucks that idle unavoidably (e.g., for power-take-off applications) or simply without the reasons of supplying accessory power for heating, cooling, or electricity. These 22% of trials are all assumed not to be amenable to APUs. Looking at the relevant 78% of the trials, the APU diesel consumption values reveal a mean and median of 0.16 gallons per hour. Ninety percent of the output values are bounded between 0.06 and 0.28 gal/hr. The averages and standard deviations are shown in Table 8. The average APU efficiency (defined as net fuel cell power out over the lower heating value of diesel) for the 780 trials over the varying accessory power cycle was about 30%.

Table 8 Summary of APU Characteristics Over Stationary Truck Accessory Cycle

	All trials		Excluding non-idlers [a] and unavoidable idlers [b]	
	SOFC diesel fuel consumption rate (gal/hr)	SOFC APU system efficiency over accessory cycle	SOFC diesel fuel consumption rate (gal/hr)	SOFC APU system efficiency over accessory cycle
Mean	0.13	0.23	0.16	0.29
Median	0.12	0.31	0.16	0.31
st. dev	0.09	0.13	0.07	0.05

[a] 14.9% of trials with 0 hours idled per day (as above)
[b] 7.4% of trials with greater than 0 hours idled per day but with little or no accessory load

Potential Diesel Savings

Switching from engine idling to the fuel cell APU would resulted in a mean 80% (81% median) improvement in fuel consumption during the stationary portion of the cycle for all trucks with avoidable idling. Extracted from the trial distribution shown in Figure 14, the ninety percent confidence interval for the trials was from 63% to 93% reduction in diesel use. For the approximately 15% of drivers who reportedly do not idle, of course, no gain would result. Likewise, for the 7% of drivers who reportedly idle with little or no accessory loading, no potential benefit is possible.

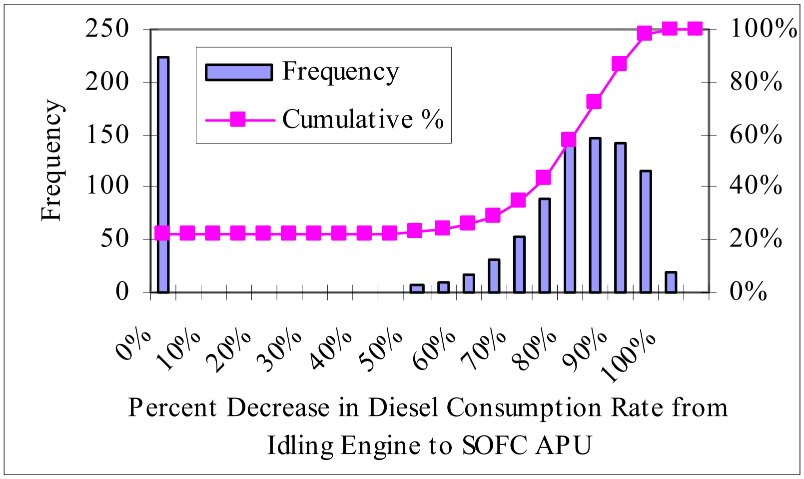


Figure 14 Distribution of Potential Fuel Consumption Reduction for SOFC APU in lieu of Idling Engine, as Percent of Idled Fuel

Subtracting total diesel consumed from the idling engine from that of the SOFC APU and then multiplying these savings by the annual idle durations for each trial (distribution shown in Figure 2), the potential diesel savings are calculated for each trial and plotted in Figure 15. For the 78% of trials with avoidable idling, the mean was 1448 gallons per year (standard deviation of 950). More importantly, it is the rightmost tail of this distribution that is the most viable, potential market for APU purchases. The 90th percentile of potential fuel savers (or 10% of trials with highest savings) annually save at least 2520 gallons of diesel, and the 95th percentile saves greater than 3020 gallons per year.

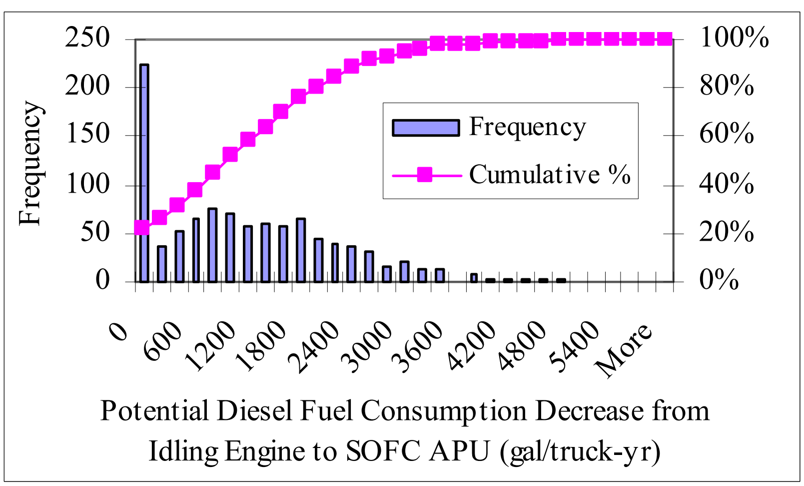


Figure 15 Distribution of Potential Fuel Consumption Reduction for SOFC APU in lieu of Idling Engine, in Annual Diesel Gallons Saved

Total Diesel Reduction

Before using the net present value economic analysis, a significant finding on total diesel reduction possibilities is possible simply from the distribution of annual idled diesel fuel savings in Figure 15. By plotting the distribution as the *cumulative* amount of diesel saved from the most frequent idlers, the extent to which market penetration of an APU system could achieve substantial benefits. From Figure 16, if the 9 percent of the heaviest idlers (≥2600 hours idled per year) had SOFC APUs, total idled diesel consumption would decrease by 32 percent. Similarly, equipping the 12 percent of idling long-haul trucks that idle the most frequently with SOFC APUs could reduce total idled fuel by about 39 percent.

