Modeling of Line-Haul Truck Auxiliary Power Units in ADVISOR 2002

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ABSTRACT

The idling of heavy-duty trucks has attracted growing concern in recent years, largely because of the associated waste of fuel, as well as the production of emissions in areas already facing challenges in maintaining and improving air quality. The use of an Auxiliary Power Unit, whether powered by a small diesel engine or a fuel cell, is thought to be one of the most promising and viable solutions to this problem. In an effort to quantify the gains in fuel economy and emissions associated with implementing such a system, a Pony Pack engine and a Nexa fuel stack were tested to map out their steady-state fuel consumption and emissions. ADVISOR's default model for a class 8 line-haul truck was then modified to include an APU module, which included several steps: modifying the existing propulsion engine and fuel cell subroutines for use in an APU application, creating input data files based on the collected experimental data, and creating a new duty cycle that incorporated a section of idling with an accessory load profile created at ITS.

After modeling the APU's performance over their individual accessory profiles within ADVISOR, two Nexa stacks connected in series, the Pony Pack, and the baseline case of engine idling at 850 RPM had average thermal efficiencies of 38.3 %, 19.5%, and 8.3%, respectively. For an average truck-driver, idling 6 hours per day, replacing idling with a Pony Pack would reduce total diesel fuel consumption by 5.9%, CO by 17%, and NO_x by 9.1%; replacing idling with two Nexa units would reduce total fuel consumption by 7.3% (diesel equivalent), CO by 37.9%, NO_x by 9.4%, and PM by 6.2%. Finally, for a trucker idling 6 hours a day at 1050 RPM, the Pony Pack would have an estimated payback period of 2.3 years, compared to 1.9 years for the PEM APU.

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ABBREVIATIONS AND ACRONYMNS

A/C: Air Conditioning
ADVISOR: ADvanced VehIcle SimulatOR, created by NREL
ANL: Argonne National Laboratory
APU: Alternative Power Unit
BSFC: Brake Specific Fuel Consumption
CI: Compression Ignition
CLD: Chemiluminescent Detector
CO: Carbon Monoxide
CO_2: Carbon Dioxide
DOE: Department of Energy
G/BHP·HR: Grams per Brake Horsepower Hour
GUI: Graphical User Interface
EPA: Environmental Protection Agency
FC: Fuel Cell
FTP: Federal Test Procedure
HWFET: Highway Fuel Economy Test
IFC: International Fuel Cells, renamed to UTC Fuel Cells
ITS: Institute of Transportation Studies (UC Davis campus)
LFL: Lower Flammability Limit
LHV: Lower Heating Value
kW: Kilowatt
MPH: Miles per Hour
NDIR: Non-dispersive Infrared
NO_x: Oxides of Nitrogen
NREL: National Renewable Energy Laboratory
PEM: Proton Exchange Membrane
PM: Particulate Matter (Soot)
PPM: Parts per Million
PNGV: Partnership for a New Generation of Vehicles
PSAT: Powertrain Systems Analysis Toolkit, created by ANL
PSI: Pounds per Square Inch
PSIG: Gauge Pounds per Square Inch
RPM: Revolutions per Minute
SLM: Volumetric Flow Rate, Standard Liters per Minute
SOC: State of Charge
SOFC: Solid Oxide Fuel Cell
UC Davis: University of California, Davis
VI: Voltage (V) versus Current (I) curve; used to characterize fuel cell performance

1.0 INTRODUCTION

1.1 Statement of the Problem

In order to examine the potential advantages and disadvantages of auxiliary power units, one must first understand engine idling. Line-haul Class 8 trucks are often required to travel hundreds of miles, and as a result, they are equipped to allow a driver to live and sleep in the cab of the truck. Many appliances can now be found within these cabs, ranging from TV's and VCR's to microwaves and toasters, and when combined with cabin heating and cooling, these accessories can create a substantial load that requires the engine to idle while the vehicle is at rest. Intuitively, this situation is less than optimal, as a powertrain designed to output 300 kW or more can be running to produce a few kilowatts for hours at a time. The result is that the engine efficiency ranges between 3 and 11% at idle, compared to the 30-45% that can be seen of diesel engines operating at full load. [4]

Although the effect of idling may first seem to have a small effect on the total fuel consumption of a line-haul truck, on an aggregate level, it is estimated that engine idling consumes between 838 million and 2 billion gallons of diesel fuel annually. [21][28] To give these values some perspective, the total fuel consumption of commercial Class 7-8 trucks was 18.5 billion gallons in 1997, corresponding to 59% of all diesel fuel consumed in the U.S. that year. [26] From the higher of these estimates, one can see that any attempt to mitigate this 10% fuel penalty could have a large effect on our total fuel consumption as a nation, an issue that has taken on new significance given the international climate of recent years.

The concern over diesel engine emissions has also increased sharply over the last decade. Although a truck may only emit about 8-15% of its on-road emissions levels while idling, on a grams per gallon of fuel consumed basis, an idling truck will actually emit twice as much oxides of nitrogen (NO_x) as it would during cruise at 55mph [4]; the reason for this being that the engine is operating in a relatively "dirty" range as well as inefficient. This fact combined with the long duration of engine idling of an average trucker leads to an estimated 59,000 tons of NO_x and 97,000 tons of carbon monoxide (CO) emitted into the atmosphere solely at idle. Not surprisingly, the magnitude of these emissions has drawn increased attention from regulatory agencies across the country.

New EPA standards regulating acceptable emissions levels will be phased in by 2004 and 2007, with the end result of reducing 1998 NO_x levels from 4.0 to 0.2 g/bhp·hr and particulate matter (PM) levels 0.05 to 0.01 g/bhp·hr. [9] Since these regulations are based on *engine* dynamometer testing over the FTP drive cycle, they would not be affected directly by any changes in the vehicle architecture to reduce engine idling. However, this legislation is a small part of a new larger-scale focus on reducing diesel emissions. For example, several cities across the country, most notably the eight-county area Houston in 2001, have enacted bans on heavy-duty truck idling for longer than five minutes in an effort to mitigate serious air quality problems. [12]

There is some debate as to the most attractive solution to the problem of engine idling. Truck stop electrification has been proposed as a near-term viable solution. This idea has its merits, namely that the existing electrical infrastructure can be utilized, the amount of power that each individual truck can consume is virtually unlimited, and the much lower operating cost of electricity relative to inefficient diesel consumption could pay for the startup costs in a relatively short period. Yet a more thorough investigation reveals that these advantages come with several limitations. First, even though tank to wheel petroleum usage and emissions production is eliminated, these gains may be greatly reduced when considering the well to tank fuel usage and emissions that occur at the generating facility. Incidentally, because coal makes up a large part of our national energy mix, any supplementing of vehicular fuel consumption with that of electricity is generally accompanied with an increase in carbon dioxide (CO_2) emissions, the most prominent of green house gases. Second, existing truck-stop parking capacity would only accommodate a small fraction of all line-haul trucks that are currently idling in the field. [21] Finally, truck drivers are reluctant to give up their flexibility in determining overnight locations that is often required by such a mobile and erratic occupation.

An auxiliary power unit (from now on condensed to APU) has the advantage of replacing operation of the propulsion engine with that of a smaller unit geared towards producing the lower at-rest power levels, while allowing an individual truck to remain a self-supporting unit. An APU can be either a scaled down diesel engine, such as those produced by Pony Pack, Inc., or a fuel cell electric generator. Pony Packs are attractive because of their relative low start up cost ($5600 for a 10hp unit [19]) and their ability to run off the main diesel fuel supply.

The two types of fuel cells that are primarily being considered for this application are PEM and SOFC stacks. Because of their projected use in the majority vehicle applications, PEM stacks are well-developed and are much closer to commercial availability. Their low operating temperature (~80ºC) suits an APU application well, but their dependence on hydrogen as a fuel necessitates separate gaseous fuel storage and possibly a reforming system if a fuel such as propane is used, adding to the volume and weight of the system. SOFC units have been demonstrated to be able to run directly on diesel fuel, but their high operating temperatures (800-1000ºC) raises certain issues regarding thermal management and efficiency losses during startup. Moreover, SOFC technology is at a much earlier stage of development for mobile applications, with assessments of its benefits being limited to unempirically validated simulations. [16]

1.2 Objectives

The main goal of this research is to build an empirically based model within ADVISOR's framework to predict fuel consumption and emissions benefits of various APU systems relative to the baseline case of engine idle. To accomplish this though, several steps had to be taken along the way.

First, the performance of the chosen fuel cell, Ballard's NEXA 1.5kW stack, was characterized. This involved varying the load across the operating range of the stack to obtain a relationship between the system voltage and the outputted current, known as a VI curve, which can then be converted into a relationship between efficiency and power. Measuring this data at different temperature conditions and at the gross and net levels gives valuable insight into cold start effects and the effect of the fuel cell accessories on system efficiency. As somewhat of a side note, the manufacturer's control strategies for water and thermal management and overall system performance are commented on.

Second, the efficiency and emissions of the Pony Pack unit were mapped out. It should be noted that the vast majority of this work, including experimental setup and data collection, was performed by fellow graduate student Ryan Hammond; his work will only be briefly summarized to give some background to the data inputted for the genset unit in the modeling section of the report.

Third, the ADVISOR model for a heavy-duty truck was modified to incorporate an APU unit. This process can be broken down into three areas: interfacing with ADVISOR's existing graphical user interface (GUI), modifying the Simulink code to include a modular APU unit, and creating data input files based on the data collected in the first and second steps described above.

The modeled performance of each of the two APU units is compared to the baseline case of engine idling. Several parameters, such as percent of idling time and engine RPM, were varied as part of a sensitivity analysis. These results are expanded to an aggregate scale to predict, with some uncertainty, the effect such a system would have on the annual fuel consumption and emissions of an average truck. Finally, the payback periods of the Pony Pack and the PEM APU are predicted based on the cost savings associated with reduced fuel consumption and estimates of the capital cost for the two devices.

2.0 LITERATURE REVIEW

At the time of model development, little to no work had been done involving the creation of a model for an APU system. Consequently, the research presented here falls into two categories: 1) the overall software package ADVISOR and its success in other applications and 2) the efforts of various organizations to build a physical APU system and demonstrate its feasibility.

2.1 ADVISOR Modeling

ADVISOR was first created at the National Renewable Energy Laboratory (NREL) in 1994 as an offshoot of DOE's Partnership for a New Generation of Vehicles (PNGV) program. Several specific goals necessitated an entirely new model creation, namely that it be fast, user-friendly, flexible, and publicly available. [31] Accordingly, the Matlab/Simulink programming environment was chosen because of its wide use in many technical fields, its self-contained GUI capability, and the extreme ease of use and transparency of Simulink block diagrams. Attempting to keep computation time to a minimum, ADVISOR utilizes a combined backward/forward facing approach. The term backward-facing means that at every time step in the simulation, the computation begins by calculating the requested road load and then passes a requested torque and speed through the wheels and each drivetrain component, resulting in the engine model outputting fuel consumption and emissions. However, after this calculation, a forward-facing loop executes that forces each component's performance limit on its downstream (wheel-side) neighbor, providing for increased accuracy. The implementation of this method can be seen in

Figure **1** on the following page.

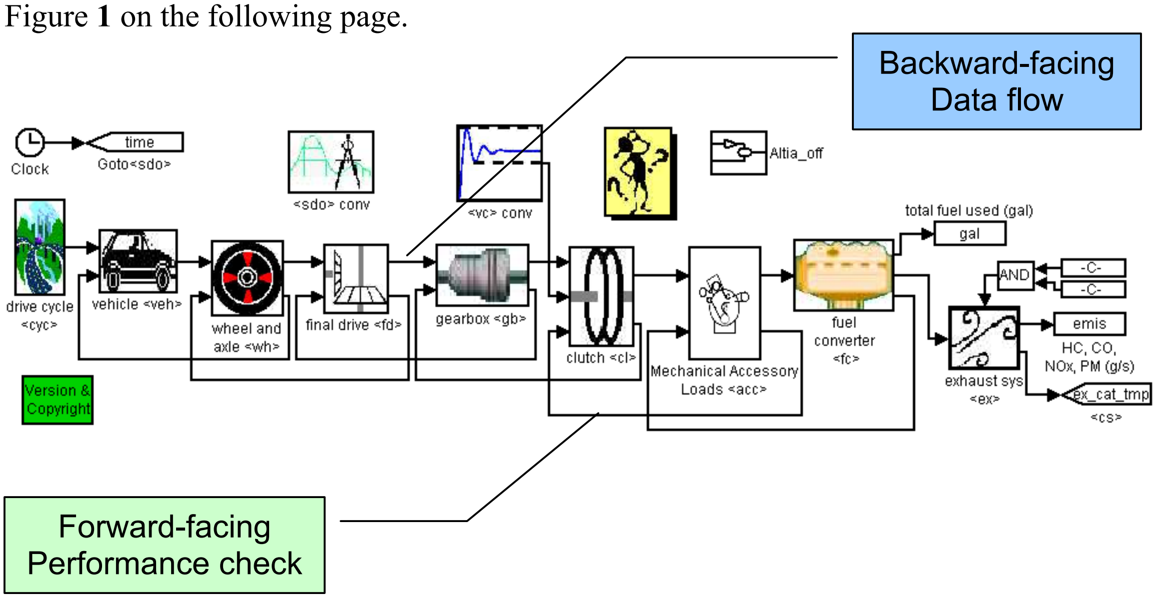


Figure 1: Example of a Simulink Block Diagram as an Illustration of ADVISOR's Backward/Forward Facing Approach

Forward-facing models are in existence, the most notable of which in the public domain being Argonne's Powertrain Systems Analysis Toolkit (PSAT). The key difference between such a model and its backward-facing counterpart is that the calculation begins with an estimation of driver input, or throttle position, and then iteratively moves down through the drive train to end up at the wheels with a value close to the requested vehicle speed. [13] The obvious disadvantage of such a method is increased time for computation (roughly speaking an order of magnitude longer for a given drive cycle).

The increased accuracy of using such a model is a topic of some debate. Its proponents argue that a forward-facing approach more closely parallels reality, and that the added complexity enables more accurate depiction of transient effects. Here, transient effects refer to the dynamics of a physical component, such as modeling the slipping of the clutch. The effect of transients on engine emissions, however, is generally not included in a model such as PSAT because it also relies on steady-state engine maps for emission characterization. One exception is the Neural Network engine model, which can be described as pseudo-dynamic, though this type of model can be implemented in a backward or forward facing structure. [23][13] In other words, taking into account that no comprehensive study comparing the two model structures has been performed, it is generally agreed that the difference in accuracy between the two is in the order of a few percent.

Since ADVISOR's creation was motivated by the PNGV program, its original focus was on modeling hybrid powertrains for small passenger vehicles in an effort to determine the optimum configuration for meeting the program's ambitious fuel economy requirement of 80 mpg. The first major validation of modeling such a vehicle came with the Honda Insight, where model agreement with EPA testing results for city and highway driving was 7% and 2%, respectively. [14] The scope of ADVISOR's applications has since broadened significantly, with models being included for virtually all vehicle types, from passenger vehicles and SUV's to transit buses and heavy-duty trucks, and propulsion systems, including conventional drivetrains, all-electric vehicles, hybrid-electric drivetrains, and fuel cells systems.

In fact, in recent years, there has been a growing concentration among the ADVISOR team on heavy-duty vehicles, presumably a result of user requests and input. The number of models and component data for such vehicles has grown so significantly that with the release of ADVISOR 2002, the program is now divided into two main projects, one including all passenger vehicle data and the other exclusively containing heavy-duty vehicle data. [2] Additionally, new models for components such as engine accessories and tire resistances specifically for heavy-duty vehicles have been added, allowing for a more accurate baseline model to be used throughout this research for purposes of comparison.

2.2 APU Characterization and Implementation

Because they face much less stringent cost restrictions than other applications ($1000/kw vs. $600/kw for heavy-duty trucks), luxury vehicles are predicted to be one of the early markets for fuel cell APU's. [18] A modern luxury vehicle may have up to 90 microprocessors on board, and with the growing trends of utilizing drive by wire technology and installing infotainment devices, it is projected that the electrical power requirement of such a vehicle will increase from about 7kW today to 20-30kW by 2010.[24] Considering the severe inefficiency of electrical power generation and distribution via an engine, an alternator, and then though the 12V bus and battery pack, it is clear that taking advantage of the efficient electricity generation of a fuel cell could have significant gains in fuel economy for the overall system.

With their long interest in utilizing hydrogen as a fuel for their luxury vehicles, it comes as no surprise that BMW has been at the forefront of passenger vehicle APU research. In 1999, they debuted a BMW 7 Series powered with a hydrogen internal combustion engine and equipped with a 5kW PEM APU. [22] The main task of the fuel cell was to run a 42V electric compressor for the air conditioning of the vehicle. This came with several advantages: 1) the inefficient mechanical compressor could be replace with its more efficient counterpart, 2) the A/C could run with the engine on or off, enabling engine shut-down during idle, and 3) the fuel cell gave new functionality to the consumer such as controlling A/C of the vehicle remotely while it is still parked. Perhaps most importantly, the system demonstrated its durability after exhibiting little performance degradation after five months of operation in 2000. [22]

While the system described above may seem ideal from an engineering perspective, a wealth of cost and infrastructure obstacles will prevent large-scale hydrogen passenger vehicle sales in the near future. As a result, BMW has formed a partnership with Delphi Automotive Systems to implement a gasoline-fueled SOFC APU system. While a PEM stack could theoretically also run on gasoline reformed into H_2, its sensitivity to CO degradation requires a nearly pure fuel stream, making the reforming system much more complex and impractical for a stack sized in the APU range. The two companies did demonstrate a SOFC proof of concept in 2001 with the integration of the APU system into the trunk of a BMW 7 Series sedan. [32] Nevertheless, a host of issues are yet to be solved, such as thermal management of a 750ºC stack and the reduction of its warm-up period from 45 minutes to a target of 20 minutes for the next generation SOFC unit. [32][22]

Referring more specifically to demonstrations of APU's on-board Class 8 heavy-duty trucks, Freightliner and XCELLSiS Corp. teamed up in 2000 to construct such a system. The truck used two PEM stacks connected in series to have a maximum voltage of 30V. Using an 1800 W inverter, the system could deliver 1.4 kW for 25 hours on a single 52 gallon 2500 psi H_2 tank. ITS-UC Davis was contracted to evaluate the benefits of such a system. As the project was aimed at demonstrating a technology still in its efficiency, ITS focused on the emissions benefits of such a system as opposed to performing a rigorous cost analysis, with the main conclusion that the APU would eliminate 1-3 metric tons of NO_x per vehicle over five years. [5]

3.0 RESEARCH METHOD

3.1 Experimental Work

Since ADVISOR is a largely empirical-based model, the first step in creating an APU module was experimentally mapping out the two APU's included in this research. The term mapping means to record the fuel consumption and emissions, if any, of each device at several load levels across its full operating range. Ryan Hammond and Matthew Forrest were responsible for the bulk of setting up each of the experiments for the Pony Pack and Nexa unit, respectively.

3.1.1 Nexa PEM Fuel Cell Stack

3.1.1.1 Experimental Setup

As opposed to earlier generations of fuel cells that were designed for research purposes and hence required large amounts of external instrumentation and technical support, the Nexa stack was manufactured with the goal of being a self-supportive power generation unit for commercial applications. Consequently, the complexity of its experimental setup, shown in Figure 2, could be greatly reduced, as auxiliary systems such as the fuel regulator, the air blower that provides both oxidant and coolant, and control electronics are all part of the pre-packaged unit.

The fuel was supplied from a tank of hydrogen stored at pressures from 2000 psig for a full tank and 500 psig for a near-empty tank needing replacement, but the Nexa regulator ensured a nearly constant 2.5 psig at the stack across the entire input pressure range. A Milwaukee Coil Resistor was used to dissipate the outputted power. A resistive current shunt produced a measurement of the net current, which was fed into a PID control loop within the LabVIEW program aimed at controlling the output power of the Nexa. This same LabVIEW program, written by Matt Forrest, recorded the net current and voltage of the system, while all gross data was data logged with the Ballard acquisition software that accompanied the Nexa stack at the time of purchase.

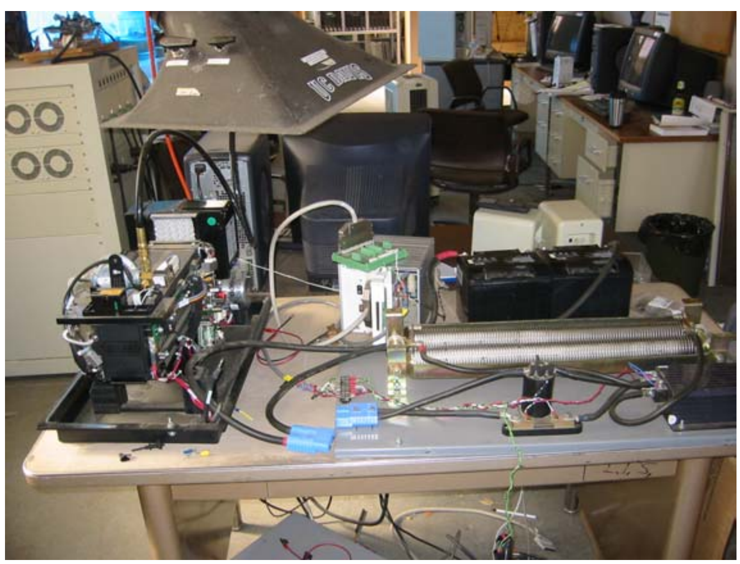


Figure 2: Nexa Stack Experimental Setup

3.1.1.2 Data Collected

Four different experiments were performed on the Nexa stack, listed below:

1. Varying the current from 0-50A_{net} in 5 A intervals with the stack at ambient temperature. (~27-40ºC)
2. Repeating the first experiment after the stack has reached its operating temperature. (~65ºC)
3. Running the stack at a constant 22 A_{net}.
4. Running the stack at a constant 44 A_{net}.

For each of these experiments, second by second net and gross data was recorded with the instruments described in the previous section. The goals of the first two were to obtain maps of the system's performance and to understand how that performance would be affected by start-up temperatures. The objectives of tests 3 and 4 were to validate H_2 combustion measurement of the Ballard software and to understand the effect of fuel purging on overall consumption, both of which will be discussed further in the following section. Only a fraction of the testing results are presented in the body of this work. All available data of interest, including hot and cold VI and efficiency curves, the stoichiometric ratio as a function of current, and an illustration of the control strategy for thermal management, can be found in figures in Appendix A.

The VI curve for the stack at operating temperature, obtained from test 2, is presented below in Figure 3. The gross voltage and current are those coming directly out of the stack; net data, in contrast, would be the voltage and current coming out of the system and therefore includes the effect of accessories such as control electronics and the air blower. Notably, the curve remains linear up to the maximum test point of ~50A_{net}, meaning that the system is not tested in the region where the voltage falls off rapidly due to mass transfer limitations.

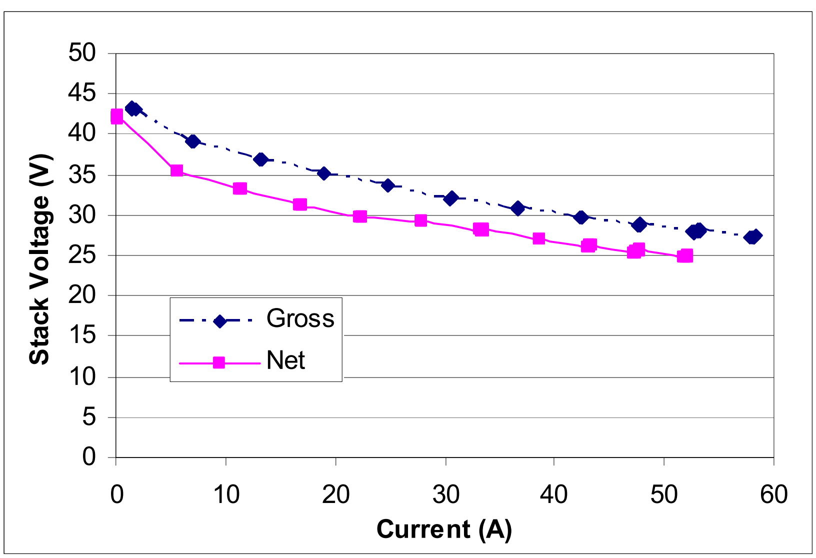


Figure 3: Gross and Net V-I Curves at Operating Temperature

As mentioned earlier, the Nexa system is not a dead-end fuel cell; it purges, or exhausts, inert constituents such as N_2 and water that migrate to the anode side and decrease performance. This results in a small amount of H_2 slip during the purge. Figure 4 below gives some insight as to how the purging is controlled and quantifies the amount of wasted H_2 during these purges. From its magnitude, one can conclude that the purge cell voltage is the sum of the voltages of two different cells, presumably the two end cells where inert gas build-up would be the greatest. When this voltage sum reaches a minimum, about 1.25V here but this value will depend on the test current, a purge is commanded, followed by an immediate voltage increase and then a period of H_2 slip. The purpose of the H_2 sensor is to ensure that the H_2 concentration in the exhaust is well below the lower flammability limit (LFL), approximately 4% for hydrogen. As a consequence, the units of H_2 leak in Figure 4 are percent concentration of LFL.

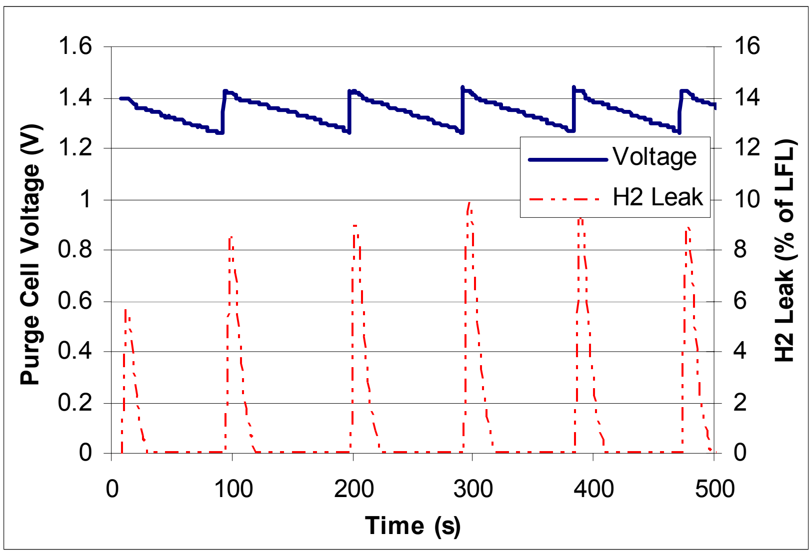


Figure 4: Purging of Hydrogen during 22 A_{net} Operation

Given that the H_2 concentration of the exhaust stream stays below 0.4%, it is not surprising that the effect of purging is a small one, accounting for less than one percent of the overall fuel consumption. [3] Ignoring the effect of purging enables one to use the following relation to calculate fuel consumption from the gross current output of the stack:

Equation 1

$$H_2\left(SLM\right) = I_{gross}\left(\frac{C}{s}\right) * \left(\frac{1_{molecule\,H_2}}{2e^-}\right) * F^{-1}\left(\frac{mole}{C}\right) * 22.41\left(\frac{SL\,H_2}{mole}\right) * 60\left(\frac{s}{\min}\right) * \left(\#cells\right)$$

$$\approx I_{gross} * 0.328$$

$$where: \quad F \equiv Faraday's\ Constant = 96{,}485\, C \cdot mol^{-1}$$

$$I \equiv Current$$

$$SLM \equiv Standard\ Liters\ per\ Minute$$

After converting this value to mass flow of fuel, one can use Equation 2 to calculate the efficiency of the fuel cell across its operating range. Using the gross current and voltage in the equation yields the gross efficiency, and the net current and voltage will correspond to the net efficiency of the system, the parameter that is of most interest to the fuel cell model in ADVISOR.

Figure 5 on the following page contains the results of the efficiency calculations. At higher power values (300-1300W), the difference between gross and net efficiencies was about 10-15%. The maximum gross efficiency of 74% occurred at zero output power. The maximum net efficiency was just under 50% and was realized at 200-400 W. The net efficiency curve dropped sharply at low output power levels as the power draw of the ancillary devices became more significant.

Equation 2

$$\eta = \frac{VI}{\dot{m}_{H_2} LHV_{H_2}}, \ where\ \eta \equiv Thermal\ Efficiency, V \equiv Voltage,\ and\ \dot{m} \equiv Mass\ Flow\ Rate$$

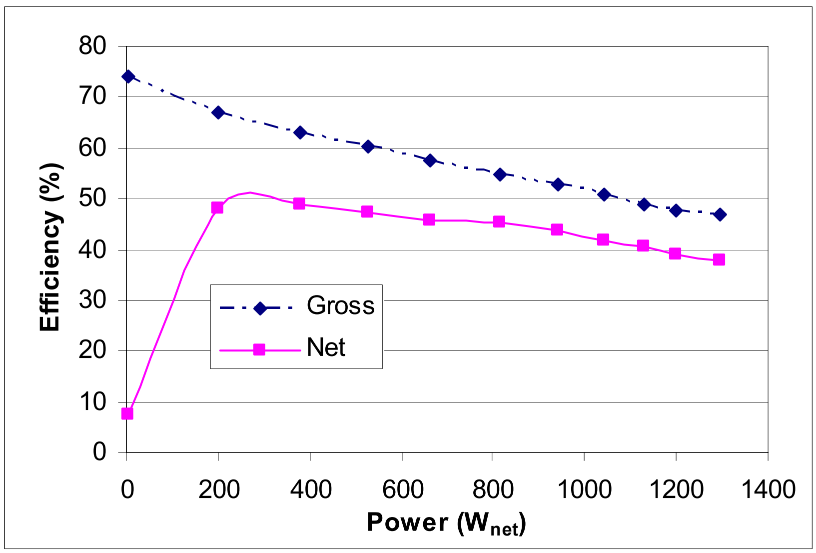


Figure 5: Gross and Net Efficiency Curves at Operating Temperature

3.1.2 Pony Pack

3.1.1.1 Experimental Setup

The Pony Pack unit, includes a Kubota Z482B two cylinder diesel engine for mechanical power generation, a Delco 105A alternator for battery charging, and a Sanden compressor able to run the trucks existing air conditioning system. These two auxiliary devices were disengaged at the time of testing in order to have all of the test load applied directly on the engine. An air-cooled eddy-current dynamometer built at UC Davis was used to vary the load of the engine. Figure 6 is a photograph of the Pony Pack while connected to the dynamometer. A Micro Motion Coriolis flowmeter measured the fuel consumption of the engine; and a sharp-edge orifice, ASME model MFC-15M-2003, measured the flow of intake air through a 50 gallon drum, in an effort to reduce the effect of oscillations on the air flow measurement.

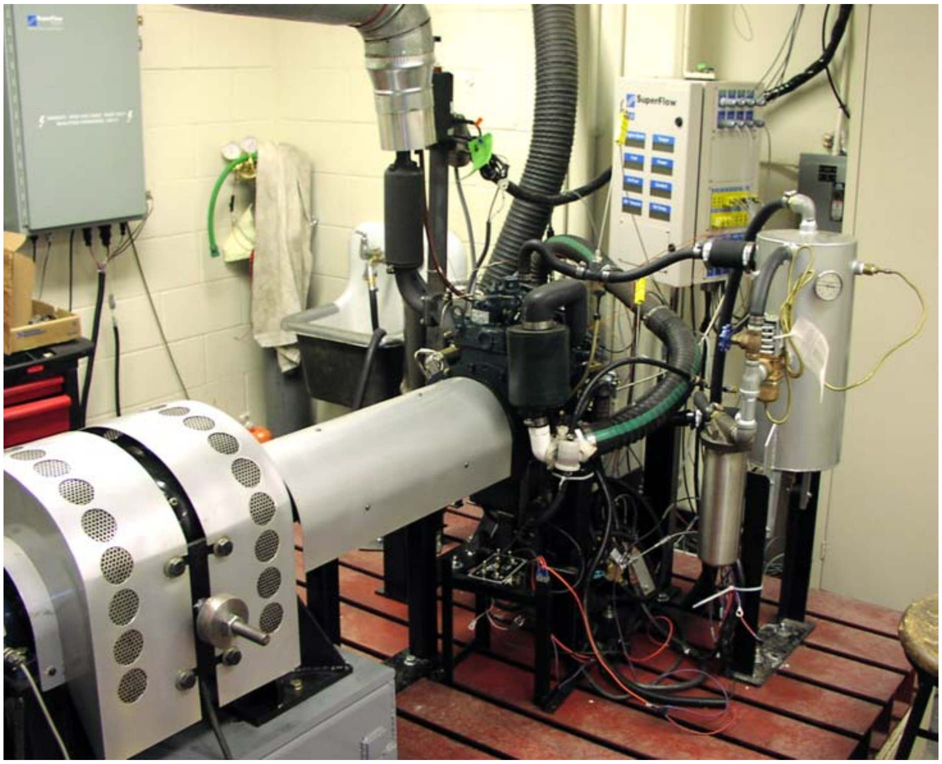


Figure 6: Pony Pack and Dynamometer Experimental Setup

Both emissions analyzers came from California Analytical Instruments [7]. The Model 300 NDIR Analyzer was able to measure concentrations of O_2, CO, and CO_2 using infra-red absorption measurements. For the measurement of NO and NO_x, the Model 400 CLD Analyzer was selected for its large measurement range of 0-3000ppm of NO_x. While in NO mode, the chemiluminescence from reaction between NO and ozone is measured and amplified with a photo diode detector and electronics, with the measured intensity being proportional to the mass flow of NO in the sample. When in NO_x mode, the detector performs the same measurement as in NO mode, after running the sample through a catalytic converter to convert all of the NO_x to NO. A limitation of this detector is that only NO or NO_x could be measured at any one time, and as a result, two different tests were performed in order to find the NO/NO_2 ratio, assuming the NO_x levels were the same for the two tests.

3.1.1.2 Data Collected

Two runs were performed across the operating range of the Pony Pack. Each run began with running the engine while it was disconnected from the dynamometer, i.e. zero load, and then consisted of increasing the torque output by some incremental amount, waiting approximately 200s for the engine to reach steady-state operation, and recording thirty seconds of data until. The thirty second periods of data were averaged to mitigate the effect of cycle-to-cycle variation and to provide one value for each parameter at every operating point of the engine. Executing two runs was a necessary step in determining the NO/NO_x ratio as a function of engine speed since the NO_x analyzer used in the experiment had to be in either NO or NO_x mode. All other measured values were averaged from the two data runs.

Figure 7 below illustrates the line of operation and the brake specific fuel consumption of the Pony Pack. As expected, the engine becomes more efficient as the load on the unit is increased. The effectiveness of the speed governor of the Kubota engine can be seen from the fact that the engine speed only varies by approximately 120 RPM across the unit's 0-10 hp range.

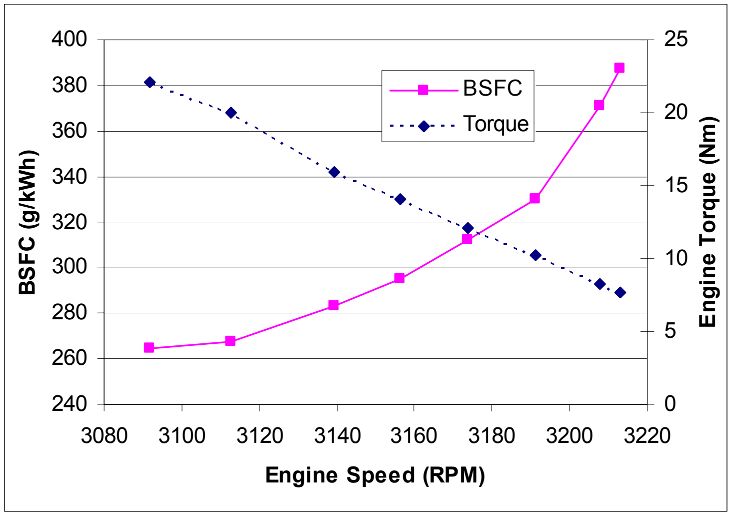


Figure 7: Operating Line and Brake Specific Fuel Consumption of the Pony Pack

In order to verify the emissions results, the CO_2 emissions in the exhaust were calculated from the fuel consumption via a carbon balance, detailed in Equation 3. A comparison of this calculated value to the exhaust measurement is shown in Figure 8.

Equation 3

$$\left(X_{CO_2}\right)_{actual} = \frac{\frac{n_C}{n_{fuel}} \cdot X_{fuel,\,inlet}}{1 + \frac{n_{CO}}{n_{CO_2}}}, \; where\ X \equiv Mole\ Fraction,\ n \equiv Number\ of\ Moles$$

This mismatch was most likely explained by an air leak in the analyzer, causing the ppm measurements of the emissions to be artificially low. This explanation was further confirmed by the high levels of oxygen measured in the exhaust, which were in the order of 15%. Since a second round of testing was not possible at the time of this writing, it was decided to correct these values using the equations below. Equation 4 uses the ratio between the calculated and measured CO_2 values to find the ratio of diluent air to engine exhaust. This ratio could then be used to correct each emission measurement; Equation 5 contains this correction specifically for NO_x, but the same form of the equation was used for CO. The corrected brake specific emissions measurements are given in Figure 9. It should be noted that even with the correction, the NO_x results may be inaccurate; experience with other emissions results suggests that the $BSNO_x$ curve should increase at lower values of torque, i.e. higher values of RPM in the chart below. However, unable to repeat the testing at the time of this writing, these corrected values were used as the inputs to the Pony Pack model.

Equation 4

$$\frac{n_{air}}{n_{exhaust}} = \frac{\left(X_{CO_2}\right)_{actual}}{\left(X_{CO_2}\right)_{meas.}} - 1$$

Equation 5

$$\left(X_{NO_x}\right)_{actual} = \left(X_{NO_x}\right)_{meas.}\left(1 + \frac{n_{air}}{n_{exhaust}}\right)$$

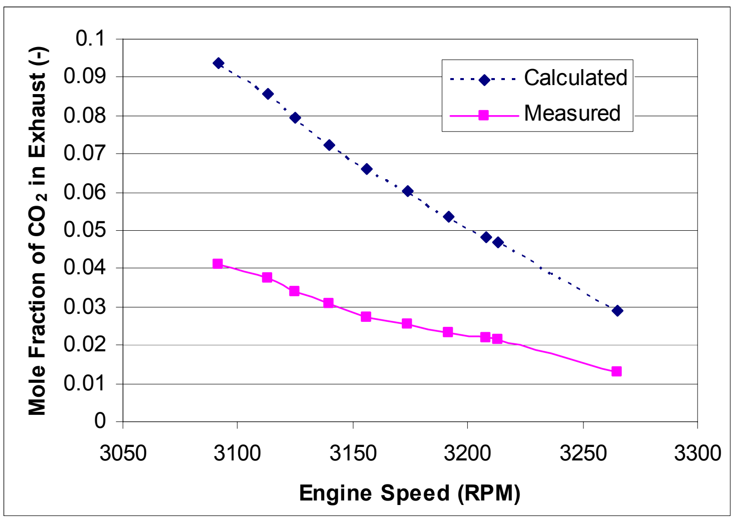


Figure 8: Effect of Dilution on CO_2 Emission Measurement

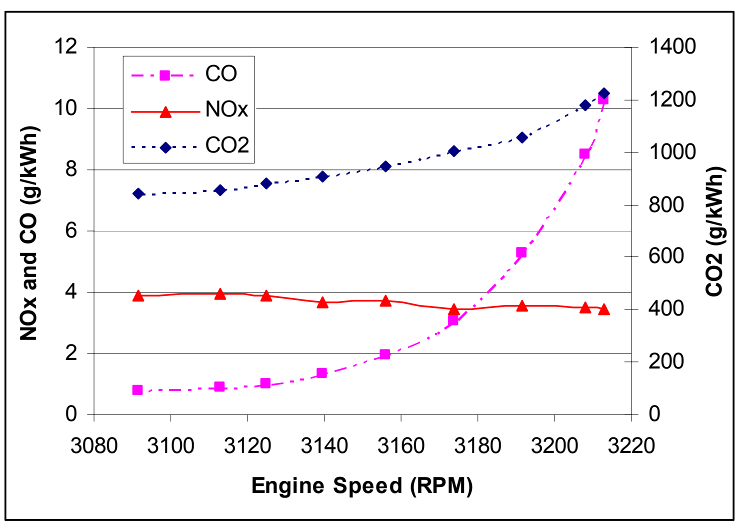


Figure 9: Corrected Brake Specific Emissions

3.2 Modeling

There were several stages in the model creation process. First, truck driver behavior, including driving, idling, and accessory use, needed to be characterized. This was accomplished by utilizing a variety of sources of information, such as literature reviews, surveys of truck drivers, EPA driving cycles, etc. This data could then be inputted into the baseline, conventional heavy-duty model within ADVISOR, and the outputs of the model were validated against existing truck fuel usage and emissions data. Finally, a separate ADVISOR model including an APU system was created, relying on the data collected in the previous section for the Pony Pack and Nexa stack as inputs.