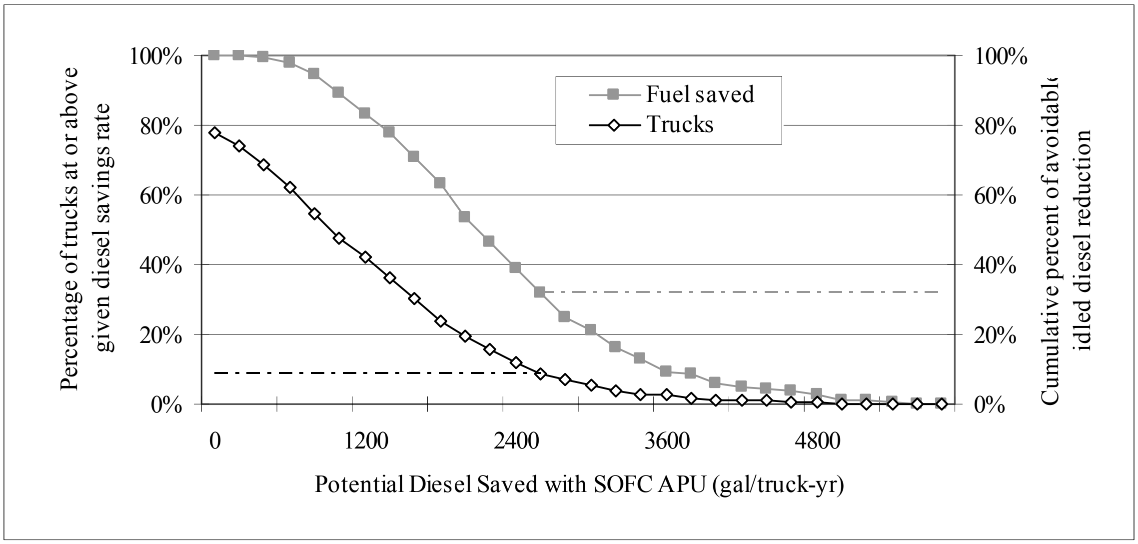


Figure 16 Estimates for Total Potential Idled Diesel Reduction Due to Percentage of Trucks Equipped with SOFC APUs, Indexed by Diesel Savings per Truck

Payback Period for SOFC APU

Applying the economic assumptions above from the "Net Present Value" section, the payback, or time at which the time-discounted benefits equal the total costs associated with the SOFC APU investment, is calculated for each of the Monte Carlo trial runs. One additional assumption is made here: the cost of SOFC APU system (including its associated auxiliary equipment) is $400 per kW of peak power, or $1,600 for the 4-kW (net) stack, based on the U.S. DOE SECA target. This brings the total cost of the SOFC APU system (stack, inverter, installation, heat pump, etc.) used here to $6,800.

In Figure 17, the distribution of trials is shown as a cumulative percent of line-haul trucks that have payback periods at or less than the given timeframe. Also on this figure (on the right side y-axis) is the corresponding number of line-haul trucks in the U.S., assuming the oft-cited VIUS number of 458,000 total line-haul trucks (2000). A payback period of 2 years is thought to be a maximum threshold parameter for line-haul truck investment (Brodrick et al, 2001). As shown in this figure, this analysis suggests that about 6 to 14 percent, based on the low to high estimates of economic factors, of line-haul truck population are likely to have payback periods less than or equal to 2 years for the purchase of a SOFC APU. Taking the middle estimate, 9 percent, or about 40,000 total trucks, out of the line-haul truck market would have a 2-year payback period. A smaller segment of the truck population, about 2.5 to 5 percent, are likely to have payback periods less than or equal to 1.5 years.

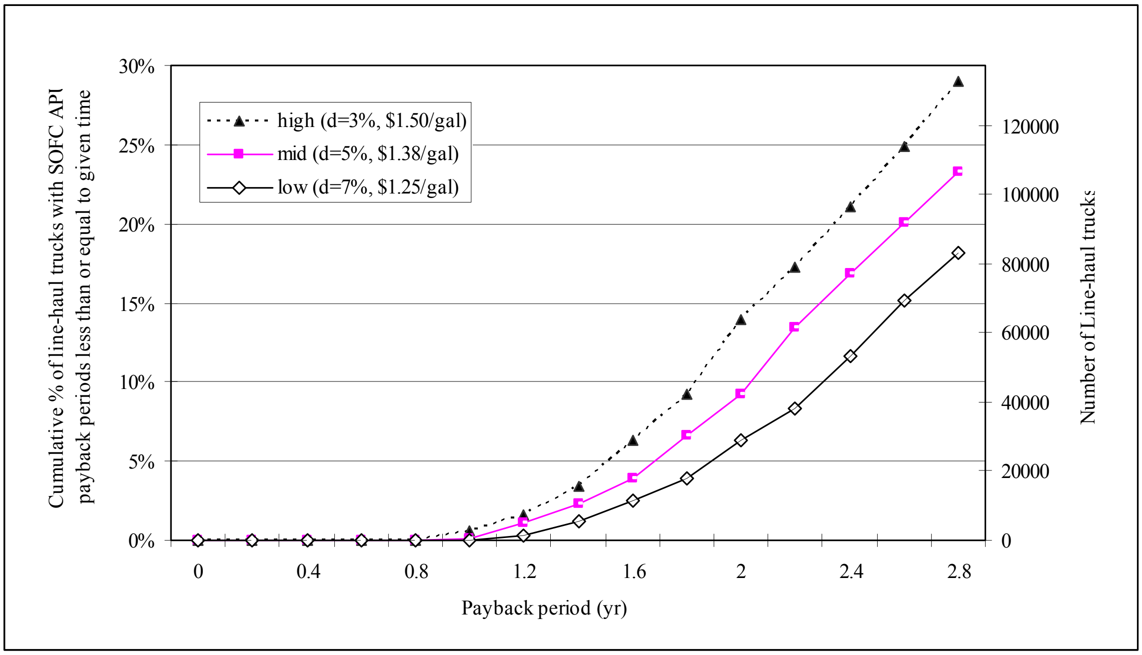


Figure 17 Estimates for Cumulative Percent (and Number) of Line-Haul Trucks with Given Payback Period

Slightly altering the results of Figure 16 to be indexed to payback period, instead of diesel savings per truck, yields Figure 18. The middle estimates for economic factors are assumed. As was commented in the section above, targeting a relatively small amount of trucks (9%) that idle most frequently for SOFC APU use could result in a relatively large (32%) reduction in the total idled diesel. Here, we see that this amount of market penetration would be targeted at those trucks with approximately 2-year (or less) payback periods.