3.2.1 Creating a Vehicle Duty Cycle

The goal of creating a representative driving cycle is to encompass the full range of truck-driver behavior and hence obtain representative emissions and fuel economy. The form of such a cycle is generally a speed versus time trace that is able to be followed by a driver on a chassis dynamometer and also serves as the primary input to the ADVISOR model. The HWFET cycle, created by EPA as the highway section of the federal testing procedure, was chosen to represent line-haul highway driving because of its wide acceptance among regulatory agencies and industry alike. This cycle requests a maximum speed of 60 mph with an average of 48 mph. A section of zero velocity was appended to this cycle to represent the idling portion of a truck driver's daily routine, and the percentage of idling time is kept as a variable input to the model. Figure 10 illustrates the entire drive cycle with the amount of idling time set to 20%.

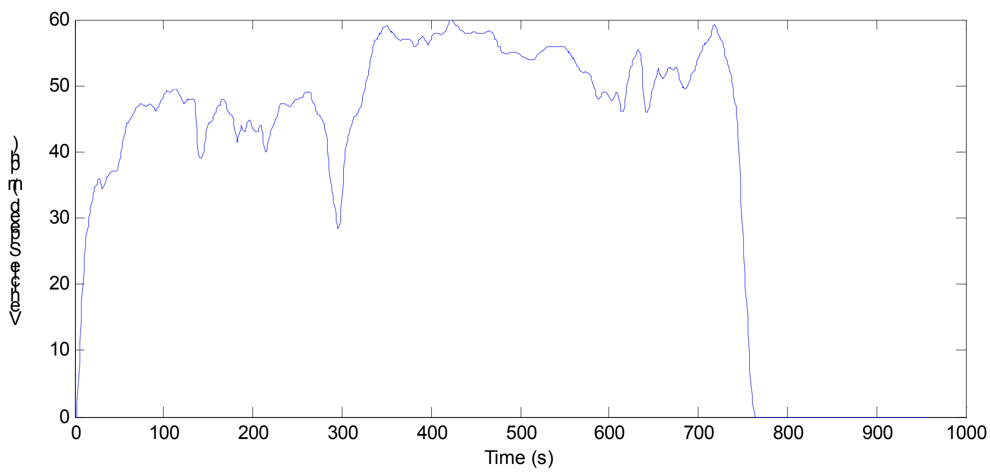


Figure 10: Speed Time Trace of the HWFET Cycle Appended with 20% Idle

The second key set of inputs to the model is information regarding the power requirements and duration of the accessories to be powered by the idling engine or APU. Table 1 lists this data for all of the pertinent accessories found in the cabin of a line-haul truck. The fraction of idle time is the result of trucker input to a survey conducted by ITS researchers. [6] Regarding the power requirement data, the source of this information varied for each accessory. The electrical power for commonly found, fully-integrated devices such as stereos and cabin lighting was measured directly with a portable Amp meter at a nearby truck retailer. For commercially available devices such as microwaves and refrigerators, the rated power from their spec sheets was used. Note that the values listed in the baseline column are end-use power values; their individual contribution to engine loading will in actuality be a greater value due to the efficiency of the alternator. Also, power requirements that differ between the two cases, such as for A/C and heating, do so because the nature of these devices differ for mechanical and electrical systems, e.g. without the aid of excess engine heat for cabin heating, the APU must generate this heat electrically.

Table 1: Estimations for Key Characteristics for Average Truck Idling [16]

Accessory used during idle time	Fraction of idle time	Power for idling base case (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 of 850 rpm. In reality and in the model these power magnitudes vary with idling rpm

This information was then incorporated into the existing variable accessory loading routine released with ADVISOR 2002. Each accessory is toggled on and off in a pseudo-random way to capture various combinations of accessory loading, and the duration of each "on" state is altered to match the idle fractions in Table 1. The resulting mechanical loading for the propulsion engine and electrical loading for the PEM APU can be found in Figure 11 and Figure 12, respectively. Note that the accessory profile for the Pony Pack will be similar to that of the propulsion engine, with the exception of having the engine fan turned off. The plot of mechanical accessory power (Figure 11) is slightly more complicated because care needs to be taken to differentiate between mechanical loads placed directly on the engine and electrical loads that must first take an efficiency hit through the alternator, which had an average efficiency of 58%.

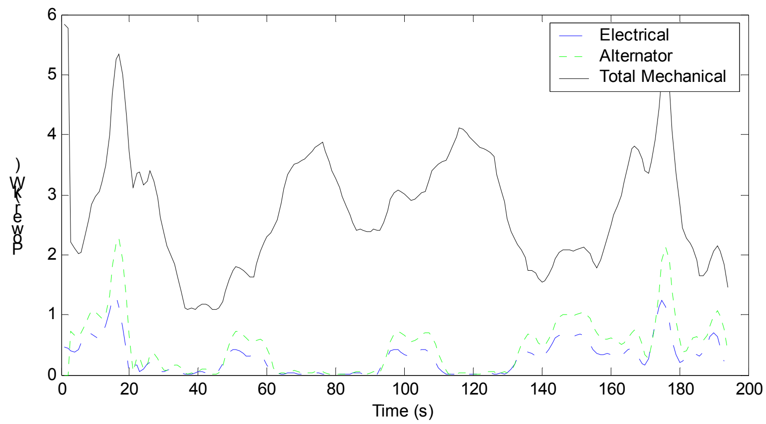


Figure 11: Breakdown of Mechanical Accessory Loading for Baseline Engine Idling

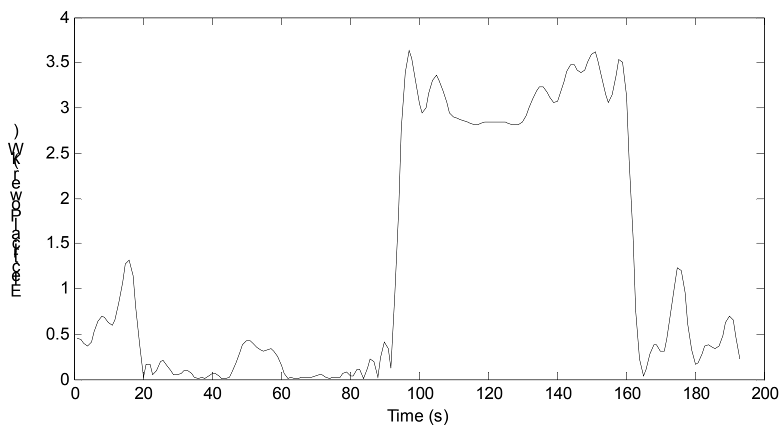


Figure 12: Electrical Accessory Loading for PEM Fuel Cell

3.2.2 Baseline Model

ADVISOR's heavy-duty truck model utilizes the Simulink code for all vehicles with a conventional drivetrain, shown below in Figure 13. Thus, the only factor that separates the heavy-duty model from those of smaller conventional vehicles is its unique set of component data files, i.e. the parameters that define each of the drivetrain elements in the model below. Table 2 lists the make and model of the most significant components, as well as some key variables and their values.

Conveniently, most of the data utilized in this study already existed in the publicly available version of ADVISOR 2002, with the exception of the engine data. ADVISOR does have fuel consumption data for engines large enough to power Class 8 vehicles, but its collection of emissions data in this range is virtually non-existent. As a result, in-house data used in a previous ITS study [10] for a 210 kW diesel engine was scaled to 330kW to match the output of a DDC Series 60 engine, commonly found in Class 8 trucks. The method of scaling employed involved three simple steps: assuming an unchanged brake specific fuel consumption map, multiplying the vector of engine torque values by the ratio of maximum scaled power to pre-scaled power, and recalculating the absolute fuel consumption (g/s) at each point of operation.

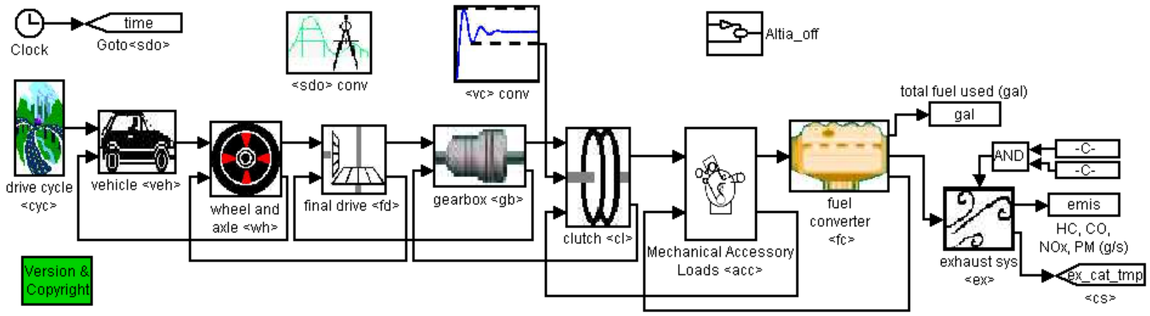


Figure 13: Simulink Block Diagram for a Conventional Vehicle

Table 2: Vehicle Component Information

Component	Make and Model	Parameter	Value	Units
Vehicle	Kent T800	Drag Coefficient, Cd	0.7	-
		Frontal Area	8.55	m2
		Mass (with Cargo)	39700	kg
Engine	DDC Series 60*	Fuel	Diesel #2	-
		Maximum Power	330	kW
		Maximum Torque	1220	Nm
		Max. Efficiency	42.5	%
Transmission	Eaton Fuller RTLO-12610B	Type	Manual	-
		Number of Gears	10	-
		Max. Efficiency	92	%
Wheel/Axle	Michelin	Radius	0.501	m
		Inertia	20.6	kg/m^2
		Rolling Resistance Coef.	0.0055	-

Along with the issue of scaling, a separate problem with the data existed in that the raw data collected did not cover the full range of operation. The white space in the left-hand plot of Figure 14 defines the region where data was lacking. This was especially problematic since the ill-defined regions of low engine torque and speed are of particular interest when estimating the fuel consumption and emissions of idle operation. Therefore, several methods of extrapolation were performed, including linear extrapolation and nearest-neighbor approximation of both absolute (g/s) and brake specific (g/kWh) data. In general, the fuel mass flow rate of an engine decreases linearly with torque for a given rpm, and as a result, linearly extrapolating the grams/second maps to lower torque values was deemed to be the most logical and accurate method, the results of which for fuel use can be seen in the right-hand plot of Figure 14. Validation of the effect of this extrapolation will be presented in the results section of this report.

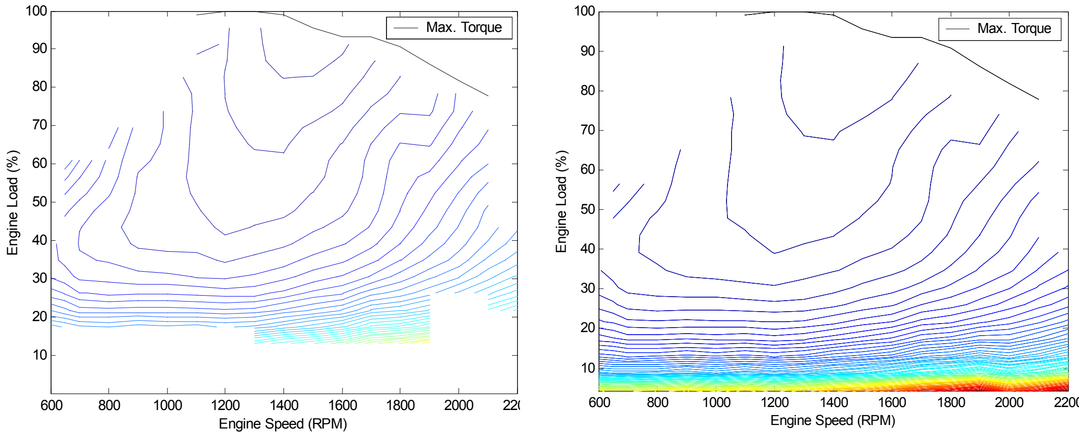


Figure 14: BSFC Engine Map Before and After Extrapolation

3.2.3 Adding the APU Module

The final and most complex step in the model creation was modifying the Simulink code to include the functionality required by the APU model. This section is meant to serve as a conceptual overview of the creation of the model and its control strategy; details on the necessary modifications can be found in Appendix B. Figure 15, which contains the overall block diagram including the added APU block, provides a useful schematic of the model but may be deceptively simple. In reality, several steps needed to be taken to make this modification successful, such as modifying the accessory block to take the accessory profile of the APU as an input and to be able to pass data to and from the APU block.

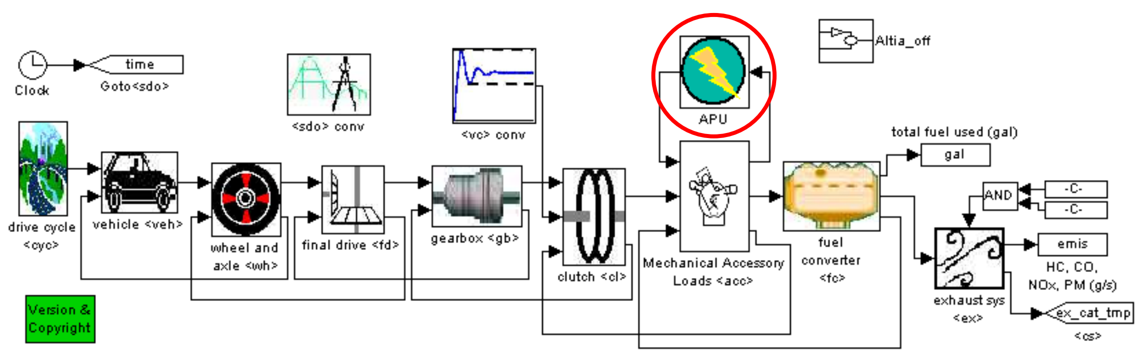


Figure 15: Modified Simulink Block Diagram for a Conventional Vehicle with the APU Module (circled in red)

A quick description of the notation used in describing the Simulink code may be necessary. Simulink block diagrams are hierarchical structures, consisting of many levels. Each level contains a collection of blocks, many of which can be opened up to show the contents of a lower level in the hierarchy. The block diagram shown in Figure 15 is the uppermost level of the model; Figure 16 contains a lower level block diagram of the APU/battery system and illustrates the contents of the control strategy block, one level down in the hierarchy.

With this in mind, double-clicking on the APU block in Figure 15 would lead one to the level containing the configurable subsystem utilized for the APU module. Configurable subsystems are blocks whose contents can be changed immediately before run-time depending on user input. The utilization of this feature, available only in Simulink 4.1 or newer versions, was essential in creating a modular APU unit that could be powered by a fuel cell, internal combustion engine, or a large battery pack. Creation of models for these three components began with using their existing models in ADVISOR 2002, and then making any necessary modifications, generally aimed at simplifying the existing models for propulsion sized devices to more accurately reflect the operation of an auxiliary power sized unit. For example, the thermal calculations of the fuel cell model were replaced by an assumption of constant coolant temperature to reflect the largely steady-state nature of APU operation, and because these thermal relations would likely not scale accurately during APU sizing. Also, in the case of the Pony Pack, the inertia-based estimations of engine speed were replaced by a constant governed engine speed.

First iterations in the design of the APU module made the power source, whether it be an engine or fuel cell, perfectly load following. It was quickly observed that not only is this an unrealistic deviation from in-use operation, it placed much more stringent requirements on the size of the APU, which then needed to be sized based on the maximum amount of power required at any instant of time. This takes on a particular amount of importance in the case of the fuel cell, since initial cost of the fuel cell and its resulting pay back period are very sensitive to the rated power of the stack. As a result, the model was modified to include a battery pack connected in parallel with the fuel cell.

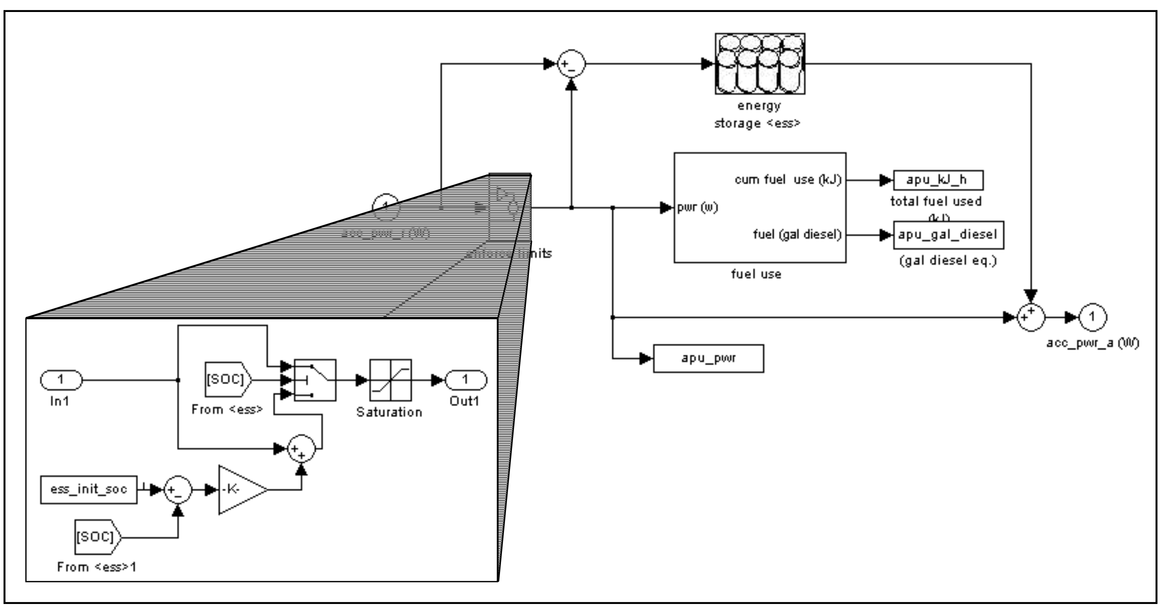


Figure 16: Block Diagram Implementation of PEM APU/Battery Power Share Control Strategy

Figure 16 contains the Simulink code that splits the requested power between the fuel cell and battery pack based on the control strategy shown in the expanded block in the bottom left corner. The battery module is contained in the block labeled energy storage, and again it is based on the internal resistance battery model pre-existing in ADVISOR. The control strategy enforces the following rules:

1. The fuel cell is perfectly load following up to its maximum power limit while the battery state of charge (SOC) is equal to or greater than its initial value (70%, by default).
2. For any power requested above this limit, the fuel cell is commanded at it maximum output and the battery pack outputs the difference between this value and the requested power.
3. Below this limit, the fuel cell outputs the requested power plus an additional amount of power proportional to the difference between the current SOC and the initial SOC of the batter, aimed at charging the battery pack in a reasonably short period of time.

An illustration of this control strategy at work during all three of the modes listed above can be seen in Figure 17. The APU unit is off during the first 800 seconds of the drive cycle because the vehicle is moving and the accessories are being powered by the propulsion engine and its alternator. From about 800 to 2250 seconds, the battery SOC equals its initial value, and the fuel cell APU outputs exactly the required accessory power. The fuel cell is then commanded at its maximum power, 2 kW for this example, because the accessory load is too high (2250 to 3300 seconds) and the SOC of the battery is less than its initial value (3300 to 3700 seconds). Since the resulting change in battery SOC is less than 1%, one can conclude that the control strategy effectively sustains the battery charge and that the fuel economy and emissions of the APU will not need to be corrected for a mismatch in beginning and final battery energy.

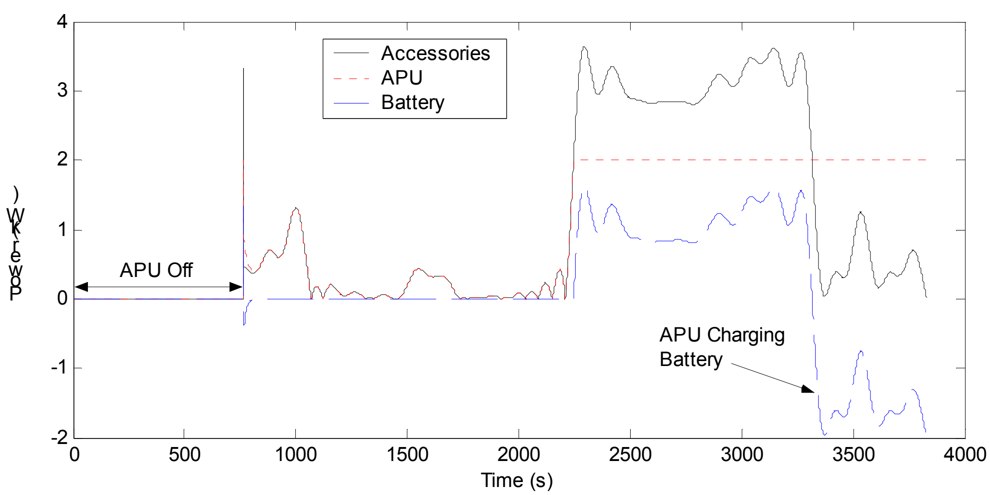


Figure 17: Illustration of Power Sharing between a 2 kW PEM Stack and Battery

Although demonstrated above to be quite functional, it is unclear whether or not this control strategy actually mimics real-world behavior. Most likely, any APU system will have the APU and battery packs connected in parallel passively, i.e. without the aid of power electronics, in an effort to minimize start-up cost. As a result, a more realistic model might take the VI curves of the fuel cell and battery pack and use them to calculate the power distribution at each time step. This option was deemed to be excessively complicated for this stage of model development but may be implemented at a later time when the performance of such a system could be demonstrated and tested on an actual truck.

4.0 RESULTS

4.1 Baseline Fuel Consumption and Emissions

Before making any judgment on the relative gains in fuel consumption and emissions of an APU system, those of the baseline model needed to be validated with experimental data. One of the most comprehensive studies in this area was carried out at a rest area in California by Clean Air Technologies International, Inc in 2002. [29] Testing 40 trucks of various models and years, data was collected at a low idle speed of 650 RPM and at a high idle speed of 960 RPM with the air conditioning on and off. Figure 18 compares this data with the predictions of the baseline model in ADVISOR. The error bars on the experimental data points represent one standard deviation about the mean value.

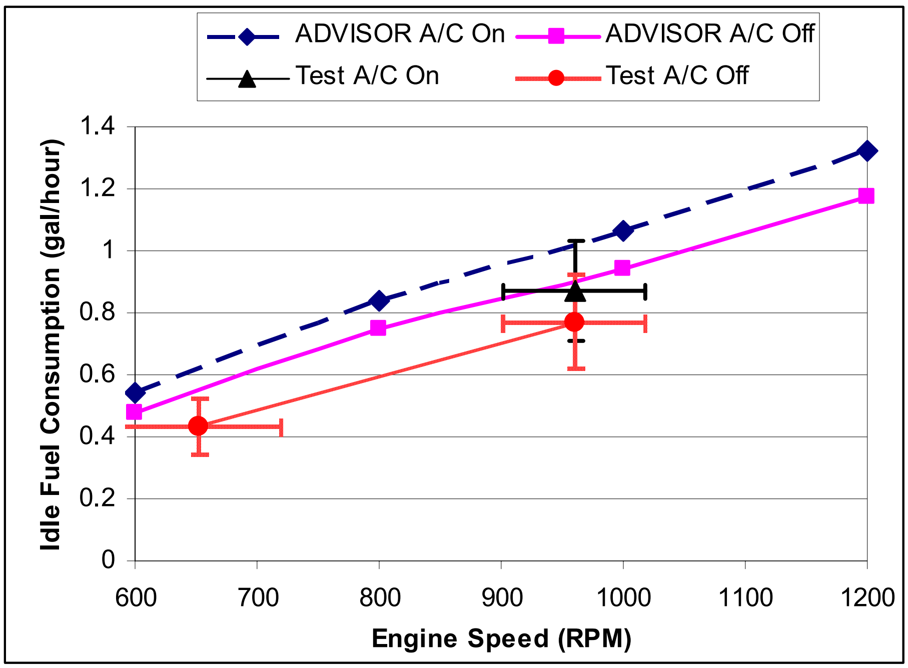


Figure 18: Modeled and Experimental [29] Fuel Consumption as a Function of Engine Speed

There are several points to make from the above graph. First, ADVISOR's predicted fuel consumption is a consistent 15% higher than the experimental results. It is unclear whether this is a result of the low-torque extrapolation of fuel usage described in the model creation section or an actual difference between the engines tested by Clean Air and the engine that was mapped and used in the model. In any case, the modeled results never deviate further than one standard deviation from the test results, indicating the accuracy of the model is sufficient. Second, the effect of air conditioning seen in the model, which increased fuel consumption by an average of 12.6%, is consistent with the 13% increase observed in the real world. Third and perhaps most important, the calculated fuel use vs. engine speed relationship follows the same curve as the experimental data, suggesting that the models results can be applied over a broad range of engine speeds.

A plot comparing the experimental and modeled emissions of PM, NO_x, and CO can be seen in Figure 19. Note that the PM values have been multiplied by a factor of 10 to be able to plot them on the same axes as the other two emissions. Also, all of the results shown are for warm engines, eliminating the difficult problem of capturing the highly non-linear effect of cold start. At first glance, the percent difference between the calculated and measured values seems to be quite high, particularly for particulate matter. The large standard deviations reported with the measured data, resulting from the strong dependence of emissions on such outside factors as operating temperature, transient effects, and engine mileage, lead to this large variation.

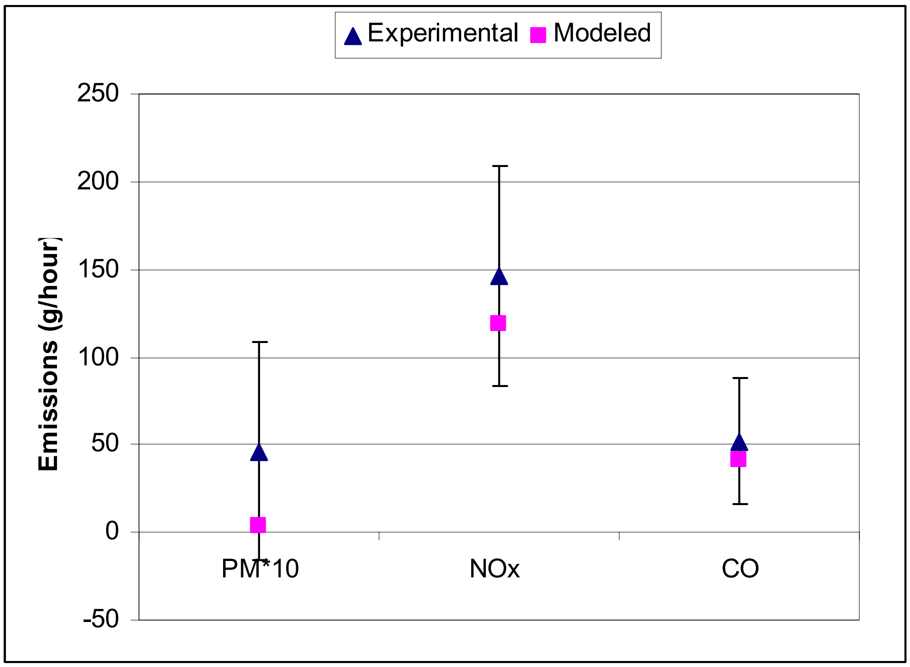


Figure 19: Modeled and Experimental [29] Emissions at 960 RPM with the A/C On

4.2 PEM Fuel Cell APU

In the experimental section, results of the testing of a single Nexa stack were presented in the form of VI and efficiency vs. power curves. Given that an electric A/C unit would require 1.7 kW (see Table 1), a 1.2 kW unit would not even provide sufficient power for continuous A/C operation without any other accessories. Consequently, the APU unit used in the model consisted of two fuel cell systems hooked up in series, having the effect of doubling the power output to 2.5kW but still maintaining the same efficiency curve. Incidentally, the design of the APU demonstration in progress at UC Davis also calls for the use of two NEXA units. The performance of this setup over the accessory loading profile detailed earlier in Figure 12 is shown in Figure 20. The average power output of the two Nexas over the entire cycle was 1.3kW, corresponding to an average net fuel cell efficiency of 38.3%.

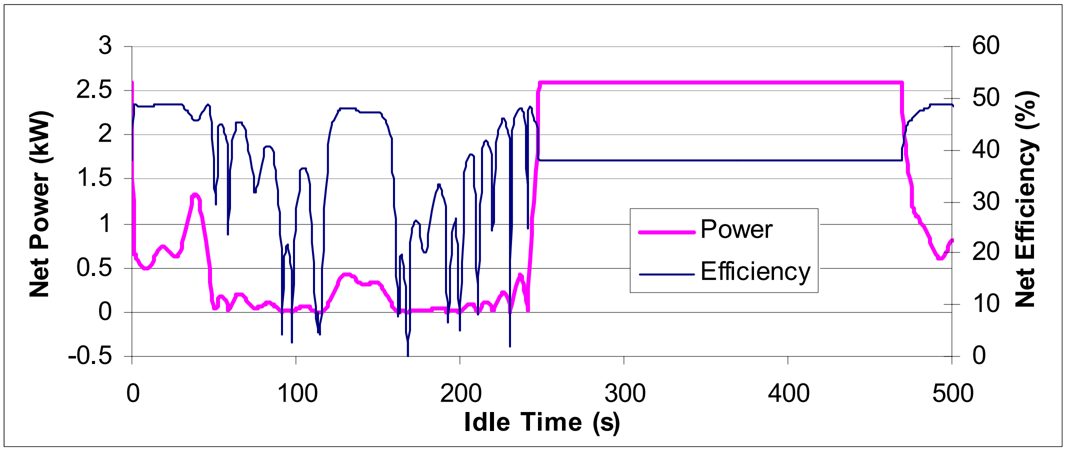


Figure 20: Modeled Second-by-Second Performance of the NEXA Stacks at Idle

Even though fuel cell efficiency and fuel consumption are the primary outputs of the APU model, the battery performance over the loading profile was also examined. The latter provides insight into the effectiveness of the selected control strategy and fuel cell size. As seen in Figure 21, the state of charge of the auxiliary battery is completely sustained. Furthermore, the low levels of power required of the battery, less than 1 kW during discharge and 2.6 kW during charge, combined with the small deviation from the initial SOC (< 1%) indicate moderate cycling of the battery, leading one to believe that battery lifetime is not being severely compromised.

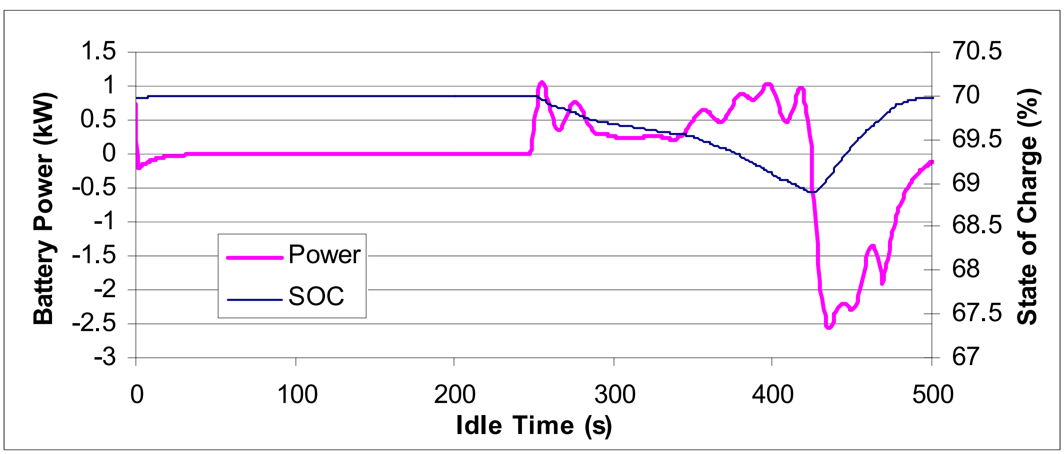


Figure 21: Modeled Second-by-Second Performance of the Battery at Idle

4.3 Pony Pack APU

The second by second power output and efficiency of the Pony Pack over its accessory loading profile are shown below in Figure 22. The maximum power requested of the unit was 5.2kW, and since the engine is rated at 7.2kW, no battery was needed for peak-shaving, making the Pony Pack engine completely load-following. The average power outputted was 2.3 kW, significantly greater than the 1.3 kW for the fuel cell case. This discrepancy has a number of reasons, including the lower efficiency of certain mechanical devices such as the A/C compressor and the efficiency loss through the alternator. The average thermal efficiency of the engine over the entire cycle was 19.5%.

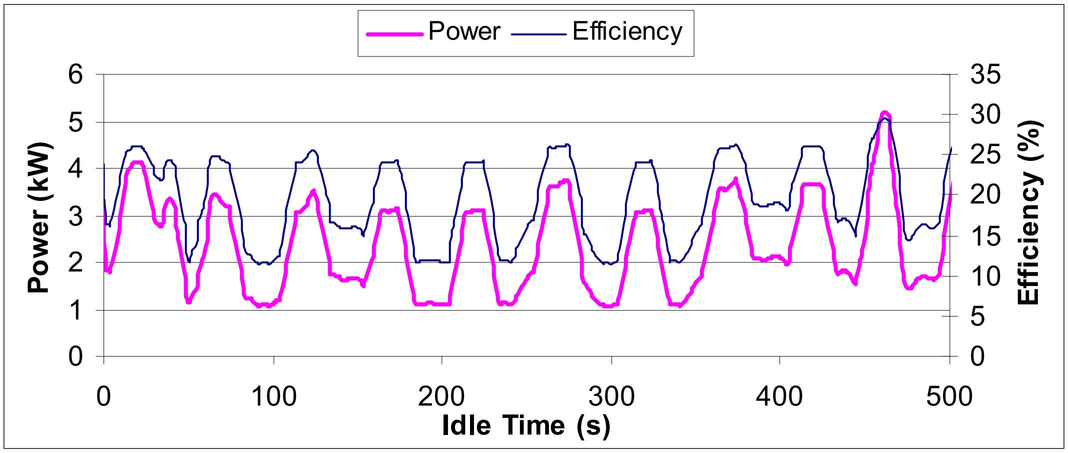


Figure 22: Modeled Second-by-Second Pony Pack Efficiency at Idle

The brake specific CO and NO_x (BSCO and $BSNO_x$) emissions of the Pony Pack engine are plotted versus time in Figure 23; PM is not included because input data for this emission were unavailable. The value for $BSNO_x$ remains relatively constant around 4 g/kWh, while the BSCO value fluctuates much more widely. This is not surprising, as the mapping of the unit shows a near-exponential increase in BSCO at low torque values and high RPM (refer to Figure 9).

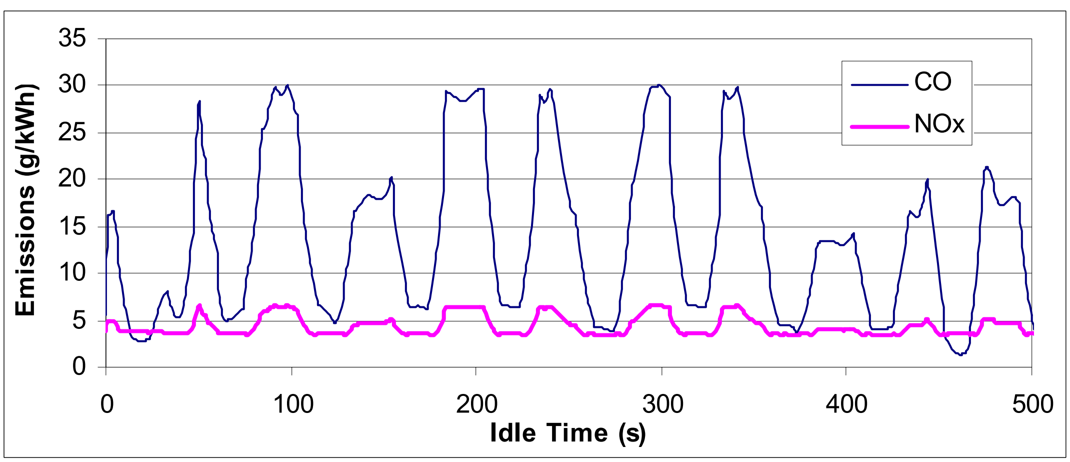


Figure 23: Modeled Second-by-Second Pony Pack Emissions at Idle

4.4 Comparison of Different Technologies

The gains in efficiency and emissions that accompany the implementation of an APU system can be more fully appreciated when looking at the net effect it has on a truck over a year of operation. In order to expand the results calculated in ADVISOR for a few minutes of idling to the annual level, several assumptions needed to be made. The assumption that is implicit in this extrapolation is that the fuel consumption and emissions of the APU will increase linearly with operation time, i.e. there are no short-term effects from transients or warm-up that would be disproportionately represented in a short cycle. In this regard, ADVISOR's reliance on steady-state maps of components as inputs is an advantage; also, all power sources, whether it be the main propulsion engine, the Pony Pack, or the Nexa stacks, were set to their operating temperature at idle to accurately predict long-term, warm operation.

In addition, some assumption regarding line-haul truck driver behavior needed to be made. Survey data reported that on average, truck-drivers are on the road about 300 days per year. [6] For each of these days of operation, it is estimated that truck-drivers are driving 9.1 hours per day [16], which is assumed to be accurately characterized by EPA's HWFET cycle. From this value, one of the primary inputs to the model, percent time spent at idle, could be related to the number of hours spent at idle per day. This parameter varies widely from trucker to trucker, the distribution of which can be found in Appendix C. As a result, most of the comparative results presented here will be across this entire range of 0 to 12 hours of idle per day. Some results will be shown with this parameter held at a constant 6 hours per day, which is generally agreed upon in the available literature to be the average idling time for truck-drivers (see Table C.1 in Appendix C).

As seen in the results from the baseline case, the baseline fuel consumption and emissions vary depending on the engine speed that propulsion engine is set to at idle. Although the value for engine speed at idle also varied widely depending on the trucker being questioned (ranging from 450 – 1600 RPM), the histogram found in Appendix C suggests that the distribution of responses may be bimodal, with peaks centered about 1050 and 650 RPM, i.e. for "high" and "low" accessory power idlers. Therefore, it was determined that all results were to be compared to the baseline case for both of these values for engine speed.