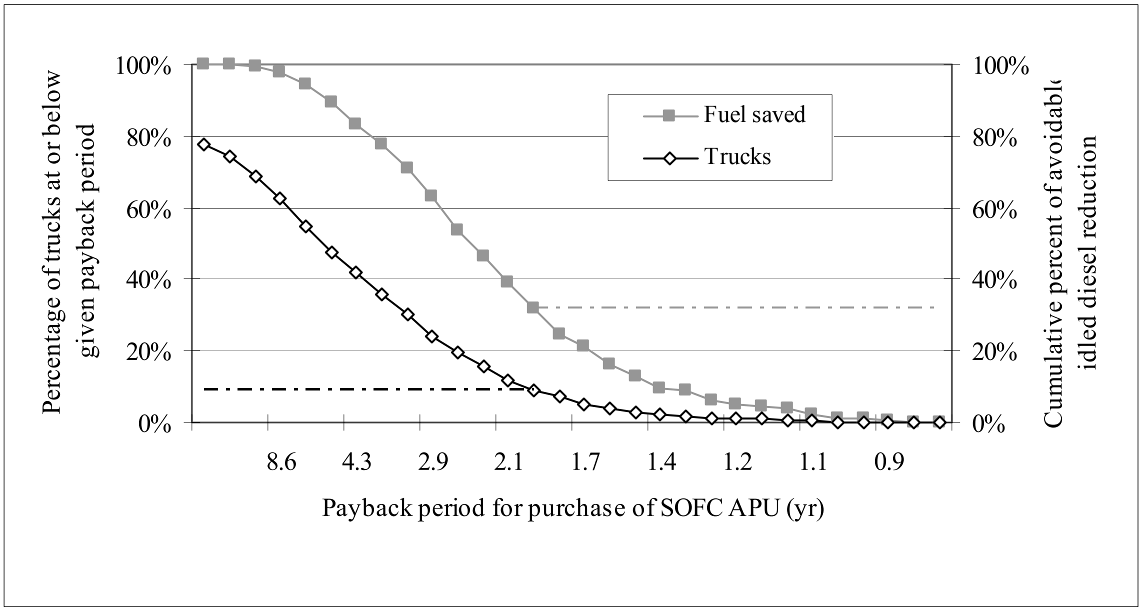


Figure 18 Estimates for Total Potential Idled Diesel Reduction Due to Percentage of Trucks Equipped with SOFC APUs, Indexed by Payback Period

SOFC Cost

In Figure 19, instead of assuming a SOFC cost of $400/kW and calculating the payback period of the investment for each truck, the payback period is held constant at 2 years while varying SOFC cost from 200-1200 $/kW. Doing so, insights are gained with respect to the U.S. DOE SECA-set SOFC target and its potential for enabling a market-feasible product for hundreds of thousands of SOFC units. Again assuming there are 458,000 total line-haul trucks, the total number of tractor-trailers with 2-yr payback is estimated. The figure suggests that if the U.S. DOE's target of $400/kW was obtained, SOFC APUs could be an economically viable product for as many as 26,000 to 60,000 truck in the field.

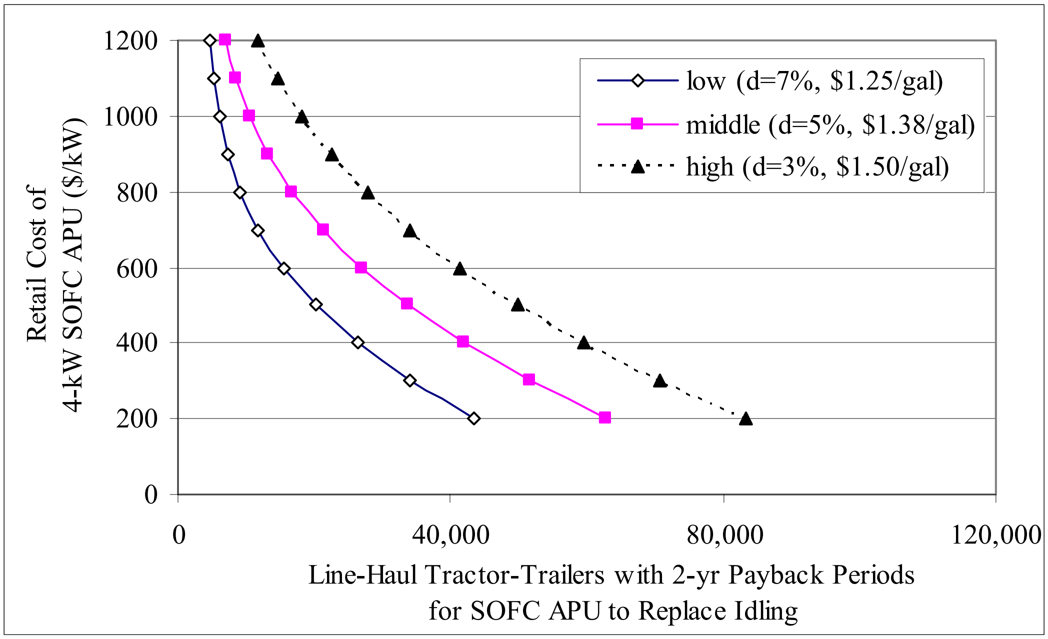


Figure 19 Estimation of Number of Line-Haul Trucks With Two-Year (or less) Payback Periods, as Function of Fuel Cell APU Cost With Varying Economic Assumptions

CONCLUSIONS

This research work, characterizing existing data on truck driver behavior, utilizing a modified ADVISOR vehicle platform, applying the probabilistic Monte Carlo method, and ultimately using net present value analysis, allows for a number of key conclusions.

- The tools employed here each offered key advantages in analyzing issues in fuel cell APU integration with line-haul trucks
  - ADVISOR vehicle model – allowed for variations in crucial system parameters like engine speed (rpm) and accessory load to estimate fuel consumption; required a formulation of a feasible control strategy to govern the interaction between the APU and the existing vehicle electric system.
  - Monte Carlo Simulation – incorporated uncertainty in key variables (rpm, accessory loads, and idling duration per truck) while also providing resolution into the broad distribution of varying truck behavior
  - Net present value analysis – utilizes the Monte Carlo-generated distributions of ADVISOR runs to assess the future market for fuel cell APUs in the line-haul truck market.
- Uncertainties in the vehicle and engine data exist. Fuel and emissions engine maps at low torque and rpm would eliminate the need for extrapolating into, and later calibrating in, these regions. More fuel, and especially emissions, testing of tractors with variation of engine idle speed and accessory power required at idle for different model year tractors would allow for a better picture of how fuel and emissions truly vary in the fleet.

- Uncertainties in driver behavior characteristics exist. Variables and their distributions here are estimated primarily based on small surveys in northern California. The extent to which the analyses here are valid nationwide is not clear, and a well-crafted nationwide survey with input from individual drivers and from fleet managers could minimize uncertainties of this report.
- Using several criteria, the optimal size of a fuel cell was determined to be 4-kW (net) rated peak power. This decision consisted of estimation of the average power required for sleeper cabs, an estimation of the demands for harsher climates, and an attempt to sparingly utilize the battery to peak-shave. In particular, a more comprehensive understanding of driver accessories from survey data and a more thorough look at battery discharge could test this choice for fuel cell rated power.
- The oft-reported industry average of 1 gallon per hour diesel consumption at idle appears to be approximately accurate. With a median of 0.87 gallons per hour, ninety percent of values were bounded between 0.52 and 1.20 gallons per hour. This value is much more sensitive to engine speed than accessory loading.
- Annual idling diesel consumption varies widely. Using the Monte Carlo simulation method, the following estimations are made-
    - As many as 15% of tractor-trailers on highways reportedly does not idle or do not idle enough to report. These likely include non-line-haul, more local trucks, perhaps without sleeper cabs.
    - About 7% of tractor-trailers idle unavoidably or do not idle for the reason of supplying "hotel load" accessory power.
    - The mean diesel fuel consumption at idle for all tractor-trailers was found to be 1500 gallons per year. Excluding those presumed to be local-haul tractors without sleeper cabs and unavoidable idlers, the mean is 1800 gallons of diesel per year. As many as 10 percent of trucks idle more than 3200 gallons of diesel per year.
- A 4-kW (net) solid oxide fuel cell (SOFC) APU operating over varying sleeper cab accessory power cycles averages 31% efficiency (LHV to net fuel cell power), consumes on average 0.16 gal diesel/hr, and reduces diesel consumption 81.5% compared to idling cycle for sleeper cabs while providing the same in-cab services (appliances, heating, cooling, etc.).
- Utilizing the SOFC to replace idling is a viable option for a sizable fraction of line-haul trucks.
    - With the operation of a SOFC APU to replace idling, 10 percent of trucks could save over 2500 gallons of diesel per year, and 5 percent could save over 3000 gallons per year.
    - A relatively small introduction of SOFC APUs into trucks in the fleet result in substantial reductions in the total amount of idled diesel reduced. For example, equipping the 9 percent of trucks that idle away over 2600 gallons per year results in a 32 percent reduction in line-haul truck idled diesel.
    - If SOFC research and development targets ($400/kW by 2011 timeframe) are achieved, sizable percentages of the line-haul trucking population (approximately 6 to 14 percent) will have payback periods less than or equal

to 2 years. This equates to a potential market for SOFC APUs from 30,000 to 60,000 units, without the consideration of policy incentives.

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APPENDIX A: 2002 pilot survey

2002 UC-Davis Truck Survey

Answer the following questions based on the vehicle that you are now driving. Estimate if necessary.

Date — July ________, 2002

1. Over the last 24 hours….
   a. How many **miles** did you drive? ______ miles
   b. How many **hours** were you **driving**? ______ hours
   c. How many **hours** were you **resting**? ______ hours
   ("resting" includes time vehicle is not driving, but should not include time spent during refuelings, loading/unloading, etc.)

2. Of the time you **spent resting in the past 24 hours**, about what percentage of the time was the **engine running ("idling")**? ______ %

3. Of the time you **spent resting**, about how much of this time do you run each of the following **electrical accessories**?

Do you have a ….	*How often do you use it during your rest period?*
☐ Stereo (not incl. walkman, battery operated stereo)………………	**% / hrs.**
☐ CB radio………………………………………………………	**% / hrs.**
☐ Television……………………………………………………	**% / hrs.**
☐ Dash-readout/company computer……………………………	**% / hrs.**
☐ Personal computer……………………………………………	**% / hrs.**
☐ Microwave……………………………………………………	**% / hrs.**
☐ Refrigerator/ electric cooler…………………………………	**% / hrs.**
☐ Overhead lamp (built-in DC)…………………………………	**% / hrs.**
☐ Light bulb (AC)………………………………………………	**% / hrs.**
☐ Coffee maker…………………………………………………	**% / hrs.**
☐ Other, please specify ______ ………………	**% / hrs.**

4. Which of the following have you used to **cool the cabin when the vehicle was at rest** in the last 24 hours, and for how long?

Do you have a ….	*How often do you use it during your rest period?*
☐ Air conditioner powered by engine	**% / hrs.**
☐ Electric air conditioner	**% / hrs.**
☐ Other, please specify ______	**% / hrs.**
☐ I never cool the cabin	**% / hrs.**

5. Are there any **other devices that require power while the engine is not running** at any other time of year?
   (for example, power take-off, engine block heater, cabin heater, fuel heater, etc.)
   ☐ Yes ☐ No
   If so, please list: ______________________

APPENDIX B: ADVISOR Electrical System Features

The original 2002 ADVISOR model contains many interchangeable vehicle components with different specifications, performance and efficiency variables, subsystem configurations, and emissions characteristics. Data from some of the most important modules for our modeling effort (the alternator, air conditioner, and cooling fan) are extracted from ADVISOR files and shown here.