Figure 24 and Figure 25 contain the gallons of diesel saved for one truck in one year and the percent reduction of fuel consumption, respectively, for both types of APUs. To be able to compare all results on the same basis, the hydrogen consumed by the PEM stack was converted directly to equivalent gallons of diesel, not including the energy lost during the process of creating the hydrogen. Both figures illustrate the same effect of engine speed; a trucker that idles at 1050 RPM versus 650 RPM would save about 1.5 times more fuel with the fuel cell APU. The difference between the two values of RPM is slightly larger for the Pony Pack, with the fuel consumption savings differing by a factor of two.

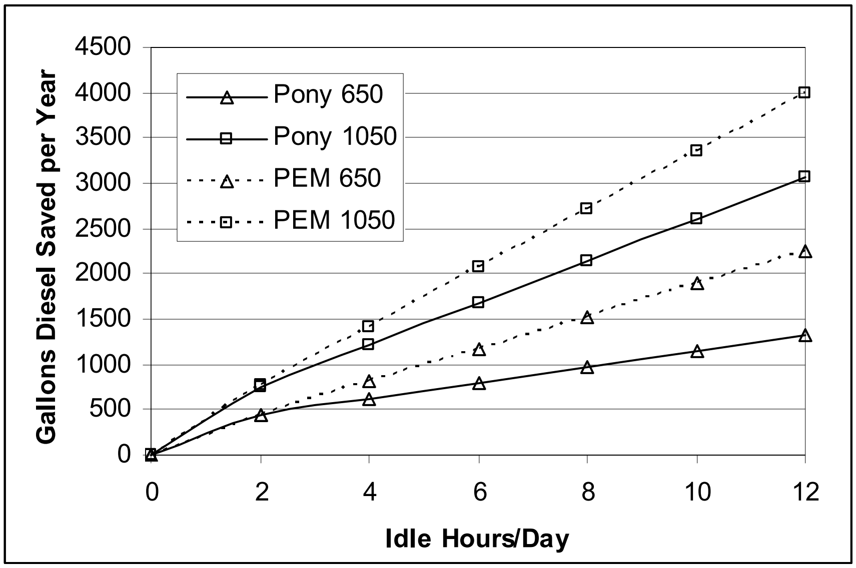


Figure 24: Annual Per Truck Diesel Savings for Both APUs for 650 and 1050 RPM

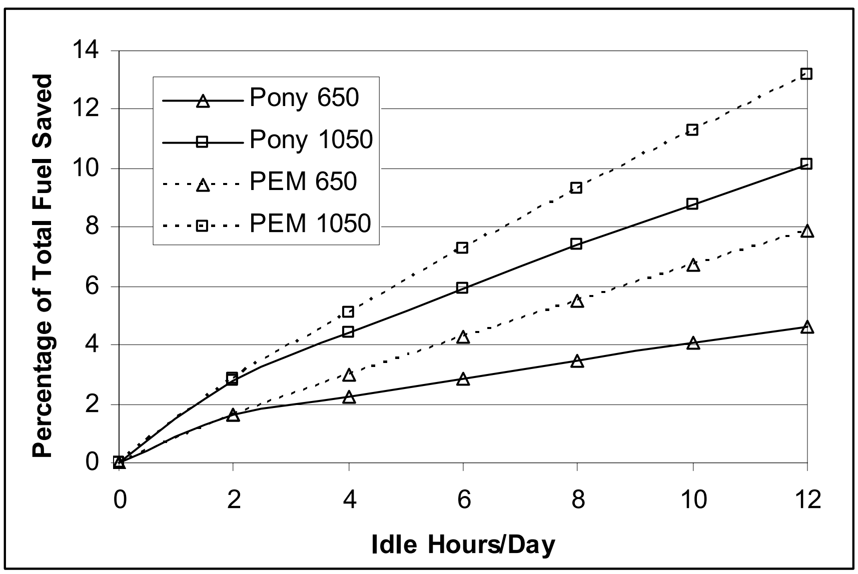


Figure 25: Percent Difference Diesel Savings for Both APUs for 650 and 1050 RPM

The percent reduction of all emissions for both devices compared to a baseline case of 1050 RPM is given below in Figure 26; more emissions comparisons, i.e. different engine speeds, absolute emissions reduction per year, etc., can be found in Appendix D. Referring to the NO_x results, a somewhat counter-intuitive conclusion can be drawn from the figure below in that the percent reduction does not differ too greatly between the two types of APUs investigated. This is especially surprising when considering that the fuel cell is known to have zero NO_x emissions, while the Pony Pack has been demonstrated to be a NO_x emitter. This can be explained by the fact that the results are presented in terms of the percent reduction of *total* NO_x emissions, i.e. those from the APU while the vehicle is at rest and the engine while the vehicle is being driven, and the absolute emissions from the Pony Pack are very small relative to those produced by the propulsion engine over the highway segment of the drive cycle.

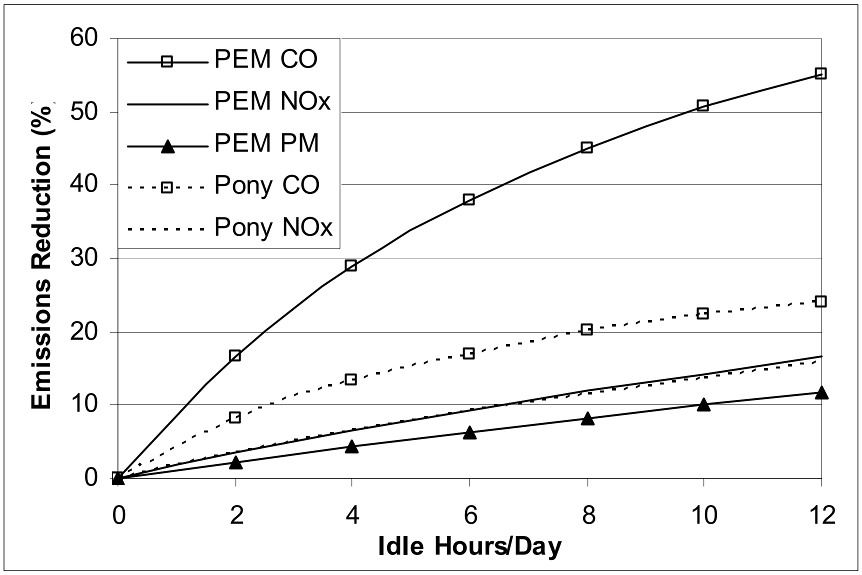


Figure 26: Percent Difference Emissions Reduction for Both APUs 1050 RPM

Conversely, a significant difference between the fuel cell and Pony Pack does arise when looking at CO emissions. The PEM APU case is seen in the figure above to reduce CO by a factor of two or more than the Pony Pack, leading one to conclude that the Pony Pack is a significant emitter of CO. PM results for the Pony Pack could not be calculated, as PM was not measured during the process of mapping out the Pony Pack. Table 3 summarizes the percent reduction of all emissions and fuel usage for both APUs for an average truck driver. It should be noted that these emissions reductions refer to the baseline case of current diesel engine technology. In reality, conventional technology will improve over the next several years to meet new emissions standards in 2007, and technologies such as PM filters and possibly NO_x adsorber catalysts may drastically reduce baseline emissions.

Table 3: Fuel Use and Emissions Reductions for an Average Truck (6 hr/day)

APU	RPM	Fuel (%)	CO (%)	NO_x (%)	PM (%)
Pony Pack	650	2.9	18.0	7.9	n/a
Pony Pack	1050	5.9	17.0	9.1	n/a
Nexa PEM	650	4.3	38.7	8.1	6.5
Nexa PEM	1050	7.3	37.9	9.4	6.2

4.5 APU Payback Periods

The commercial success of an APU will be dependent in part upon its ability to pay for itself over a finite period of time. It should be noted that the calculation made here does not include cost savings related to maintenance or non-monetary costs such as those associated with emissions. The calculation of a payback period involved a number of assumptions regarding the cost of fuel and the initial capital cost of the APU system. These values could be readily obtained for the Pony Pack scenario. The average price of diesel in California in 2003 was \$1.44/gallon [8], and the Pony Pack can be purchased for \$5600. [19]

On the other hand, obtaining these values for an H_2-fueled PEM scenario can be a good deal more difficult. Because neither the infrastructure for hydrogen fuel nor the mass production of fuel cells is yet to be implemented, the best estimate for these values are the cost targets set by government and industry researches. DOE's goal for 2015 is to have hydrogen available for the same price as gasoline, \$1.50 per gallon gasoline equivalent or \$1.49 per kg H_2. [11] A market characterization carried out at ITS UC Davis estimated the cost of a 3-6kW PEM or SOFC APU to be between \$4000-8000 around the same time period. [15] The 2.3kW PEM is both the simpler of these two fuel cell technologies and below the power range investigated in this study; consequently, the low-end estimate of \$4000 was selected.

It should be noted that cost estimates for the PEM and Pony Pack APUs pertain to 2015 targets and current information, respectively, and as a result, a direct comparison between the two may be questionable. In spite of this, there are a few factors that make this calculation more valid than it may seem at first glance. For example, it is unlikely that the price of diesel will significantly decrease over the next decade; in fact, it will most likely follow a pattern of increasing price, offsetting any reduction of the price of the Pony Pack brought about by larger production. Additionally, billions of dollars are being poured into fuel cell research in an effort to reduce their cost and the cost of their fuel to the consumer, whereas diesel engine technology and fuel distribution has been greatly refined over the last century and will not be significantly improved over this timeframe. Still bearing this caveat in mind though, the payback period calculations were carried out and are summarized in Table 4 for an average truck driver.

Table 4: Payback Periods for Both APUs for an Average Truck (6 hr/day)

APU	Engine Speed (RPM)	Gallons Diesel Saved/Year	H_2 Usage (kg/yr)	Dollars Saved per Year	Payback Period (years)
Pony Pack	650	789	0	1136	4.9
Pony Pack	1050	1685	0	2427	2.3
Nexa PEM	650	1168	186	1405	2.8
Nexa PEM	1050	2065	186	2697	1.5

It would be less than prudent to focus only on the average driver, as the smaller group of truck drivers in the high idling range may be disproportionately represented in early market penetration.

Figure **27** contains the payback period results across the full range of idle hours per day. Having a lower start-up cost and higher efficiency during operation, the PEM APU has a shorter payback period across the board. Based on truck-driver opinion, an approximation of 2 years is thought to be a maximum payback period for commercialization. [6] Keeping this in mind and looking at the figure below, marketing the Pony Pack to low speed idlers for any amount of idling per day would be improbable. However, truckers that would otherwise idle at 1050 RPM would reach this threshold at 4 hours/day for the PEM APU and 7 hours/day for the Pony Pack, forming a significant fraction of truck-drivers as a whole.

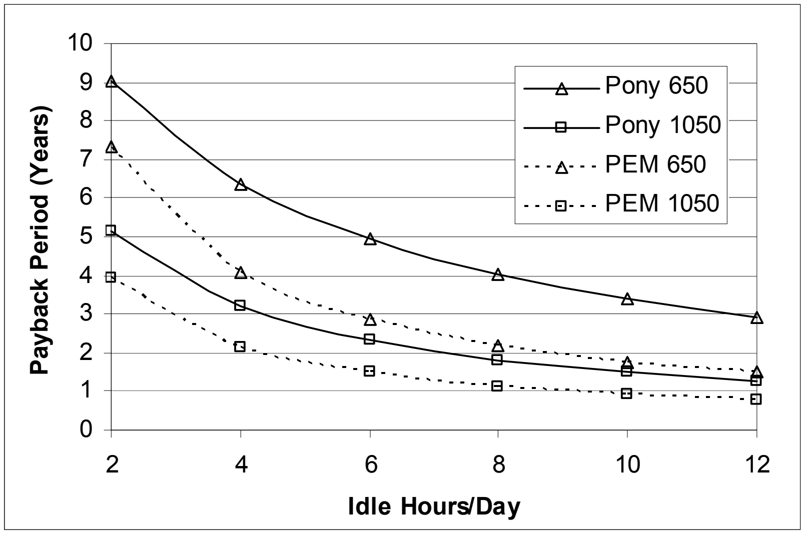


Figure 27: Payback Periods for Both APUs for 650 and 1050 RPM

5.0 CONCLUSIONS

The body of this work, including the testing of a Pony Pack diesel engine and Nexa PEM stack, the characterization of truck driver behavior at idle, and the creation of an APU model within ADVISOR, revealed the following key conclusions:

- The Nexa stack and Pony Pack unit had maximum experimental efficiencies of 49% and 30%, respectively.
- To have the same accessory functionality, an electrical APU system requires an average of 1.3kW compared to 2.3kw for its mechanical counterpart.
- Two Nexa stacks, hooked up together in series, were able to provide a maximum power of 2.5kW, sufficient for an APU application.
- Run over their respective accessory profiles, the Nexa stack and Pony Pack had average thermal efficiencies of 38.3 and 19.5%, compared to 8.3% for baseline idling at 850 RPM.

Using the outputs from the ADVISOR model, and assuming that the average truck driver drives 9.1 hours per day, idles 6 hours per day at 1050 RPM, and is on duty 300 days out of the year, the following conclusions could be made on the annual fuel use, total emissions reductions, and cost benefits for one truck:

- Using a Pony Pack would reduce total diesel consumption by 5.9%, CO by 17%, and NO_x by 9.1%. The reduction of PM could not be determined due to a lack of input data.
- Using two Nexa units under the same conditions would reduce total fuel consumption by 7.3% (diesel equivalent), CO by 37.9%, NO_x by 9.4%, and PM by 6.2%.
- A Pony Pack that costs $5600 would have a payback period of 2.3 years.
- A PEM APU purchased at the target cost of $4000 operating on hydrogen with a target cost of $1.50 per gallon gasoline equivalent would have a payback period of 1.9 years.

REFERENCES

[1] Abrams, F., 2000. "Fuel for Thought." American Trucking Association, Fleet Wonder Magazine, Alexandria, VA. Website: http://www.greentruck.com/news/fo0500.html. Visited December 7, 2001.

[2] ADVISOR Documentation, 2002. Website: http://www.ctts.nrel.gov/analysis/advisor_doc/advisor_doc.htm. April 30.

[3] Ballard Power Systems, 2002. "Nexa Power Module Installation Manual." July 11.

[4] Brodrick, C.J., H.A. Dwyer, M. Farshchi, D.B. Harris, F.G. King Jr., 2002. "Effects of Engine Speed and Accessory Load on Idling Emissions from Heavy-Duty Diesel Truck Engines." *Journal of the Air & Waste Management Association*, 52: 174-185, September.

[5] Brodrick, C. J., M. Farshchi, H.A. Dwyer, S.W. Gouse III, M. Mayenburg, and J. Martin, 2000. "Demonstration of a Proton Exchange Membrane Fuel Cell as an Auxiliary Power Source for Heavy Trucks." *Society of Automotive Engineers Technical Paper Series*. 2000-01-3488.

[6] Brodrick, C. J., N.P. Lutsey, Q.A. Keen, D.I. Rubins, J.P. Wallace, H.A. Dwyer, D. Sperling, D., and S.W. Gouse III, 2001. "Truck Idling Trends: Results of a Northern California Pilot Study." *Society of Automotive Engineers Technical Paper Series.* 2001-01-2828.

[7] California Analytical Instruments. www.gasanalyzers.com. Accessed June 23, 2003

[8] California Energy Commission, 2003. "Causes for Gasoline & Diesel Price Increases in California." May 1, 2003. http://www.energy.ca.gov/2003_price_spikes/2003-05-01_GASOLINE.PDF

[9] DieselNet, Emissions Standards: USA, Heavy-duty Truck and Bus Engines. http://www.dieselnet.com/standards/us/hd.html. Accessed June 3, 2003.

[10] Dwyer, H.A., Tang, J., Brodrick, C.J., Khau, L., Becker, C., Wallace, J., 2001. "The Influence of Grade on the Operating Characteristics of Conventional and Hybrid Electric Transit Buses." *Society of Automotive Engineers Technical Paper Series.* 02TB-73.

[11] FreedomCar, http://www.cartech.doe.gov/freedomcar/technical-goals.html. Accessed July 6, 2003.

[12] Goldsmith, R., 2001. "New Law may aid mitigation process." Envision, TxDOT Environmental Affairs Division, Volume 7, Issue 2.

[13] Hardy, K., Rousseau, A., "PSAT: Argonne's Vehicle System Modeling Tool." https://www.psat.anl.gov/pdfs/psat-review.pdf. Accessed June 17, 2003.

[14] Kelly, K., Rajagopalan, A., 2001. "Benchmarking of OEM Hybrid Electric Vehicles at NREL." NREL/TP-540-31086, August. http://www.ctts.nrel.gov/analysis/pdfs/fy01_benchmark_milestone.pdf.

[15] Lutsey, Nicholas, Brodrick, C.J., Sperling, D., Dwyer, H.A., 2003. "Markets for Fuel Cell Auxiliary Power Units in Vehicles: A Preliminary Assessment." *Transportation Research Board 82nd Annual Meeting Proceedings.*

[16] Lutsey, N., Wallace, J., Brodrick, C.J., Dwyer, H.A., Sperling, D., 2003. "Modeling Auxiliary Power Options for Heavy-Duty Trucks: Engine Idling vs. Fuel Cells." *Society of Automotive Engineers Technical Paper Series*. Submitted for Publication.

[17] Maldonado, Hector, 2002. "Development of Heavy Duty Truck Chassis Dynamometer Driving Cycles for Source Testing for Emissions Modeling." California Air Resources Board. 12th CRC On-Road Vehicle Emissions Workshop. April 15-17.

[18] McConnell, D., 2000. "Transportation Applications for Solid Oxide Fuel Cells-Auxiliary Power." Presentation delivered to the U.S. Department of Energy in June. http://www.netl.doe.gov/scng/publications/fuelcell/seca/seca_pres/secabppn.pdf.

[19] Pony Pack, Inc. http://www.ponypack.com/. Accessed June 11, 2003.

[20] SAE, 2000. "Information Relating to Duty Cycles and Average Power Requirements of Truck and Bus Engine Accessories." SAE J1343. August

[21] Stodolsky, F., L. Gaines, A. Vyas, 2000. "Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks." ANL/ESD-42, Argonne National Laboratory: Argonne, IL.

[22] Tachtler, J., T. Dietsch, and G. Gotz (2000). "Fuel Cell Auxiliary Power Unit – Innovation for the Electric Supply of Passenger Cars." Society of Automotive Engineers Paper 2000-01-0374.

[23] Tóth-Nagy, C., 2001. "Emission Modeling with Artificial Neural Network." Proceedings of the Joint ADVISOR/PSAT Vehicle Systems Modeling User Conference, August. http://www.ctts.nrel.gov/analysis/pdfs/30762.pdf

[24] Traub, N., "Dual/Higher Voltage – A Global Opportunity." SAE Strategic Alliance, http://www.sae.org/42volt/dual_higher_sum.pdf. Accessed June 18, 2003

[25] Truck Maintenance Council, 1995. *Analysis of Costs from Idling and Parasitic Devices for Heavy Duty Trucks*, Truck Maintenance Council Recommended Procedure 1108, American Trucking Associations, Alexandria, Va., March.

[26] U.S. Department of Commerce, Bureau of Census, 1997. *Vehicle Inventory and Use Survey*.

[27] U.S. Department of Energy, 2000. "Technology Roadmap for the 21st Century Truck Program." December.

[28] Van den Berg, A.J., 1996. "Truckstop Electrification: Reducing CO_2 Emissions from Mobile Sources While They are Stationary." *Journal of Energy Conversion Management.,* Vol. 37 (6-8), 879-884.