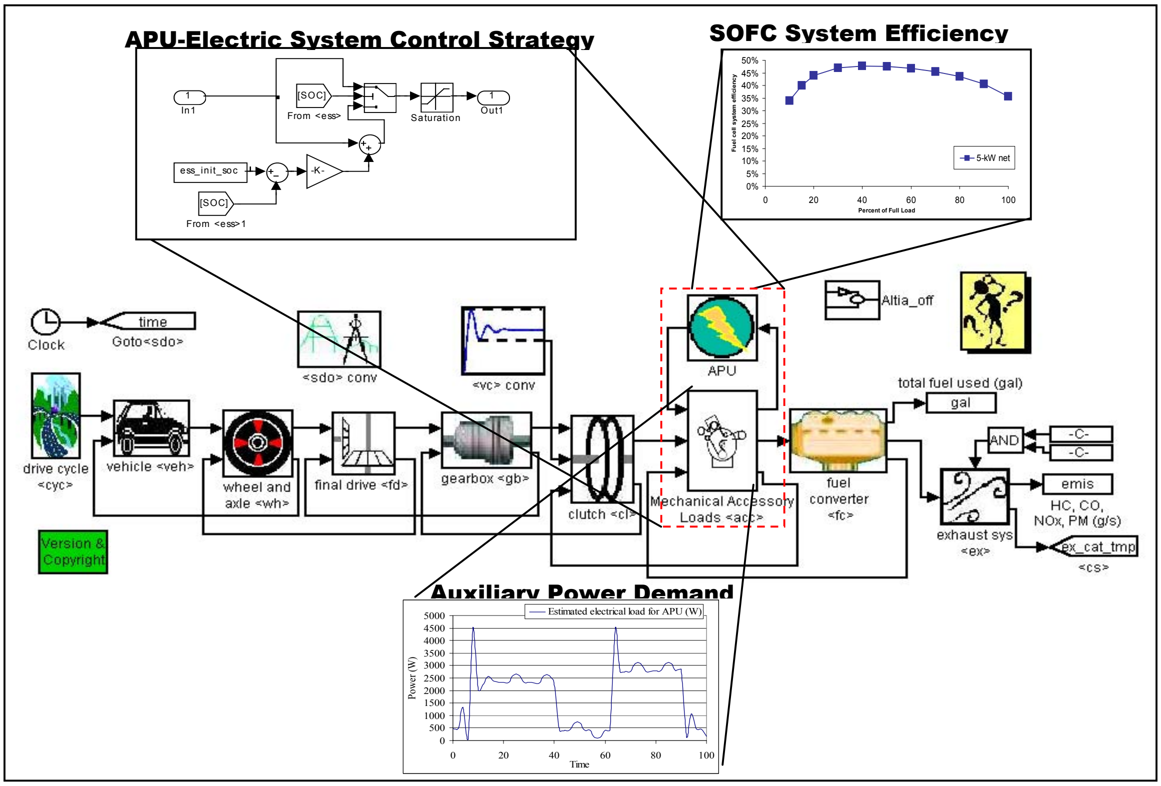


FIGURE B1 ADVISOR Model with Addition of APU Module Interacting with Conventional Systems

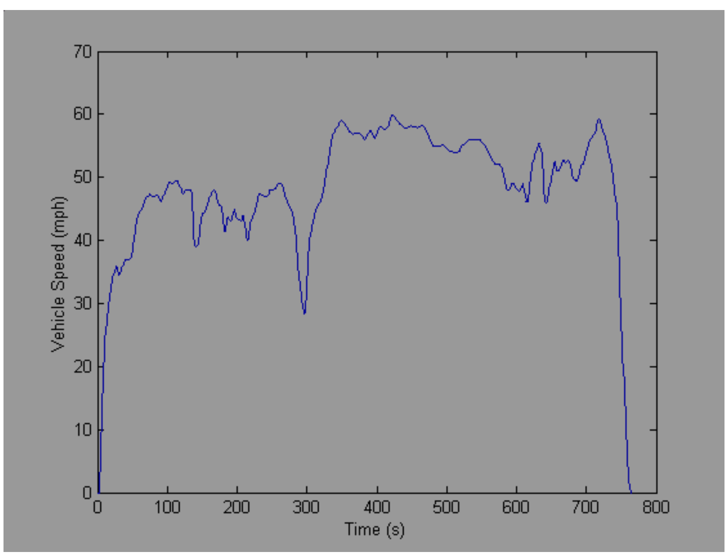


FIGURE B2 U.S. Highway Federal Emissions Testing Cycle (from ADVISOR)

TABLE B1 ADVISOR Alternator (14 V) Characteristics

Maximum delivered current (A)	Maximum delivered power (W)	Engine speed (rpm)	Shaft power (kW) drawn for given fraction of maximum alternator power load				
			0	0.25	0.5	0.75	1
0	0	0	0	0	0	0	0
0	0	333	0	0	0	0	0
80	1120	667	0	0.46665	0.8	1.4	1.86665
130	1820	1000	0	0.75835	1.31885	2.1	3.03335
145	2030	1333	0	0.84585	1.471	2.3423	3.38335
150	2100	1667	0	0.84675	1.6154	2.5403	3.6207
155	2170	2000	0	0.90415	1.66925	2.6681	3.807
158	2212	2333	0	0.95345	1.84335	2.86035	4.1736
160	2240	2667	0	1.03705	1.8983	2.94735	4.3077

TABLE B2 ADVISOR Air Conditioner Characteristics

Engine speed (rpm)	Shaft power (W) for air conditioning
0	0
500	1000
1000	2417
1500	3833
2000	5250
2500	6666

TABLE B3 ADVISOR Engine Cooling Fan Characteristics

Engine speed (rpm)	Shaft power (W) required by engine cooling fan
0	0
500	595
1000	2148
1500	7500
2000	16653
2500	29606

APPENDIX C: Idling Emissions Data

Most available data involves default engine settings with all nonessential accessories disengaged and different testing procedures and model years are involved. Because of these limitations, it may be slightly misleading to simply average these values. However, some attempt is made here at making a "weighted average" of the existing data. This "weighting" process is not statistically rigorous, for it compiles testing of different trucks at different facilities by different research groups under slightly different conditions. Emissions testing of two trucks at the same facility (with the same mode) was given equal weight to testing the same truck in two different modes (at two different facilities). Using this method allowed the inclusion of all available data and was deemed appropriate under the circumstances for estimates. Because the data is based primarily on engine testing without "hotel load" accessories and at low engine speeds, estimates on idling emissions will be conservatively low. The more comprehensive EPA study (Lim, 2002), which was not used in the weighting process, confirms as much in Figure 1 for NO_x and CO_2 emissions.

TABLE C1 Idling Emissions (g/hr) from McCormick et al, 2000

Emissions	Engine	THC	CO	NO x	PM
Truck 764	DDC S60, 12.7 L, 450 hp	7.86	67.14	62.70	1.08
Truck 779	DDC S60, 12.7 L, 450 hp	6.06	47.40	76.80	1.92
Truck 780	DDC S60, 12.7 L, 450 hp	3.60	43.56	85.74	1.68
Truck 778	DDC S60, 12.7 L, 450 hp	12.54	99.36	83.10	1.38
Truck 804	DDC S60, 12.7 L, 450 hp	8.40	67.38	93.06	2.16
Truck 803	DDC S60, 12.7 L, 450 hp	6.18	49.68	81.66	1.44
Truck 884	DDC S60, 12.7 L, 360 hp	10.26	109.38	107.04	1.32
Truck 921	DDC S60, 11.1 L, 330 hp	6.90	53.46	115.14	1.02
Truck 885	DDC S60, 12.7 L, 360 hp	6.54	128.28	91.44	1.08
Truck 911	DDC S60, 11.1 L, 365 hp	6.18	62.10	102.30	1.14
Average		7.45	72.77	89.90	1.42
Stdev		2.49	29.26	15.42	0.39

TABLE C2 Idling Emissions from Automotive Testing Laboratories (Traver, 2002)

		Emissions (g/hr)							
		THC		PM		CO		NO x	
Lab	Tests	Avg.	std. dev.	Avg.	std. dev.	Avg.	std. dev.	Avg.	std. dev.
A	2	13.86	3.24	2.28	0.42	15	8.4	81.6	0.12
B	3	9.42	0.54	2.28	0.12	18	0.6	82.8	0.78
D	3	9.36	0.42	1.2	0.24	69.6	1.2	88.8	19.5
E	3	7.8	5.46	2.58	0.3	26.4	0.6	131.4	5.58
F	9	7.14	1.62	1.38	0.3	12.6	1.8	75.6	3.9

TABLE C3 Idling Emissions from WVURC, 2002

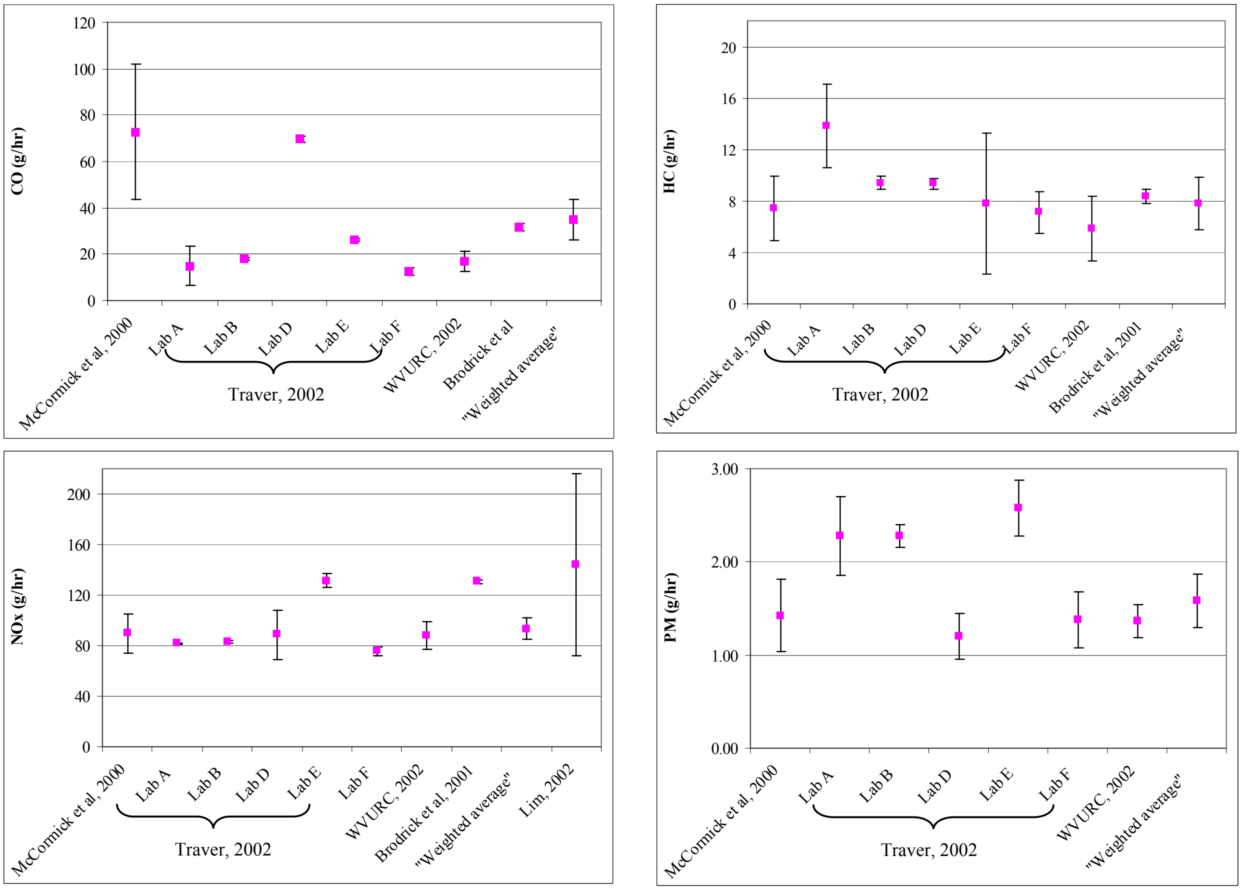
Sequence number	Emissions (g/hr)			
	CO	NO x	HC	PM
3668-01	16.98	73.32	10.45	1.362
3669-01	20.58	93.96	2.39	1.464