[29] Vojtisek-Lom, M., Lambert, D.C., Wilson, P.J., 2002. "Real-world Emissions from 40 Heavy-Duty Diesel Trucks Recruited at Tulare, CA Rest Area." *Society of Automotive Engineers Technical Paper Series.* 2002-01-2901.

[30] Webasto, 2001. "Essential Power Systems Workshop: Cab/Engine Heaters." December 12. http://www.trucks.doe.gov/pdfs/V/108.pdf. Accessed August 6, 2002.

[31] Wipke, K., Cuddy, M.R., Burch, S.D., 1999. "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach." NREL/JA-540-26839, September.

[32] Zizelman, J., Shaffer, S., Mukerjee, S., 2002. "Solid Oxide Fuel Cell Auxiliary Power Unit – A Development Update." *Society of Automotive Engineers Technical Paper Series*. 2002-01-0411.

APPENDIX

Appendix A: Detailed Results of Nexa Stack Testing

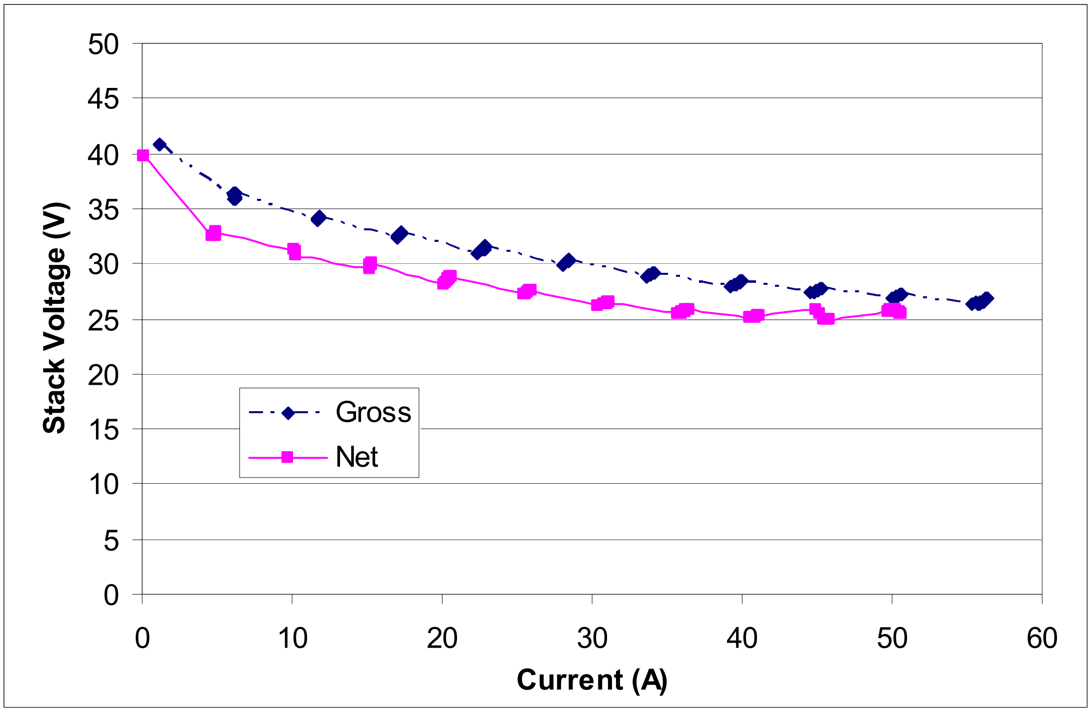


Figure A.1: Gross and Net V-I Curves at Ambient Temperature

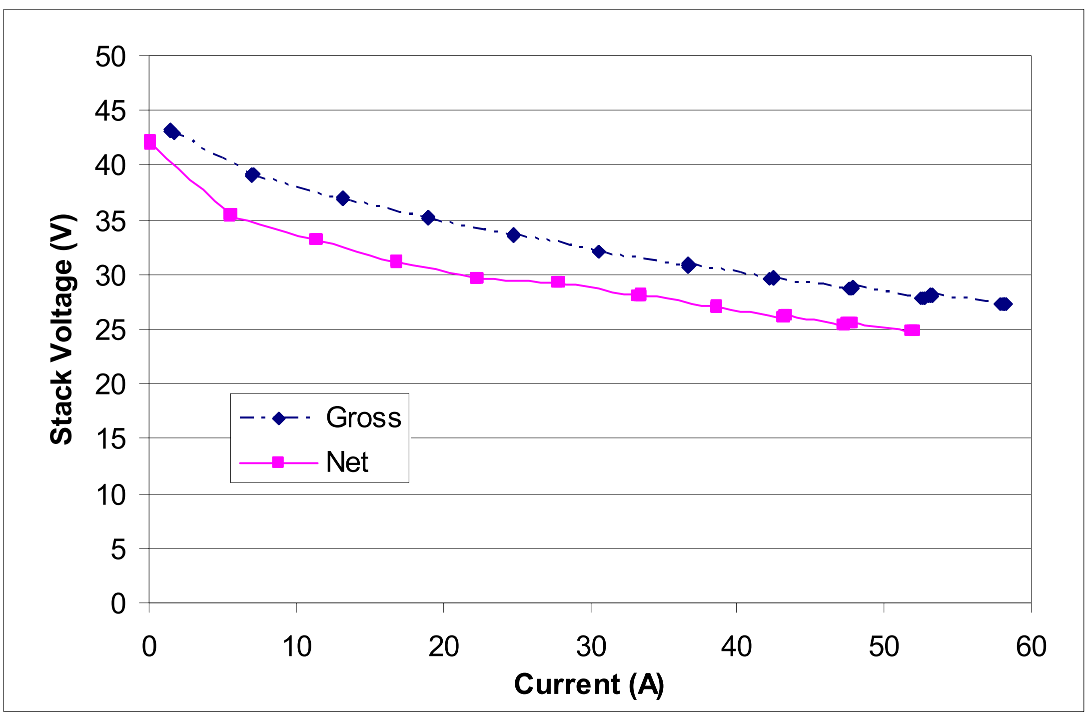


Figure A.2: Gross and Net V-I Curves at Operating Temperature

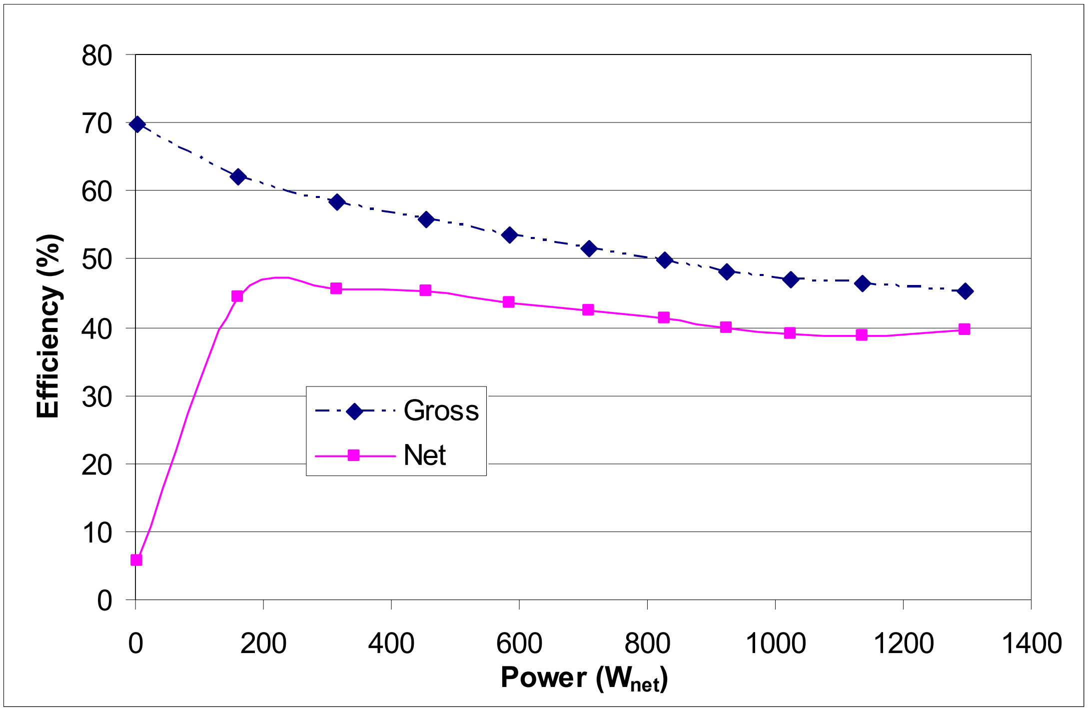


Figure A.3: Gross and Net Efficiency Curves at Ambient Temperature

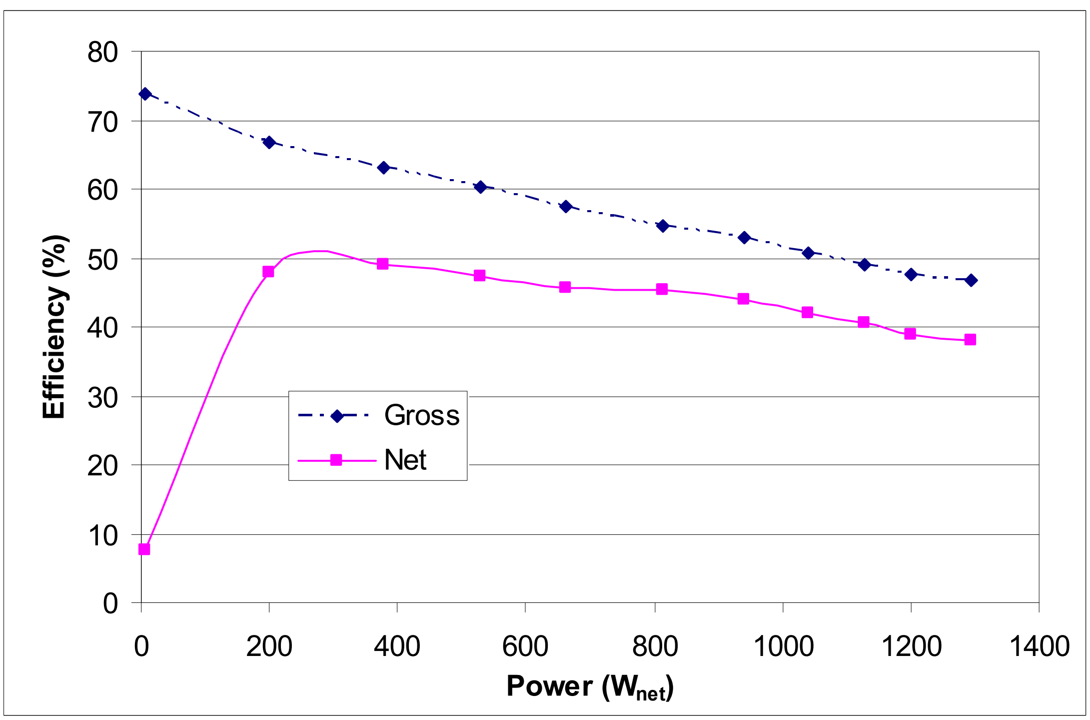


Figure A.4: Gross and Net Efficiency Curves at Operating Temperature

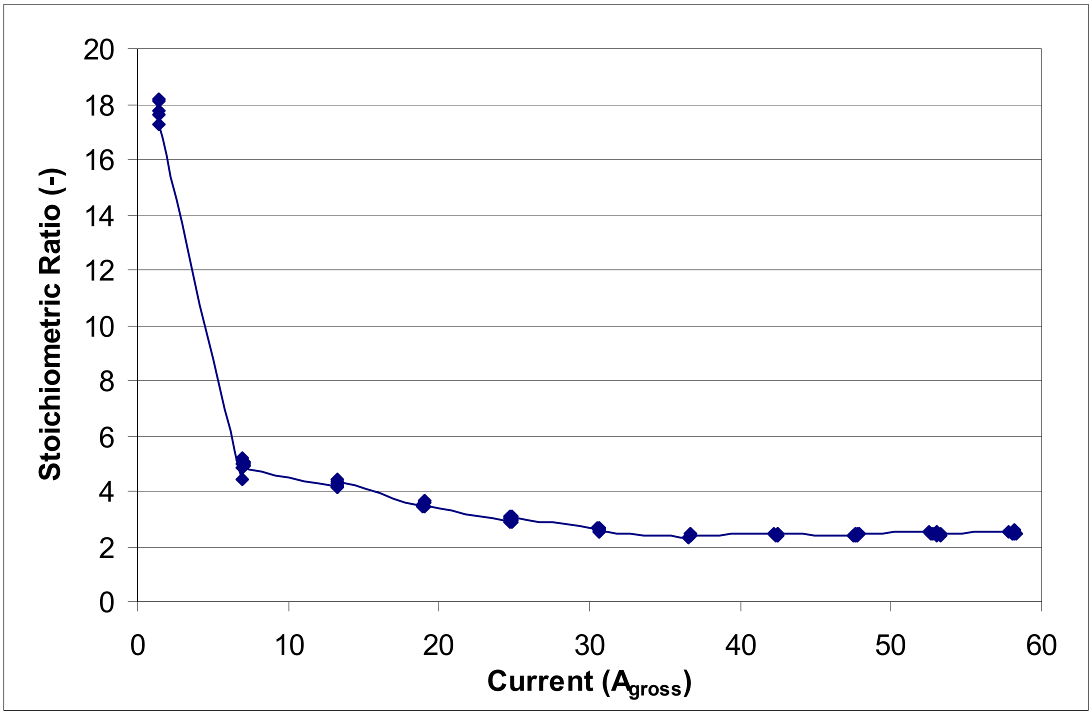


Figure A.5: Stoichiometric Ratio versus Gross Current

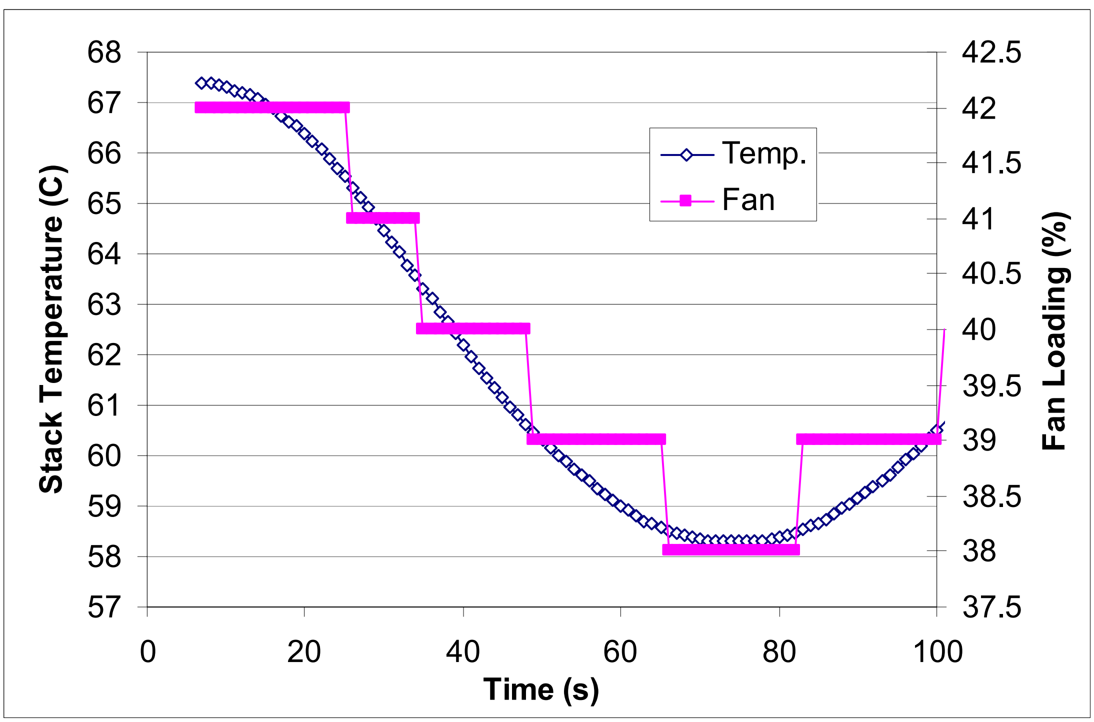


Figure A.6: Thermal Management Control Strategy

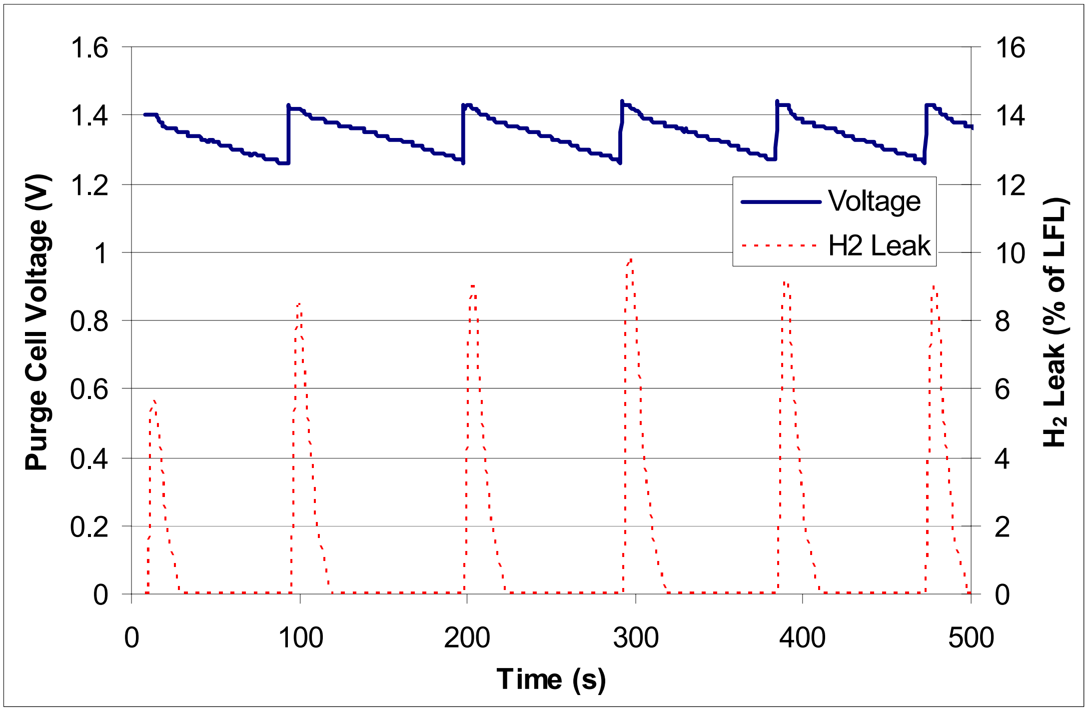


Figure A.7: Hydrogen Purging During 22 A_{net} Output

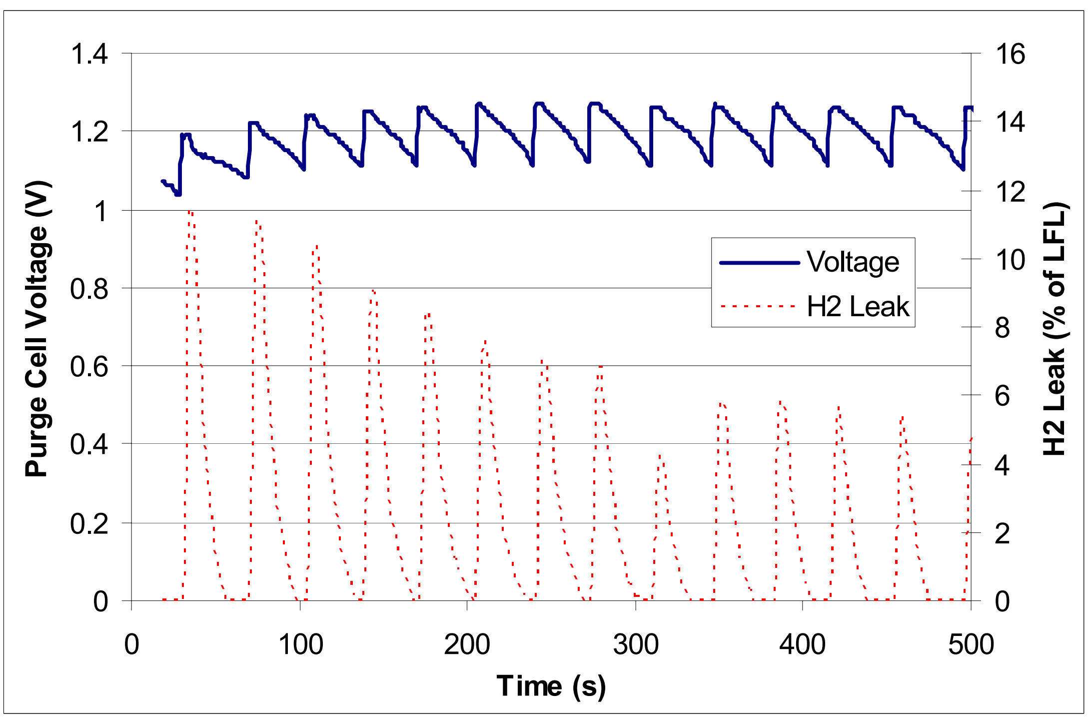


Figure A.8: Hydrogen Purging During 44 A_{net} Output

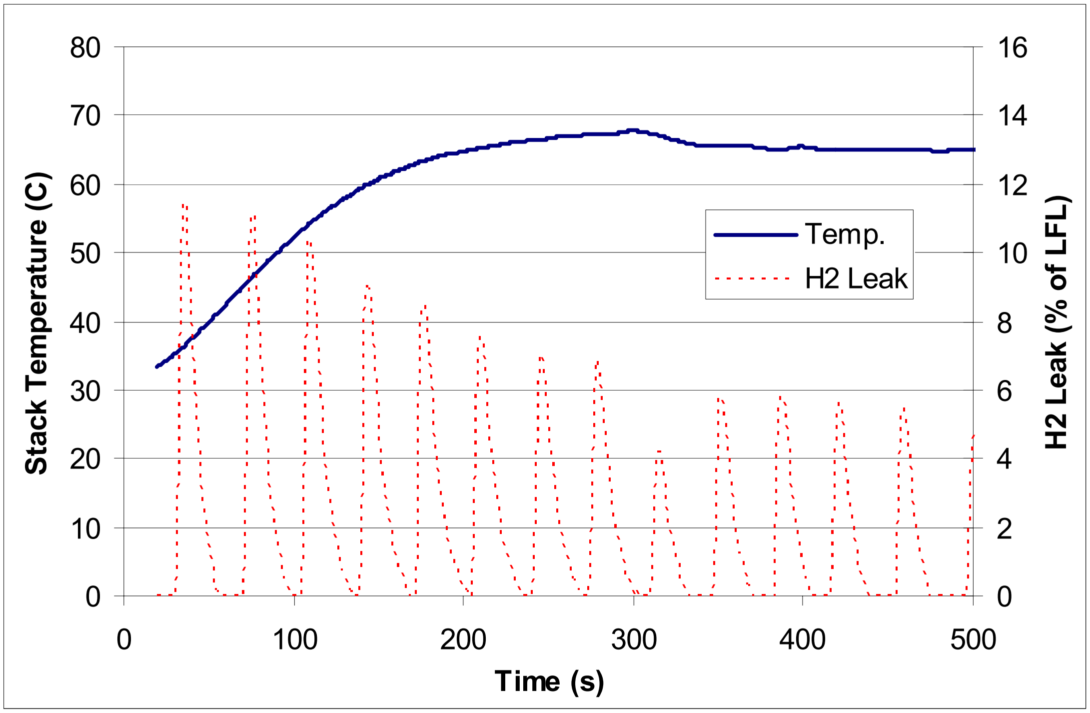


Figure A.9: Effect of Temperature on Purging During 44 A_{net} Output

Appendix B: A "How to" guide concerning modifications within ADVISOR

Appendix B.1: Input Data Files

Creating the m-files in Matlab that are to provide all of the necessary input data for the two APUs is probably the most straightforward part of the model creation. The most efficient and least problematic method for writing the files is to begin with a data file for a similar component that is pre-existing within ADVISOR. There are two main reasons for this: first, ADVISOR's data files are already in a user-friendly, well-commented format that is easy to modify, and second, there are many extraneous variables, such as thermal coefficients, fuel LHV, etc., that will not need to be changed for a similar type of engine or fuel cell, but will result in an error if not properly loaded.

For the Pony Pack, any one of the diesel engine files, which are the data files prefixed by "**fc_ci**" for **f**uel **c**onverter – **c**ompression **i**gnition, could be chosen. For the Nexa stacks, the ADVISOR file fc_anl50_h2.m was used as a starting point. The sections of code on the following pages contains only the variables that required changing for each of the two APU files, including descriptive parameters in the top sections and then the most crucial variables in the bottom sections, such as fuel flow rate, each of the four emissions, etc. After the changes were made, the file names were renamed to be fc_ci7_pp_emis.m and fc_2nexa_h2.m for the Pony Pack and PEM stacks, respectively.

Matlab Code for Pony Pack Input Data

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_description='Pony Pack Kubota 0.5L Diesel Engine';
fc_version=2002; % version of ADVISOR for which the file was generated
fc_proprietary=0; % 0=> non-proprietary, 1=> proprietary
fc_validation=1; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and has been verified
fc_fuel_type='Diesel';
fc_disp=0.479; % (L) engine displacement
fc_emis=1;      % boolean 0=no emis data; 1=emis data
fc_cold=0;      % boolean 0=no cold data; 1=cold data exists
disp(['Data loaded: FC_CI7_PP_emis.m - ',fc_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPEED & TORQUE RANGES over which data is defined
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (rad/s), speed range of the engine (converted from RPM)
fc_map_spd=[3150]*pi/30;

% (W), power range of the engine
fc_pwr_map= [2.57  2.77  3.41  4.02  4.64  5.25  6.52  7.15]*1000;

% (N*m), torque range of the engine (converted from power range)
fc_map_trq=[.01 fc_pwr_map/fc_map_spd];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUEL USE AND EMISSIONS MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% (g/s) , fuel use map indexed horizontally by fc_map_trq
fc_fuel_map=[0.176      0.277 0.285 0.313 0.349 0.380 0.413 0.484
      0.525];

% (g/s), engine out HC emissions indexed horizontally by fc_map_trq
fc_hc_map=zeros(size(fc_fuel_map));

% (g/s), engine out CO emissions indexed horizontally by fc_map_trq,
%converted from g/hr
fc_co_map=[37.30  25.50 22.77 17.29 11.90 8.77  6.80  5.45  5.43]/3600;

% (g/s), engine out NOx emissions indexed horizontally by fc_map_trq,
%converted from g/hr
fc_nox_map=[5.73  8.91  9.71  12.08 13.90 17.11 19.28 25.45
      27.63]/3600;

% (g/s), engine out PM emissions indexed horizontally by fc_map_trq
fc_pm_map=zeros(size(fc_fuel_map));