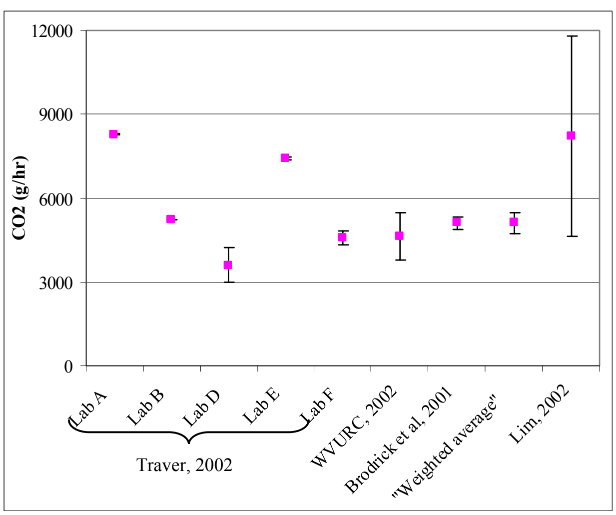
3674-01	22.32	77.94	7.50	1.386
3674-05	18.66	79.32	6.90	1.476
3674-09	18.72	80.64	6.30	1.176
3680-01	15.48	103.32	4.25	1.038
3680-05	12.00	97.26	4.88	1.608
3680-09	9.60	97.08	3.97	1.362
Average	16.79	87.86	5.83	1.359
St. dev.	4.29	11.24	2.51	0.179

TABLE C4 Idling Emissions from Brodrick et al, 2002

Mode	Precondition	AC on	Engine speed (rpm)	Tests		HC	CO	NO x
1	55 mph cruise	no	600	4	g/hr	1.80	14.60	103.68
					st. dev	0.33	2.34	14.18
2	city	no	600	7	g/hr	2.93	15.94	105.22
					st. dev	1.03	1.98	5.36
3	urban	yes	600	2	g/hr	1.44	15.33	166.00
					st. dev	0.20	0.58	5.00
4		yes	1050	1	g/hr	NA	86.20	253.85
					st. dev	-	-	-
5		yes	1050	1	g/hr	86.40	190.00	225.00
					st. dev	-	-	-

FIGURE C1 Comparison of Idling Emissions Test Data





	Emission rates (grams/hr)	
Emission	**"Weighted Average"**	**Lim, 2002 averages**
NOx	93.2	144
PM	1.6	-
HC	7.8	-
CO	35.0	-
CO2	5119	8224

APPENDIX D Solid Oxide Fuel Cell (SOFC) Characteristics and Assumptions

Two types of fuel cells, highly efficient electrochemical power plants, are under consideration for this APU application. However, both types have their share of disadvantages that are yet to be worked out in research and development efforts. Direct hydrogen proton electrolyte membrane (PEM) fuel cells may be easier to operate and are more compact currently and give higher efficiencies, but without an existing infrastructure making such systems marketable widely could be difficult. Therefore, largely, due to their robustness in operating on available hydrocarbon fuels, the planar solid oxide fuel cell (SOFC) with a partial oxidation reformer is chosen for this assessment. The SOFC system can utilize carbon monoxide as a fuel, opposed to the gas's role as a contaminant in PEM systems, and has a relatively high tolerance toward sulfur (Appleby, 1989). The potential drawbacks of SOFCs (i.e., high temperature and long start-up time) are downplayed in this application because of the smaller APU size and the ability of truck drivers to know roughly when they will rest. The case for SOFCs for transportation APU applications has been made elsewhere (Zizelman, et al, 2002; Lutsey et al, 2003). The following characteristics describe the TIAX modeled system for a SOFC system (Stratanova, 2002):

- System efficiency is defined by fuel feed rate into fuel cell system and by total power delivered to the power electronics
- Conversion efficiency of the power electronics are not included in this calculation; However, a 90% power electronics conversion efficiency was assigned to power for the parasitics (powered by AC)
- Assumed 90.5% fuel utilization (independent of part load) and 0.7V cell voltage at 100% power
- Reformer operates at equilibrium and reformer efficiency is not a function of turndown (part load)
- System package heat loss supplemented by additional fuel to the reformer; system heat loss is assumed independent of system part load
- Controls, actuators system package blower are a constant load of 69W
- At 100% full load; total parasitics are 0.88-kW out of net of 5-kW; Shell (system) heat loss is 0.26-kW
- Process air blower and other parasitics are proportional to fuel cell load and are calculated through a stack energy balance
- Change of pressure of system with load is assumed to have negligible impact on stack efficiency and reformer efficiency

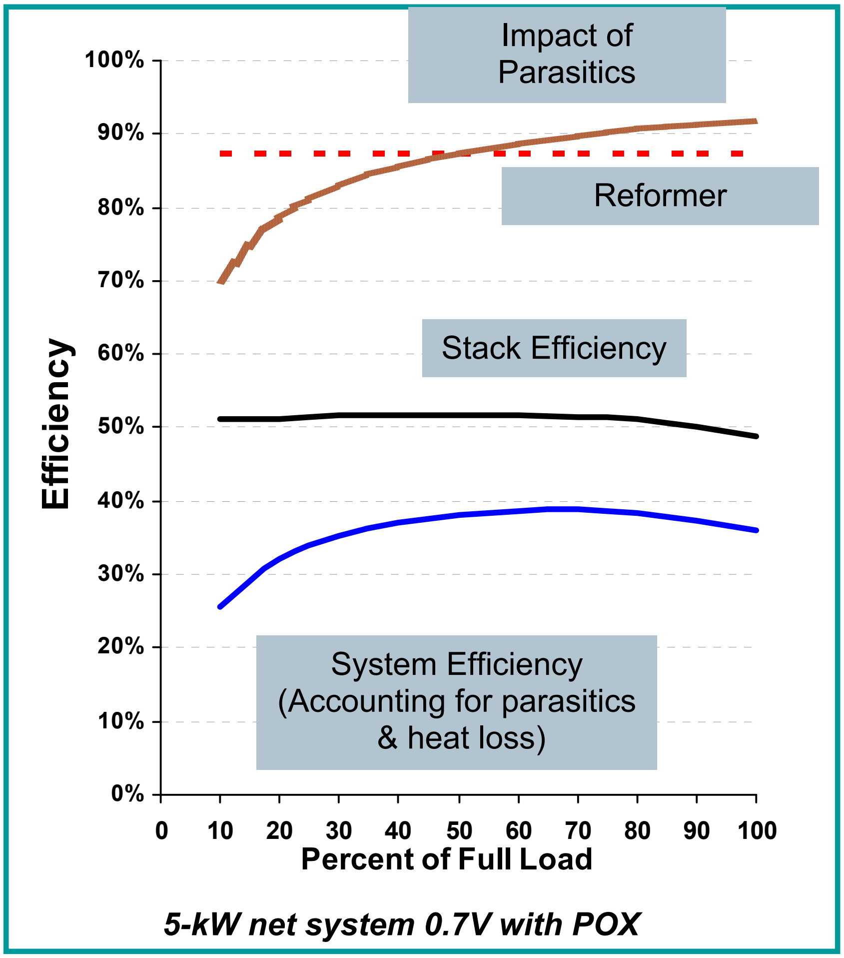


FIGURE D1 SOFC Efficiency for 5-kW Net System with POx Reformer (Stratanova, 2002)

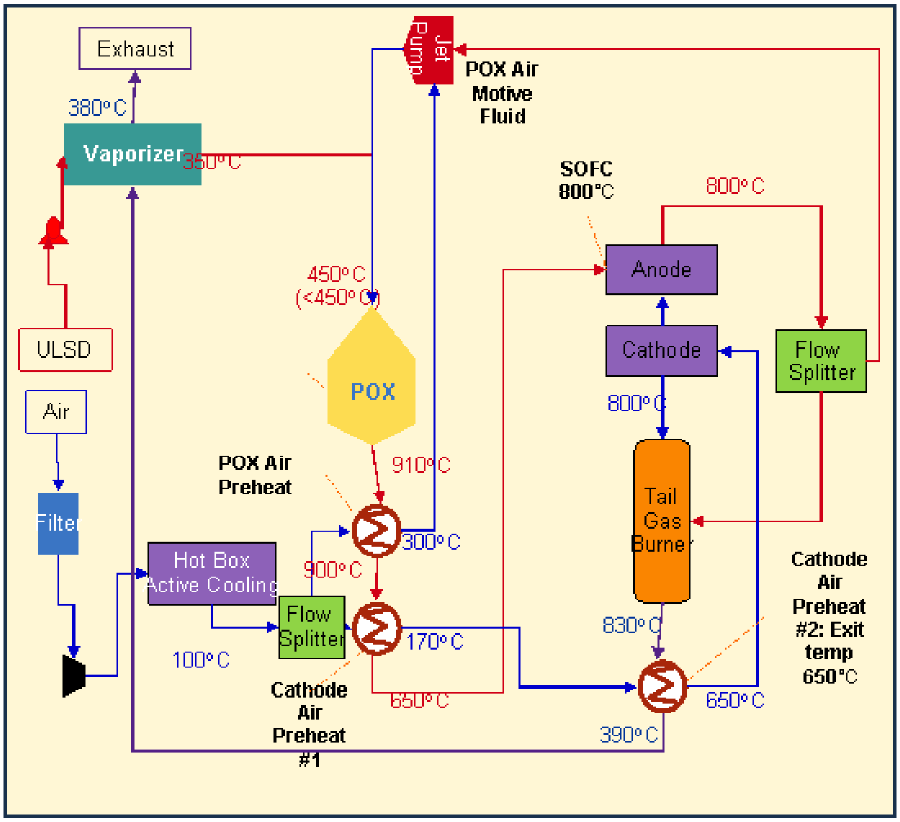


FIGURE D2 Systems Schematic for TIAX SOFC Model (Stratanova, 2002)

APPENDIX E Diesel Fuel Price

FIGURE E1 Diesel Retail Price (EIA, 2003)

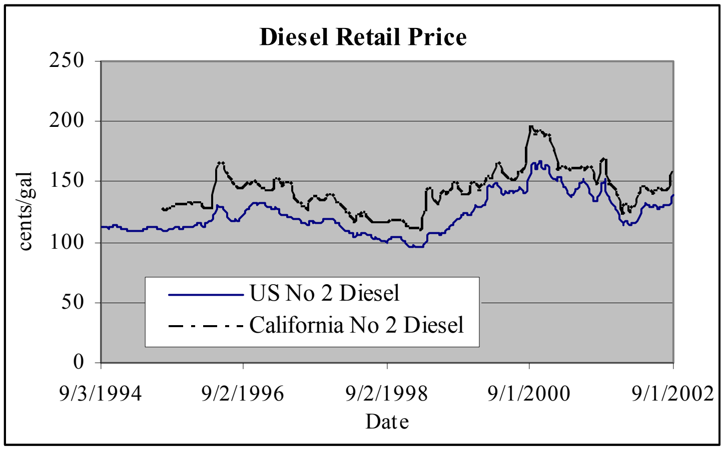


TABLE E1 Diesel Retail Sales Prices (EIA, 2003)

Dates		Average diesel price over given dates ($/gal)	
From	To	U.S. No. 2 Diesel	CA No. 2 Diesel
4/26/1999	4/17/2000	1.25	1.46
4/24/2000	4/16/2001	1.50	1.69
4/23/2001	4/15/2002	1.32	1.46
4/22/2002	4/14/2003	1.44	1.56
4/26/1999	4/14/2003	1.38	1.54