% (g/s), engine out O2 emissions indexed horizontally by fc_map_trq,
%converted from g/hr
fc_o2_map=[7778   6554  6438  6062  5610  5166  4737  3867  3318]/3600;

% (g/s), engine out exhaust flow indexed horizontally by fc_map_trq
fc_exflow_map=[12.41 12.31 12.29 12.22 12.16 12.09 12.00 11.87 11.78];
```

Matlab Code for Nexa Stacks Input Data

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FILE ID INFO
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_description='NEXA Stacks - 2.5kW (net) Ambient Pressure Hydrogen
Fuel Cell System';
fc_version=2002; % version of ADVISOR for which the file was generated
fc_proprietary=1; % 0=> non-proprietary, 1=> proprietary, do not
distribute
fc_validation=1; % 0=> no validation, 1=> data agrees with source data,
% 2=> data matches source data and data collection methods have been
verified
disp(['Data loaded: FC_2NEXA_H2.m - ',fc_description]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FUEL USE AND EMISSIONS MAPS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc_pwr_map=[6.44 199.04 378.95 528.26 662.01 813.88   940.13     1041.13
1128.29 1200.96 1295.41]*2; % W (net) including parasitic losses

fc_eff_map=[17.6  47.9  48.9  47.4  45.7  45.4  43.8  41.9  40.4    39.0
      38.0]/100; % efficiency indexed by fc_pwr

% create fuel consumption map (g/kWh)
fc_fuel_lhv=120.0*1000; % (J/g), lower heating value of the fuel
fc_fuel_map_gpkWh=(1./fc_eff_map)/fc_fuel_lhv*3600*1000;

% create fuel use map (g/s)
fc_fuel_map=fc_fuel_map_gpkWh.*fc_pwr_map/1000/3600; % used in block
diagram

% (g/s), engine out HC emissions indexed horizontally by fc_pwr_map
fc_hc_map=zeros(size(fc_fuel_map));

% (g/s), engine out CO emissions indexed horizontally by fc_pwr_map
fc_co_map=zeros(size(fc_fuel_map));

% (g/s), engine out NOx emissions indexed horizontally by fc_pwr_map
fc_nox_map=zeros(size(fc_fuel_map));

% (g/s), engine out PM emissions indexed horizontally by fc_pwr_map
fc_pm_map=zeros(size(fc_fuel_map));

% (g/s), engine out O2 emissions indexed horizontally by fc_pwr_map
fc_o2_map=zeros(size(fc_fuel_map));
```

Appendix B.2: ADVISOR's GUI

As was the case when creating input m-files, creating a GUI for the APU model began with pre-existing GUI files within ADVISOR. With the release of ADVISOR 2002, all GUI files were converted from .m files to .fig files. This change may seem minor, but it enabled the use of "guide," Matlab's graphical GUI editor. The GUI file optionlist.fig is used in ADVISOR to organize the data libraries for all components and served as an apt starting point in creating an APU graphical interface. Below is a summary of the GUI creation process.

Entering the following code at the command prompts brings up Figure B.2.1. Utilizing the buttons on the left, everything seen in the window is fully customizable.

```
>> guide optionlistfig.fig
```

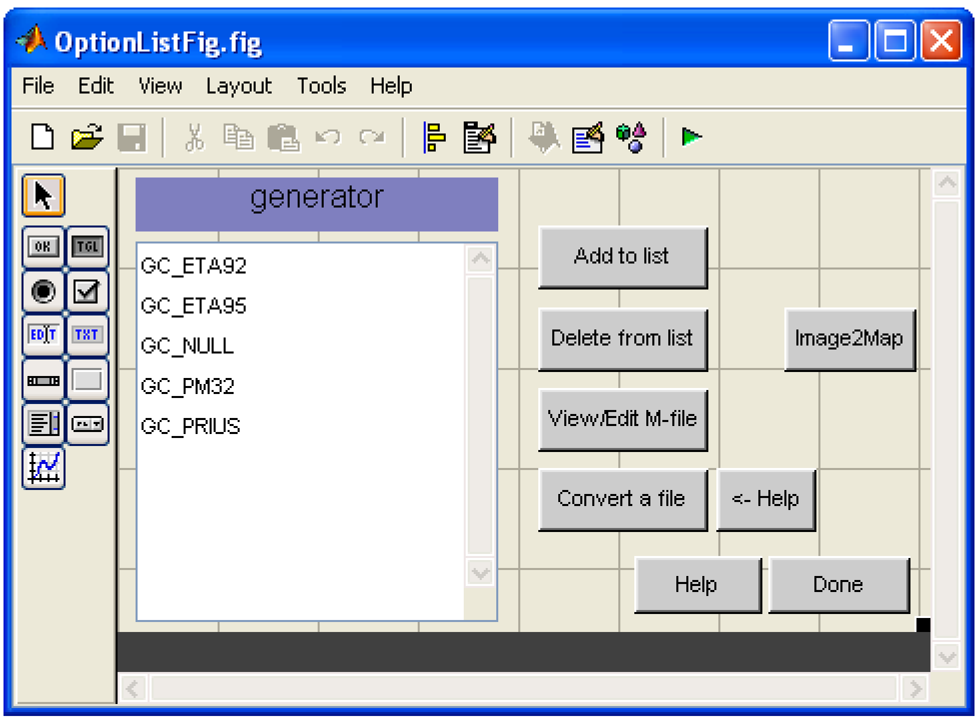


Figure B.2.1: ADVISOR's Component Selection Window Displayed in GUIDE

Several changes needed to made, ranging in complexity from changing the text strings for display purposes to editing the callbacks for each button. A callback is a line of Matlab code that is executed when a GUI item, a button for example, is selected. The original buttons used for editing the list of component data from the original figure were replaced with edit boxes where pertinent variables could be entered for the APU model. Shown below in Figure B.2.2 for the fuel cell, these include the operating temperature, a variable used to scale the maximum power of the unit, and two Boolean variables that serve as inputs to the control strategy. After making all of the necessary changes, the figure was renamed to be "apu_gui.fig," and the following command displays the new figure in GUIDE.

```
>> guide apu_gui.fig
```

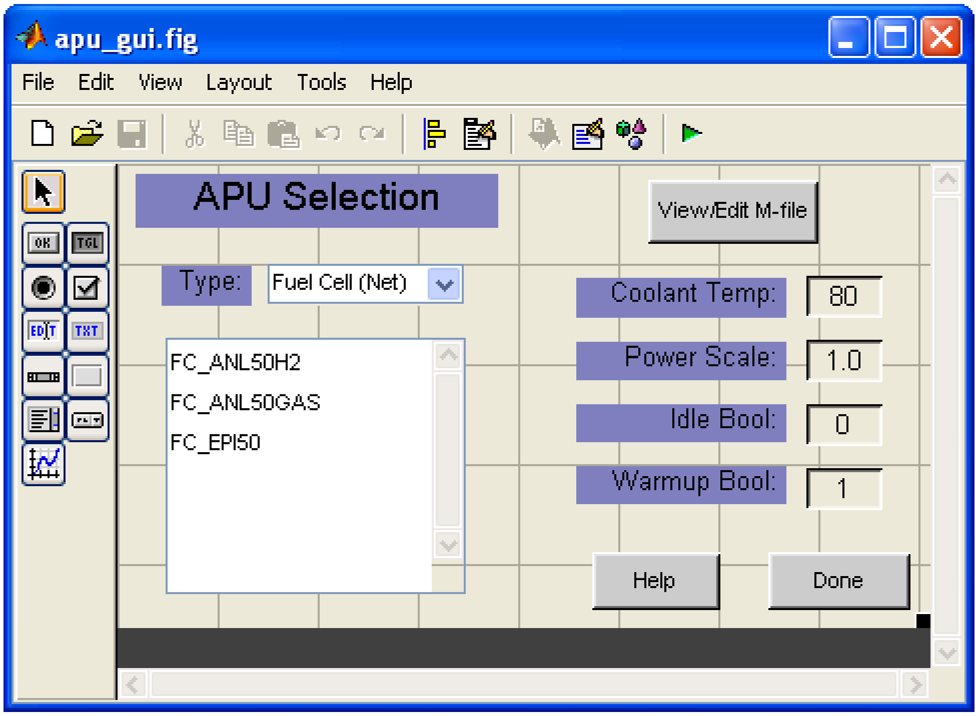


Figure B.2.2: Optionlistfig Modified for the APU Model, Displayed in GUIDE

This figure is now ready to be used by ADVISOR's main input window. The file Inputfigcontrol.m was modified to include a section of code that checks if the vehicle file name, shown in the uppermost pull-down menu as "TractorTrailer_APU_in" in the figure below, is one of the APU vehicle files; if so, the "APU" button is placed at the bottom of the other component buttons. Clicking on this button executes the following code and opens the figure that was created in GUIDE, shown in the bottom left corner of Figure B.2.3.

```
>> h = open('apu_gui.fig');
   figure(h);
```

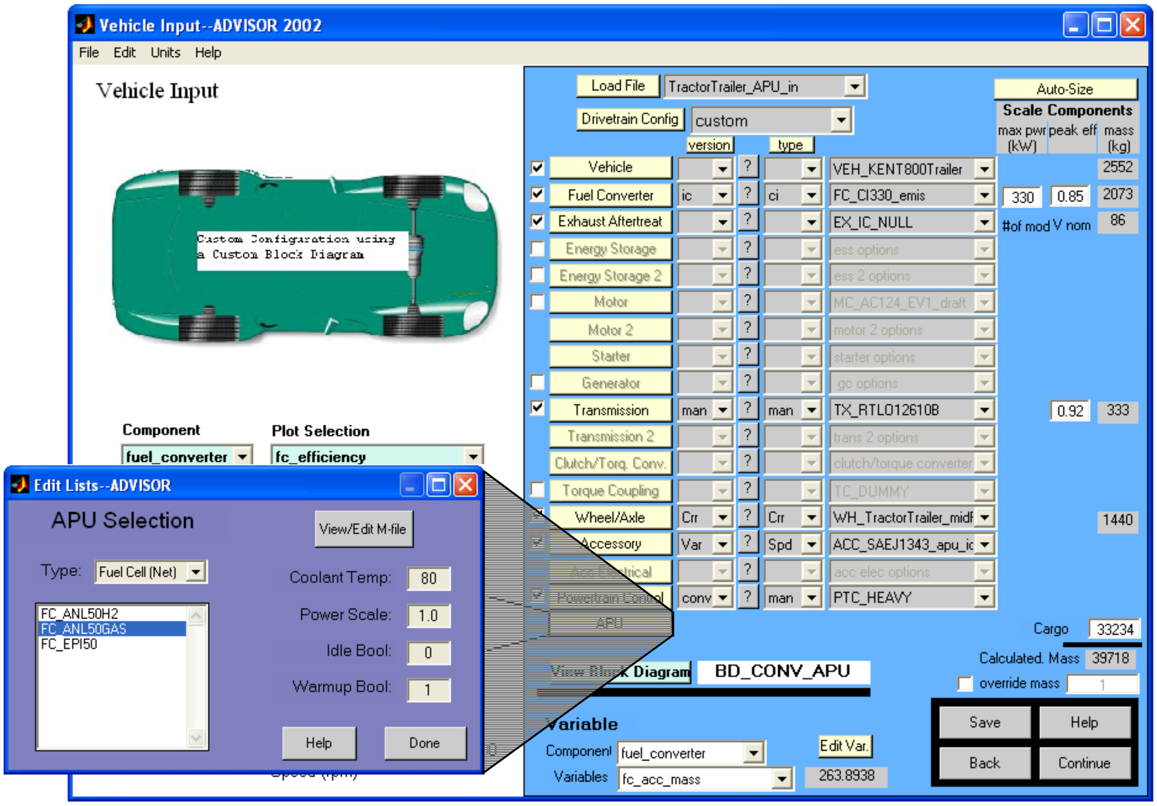


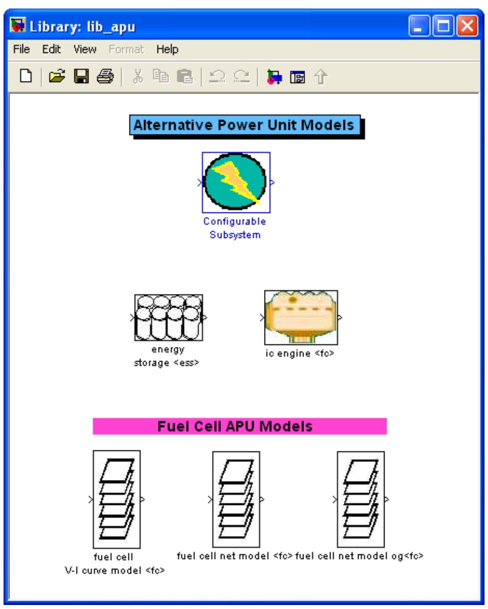
Figure B.2.3: ADVISOR's Main Input and APU Selection Windows

Appendix B.3: Simulink Block Diagrams

Working with the block diagram structure of Simulink may be more user-friendly than sorting through the collection of GUI files, but this should not be mistaken for a lack of complexity, as all of the actual modeling is calculated within these block structures. In other words, Simulink may be less challenging from a programmer's perspective, but much more so from an engineering point of view.

As mentioned briefly in the body of this work, the advent of Configurable Subsystems in Simulink 4.1 greatly simplified the tasks of creating a modular APU model, whose power generator, whether it be a fuel cell or diesel engine, could be readily interchanged. Each of these subsystems requires a library, including all of the possible block diagrams for the module; the library created for the APU is shown here on the left in Figure B.3.1. Each of these member blocks originated as models for propulsion-sized components and were then modified to more closely resemble the operation of an APU. Each of these blocks have to have the same overall format, i.e. the same number of inputs and outputs.

Figure B.3.1: Simulink APU Library



The energy storage block is the model of the battery, which, depending on its input data, can serve as either the auxiliary battery in the fuel cell APU model or as a larger battery pack capable of providing hours of power as a potential APU of its own. All of the thermal calculations were removed for the engine and fuel cell models, in an effort to avoid unnecessary complexity. The engine model needed to be modified to take as input only requested power, as opposed to requested torque and speed values, in order to match the format of the other APU blocks. The speed of the engine is now an input within the block itself, stored under the variable name "apu_spd_cmd." Along the same lines, all of the 2-d interpolations of the input maps used to calculate fuel use and emissions of the engine needed to be converted to 1-d calculations, to reflect the operating line resulting from the speed governor of the Pony Pack.

Figure B.3.2 illustrates the communication between the configurable subsystem and its corresponding library. Double-clicking on the APU block within the overall block diagram opens the widow on the upper right. This block contains the configurable subsystem block and some control strategy calculations to determine if the APU is on or off. Right-clicking on this block gives the user a pull-down menu, where he/she is able to customize this block and select any of the members of the library shown above.

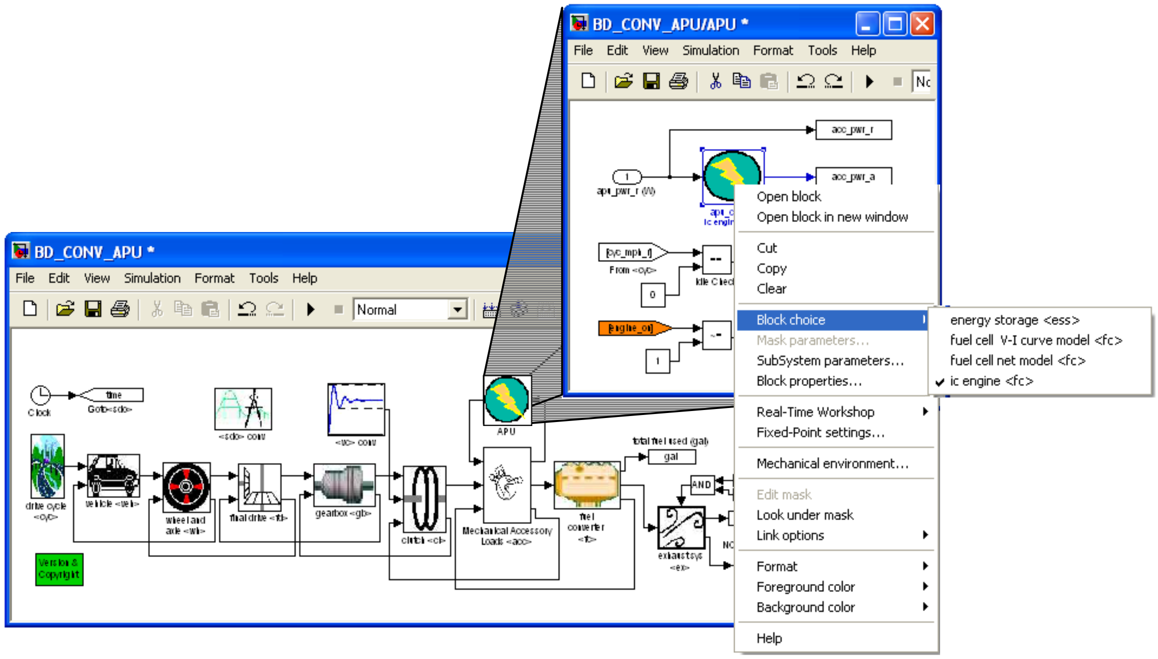


Figure B.3.2: Illustration of Configurable Subsystem/Library Interaction

Appendix C: Truck-Driver Behavior from Survey Data and Literature

The following two figures are results from a nation-wide survey conducted by researchers at ITS Davis in 2003 that is yet to be published. Approximately 365 truck-drivers were interviewed, but after filtering out certain incomplete or inconsistent responses, around 320 surveys remained for data reduction. The term "Frequency" on the y-axis of the figures below means the total number of truckers (out of the 320) responding within each group on the x-axis.

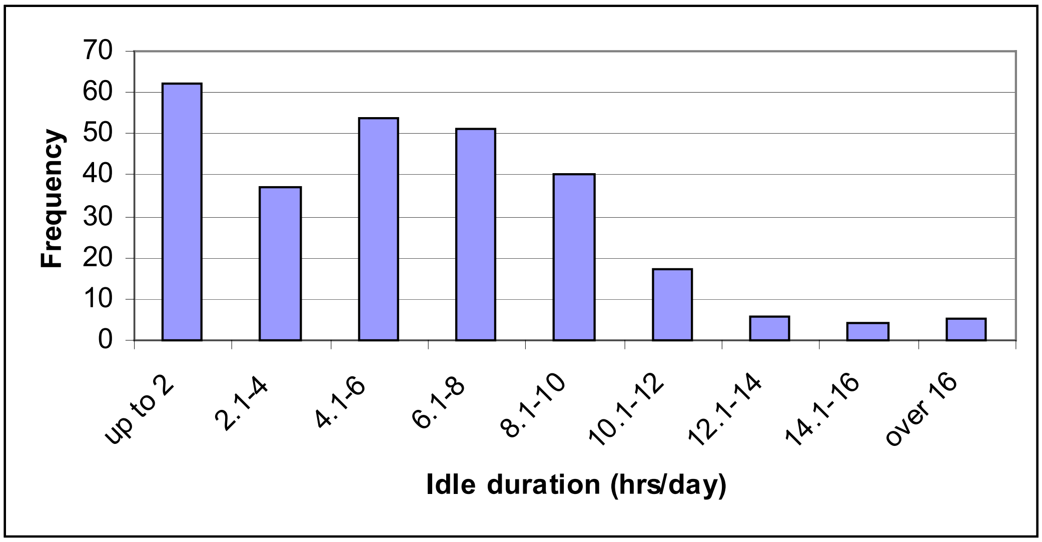


Figure C.1: Histogram of Idle Hours per Day Reported by Truck Drivers

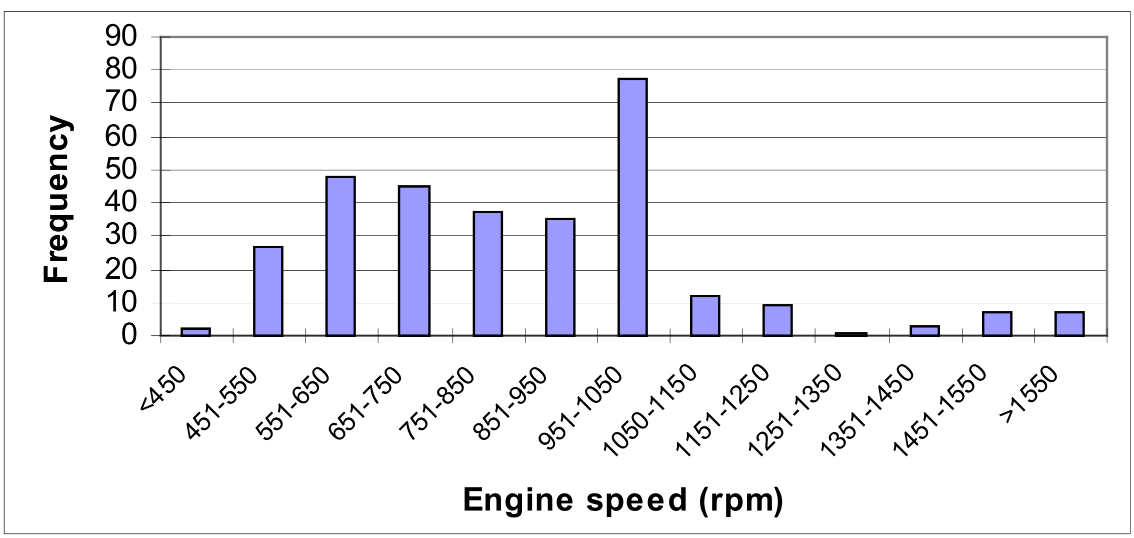


Figure C.2: Histogram of Engine Speed at Idle Reported by Truck Drivers

Table C.1 Idling Estimates for Heavy Duty Trucks from Available Studies [16]

Study	Estimated average idling duration [a]		Comments
	Hours per day	Percent of engine run-time	
TMC, 1995 [25]	6	40	Estimation used in calculations
Stodolsky et al, 2000 (base case) [21]	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 [30]	5	36	Based on average sleeping time in truck, *not* actual time with engine idling
Maldonado, 2002 [17]	6.5	42	Datalogs of 84 trucks over 1600 total hours in California fleets, without distinction between nondiscretionary and avoidable resting idling
Pilot Survey [6]	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

Appendix D: Detailed Comparison of PEM and Pony Pack Emissions Reductions

The following figures contain the total tonnage and percent reduction of each emission, CO, NO_x, and PM, accompanying the use of a Pony Pack and PEM APU. As explained in the body of this work, the numbers 650 and 1050 are the RPM that the propulsion engine is idling at for the baseline comparison. Notably, the emissions reductions, particularly those seen with CO and PM, were not very sensitive to varying baseline RPM, presumably a limitation of the incomplete raw emissions data maps used to model the propulsion engine. The PM plots only pertain to the PEM APU because PM data was not collected while mapping out the Pony Pack.

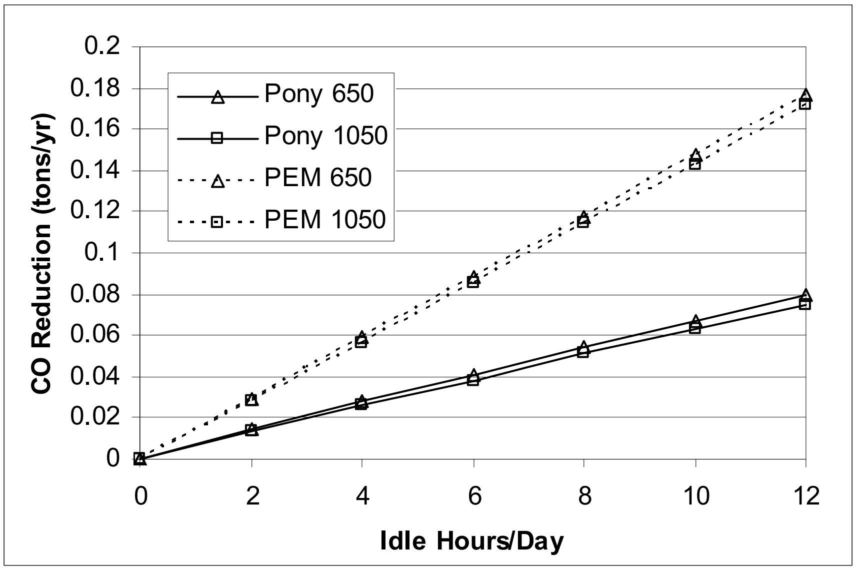


Figure D.1: Annual Per Truck CO Reduction with Both APUs

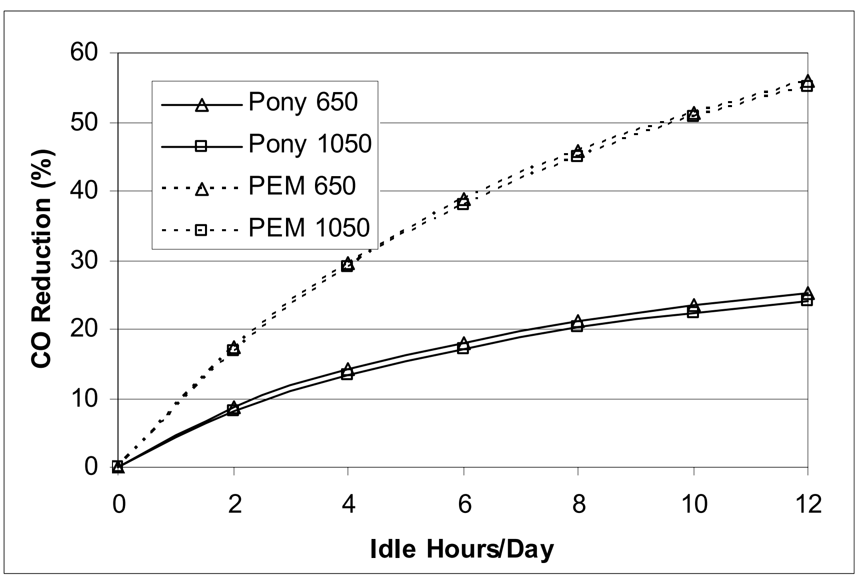


Figure D.2: Percent Reduction of Total CO Emissions with Both APUs

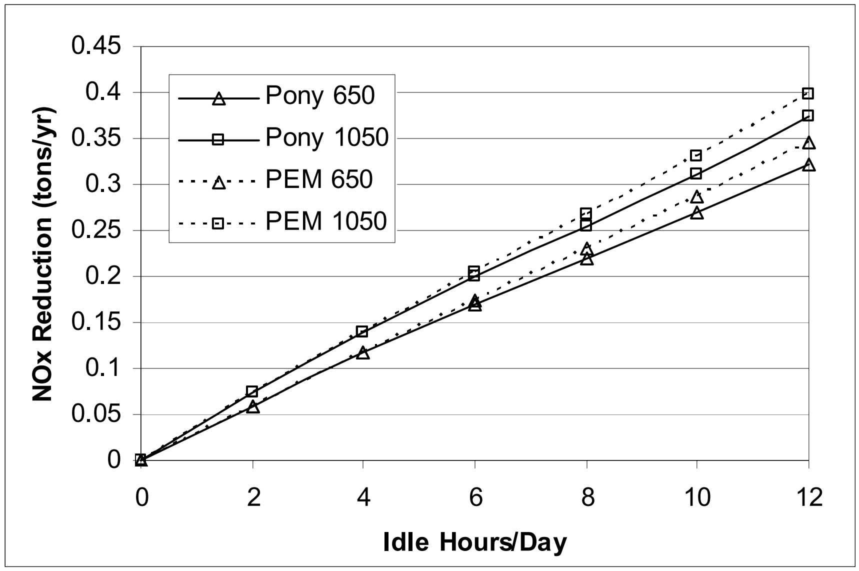


Figure D.3: Annual Per Truck NO_x Reduction with Both APUs

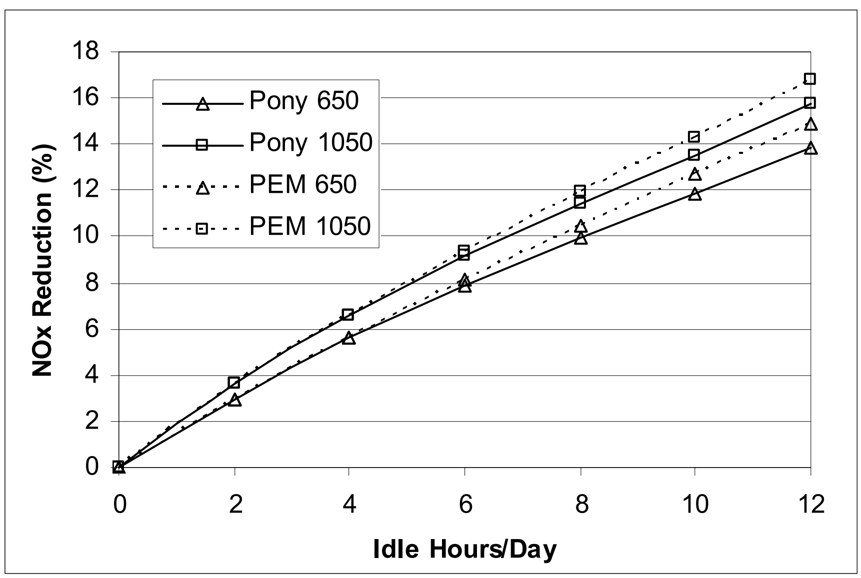


Figure D.4: Percent Reduction of Total NO_x Emissions with Both APUs

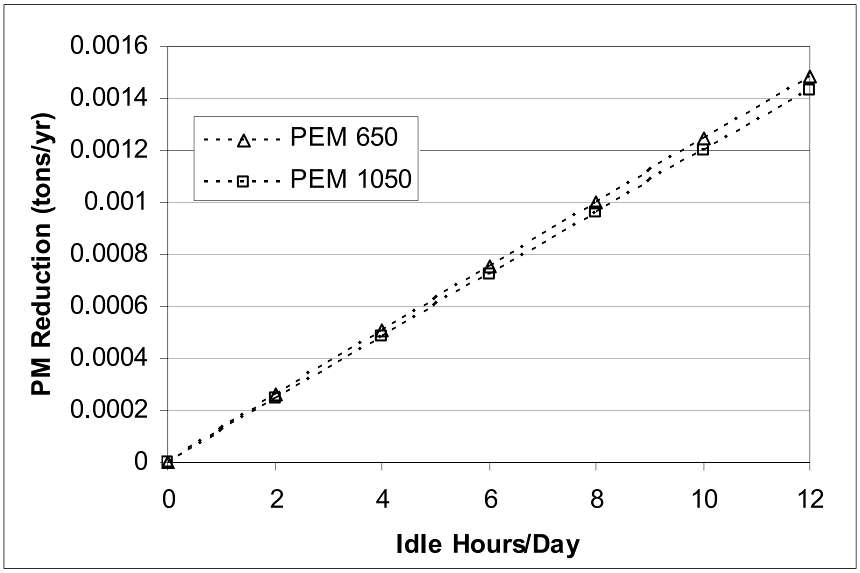


Figure D.5: Annual Per Truck PM Reduction with PEM APU

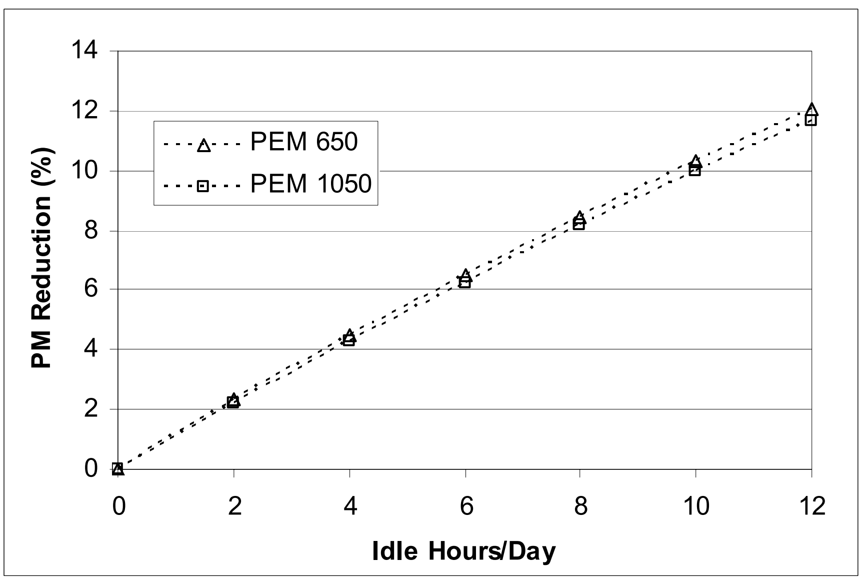


Figure D.6: Percent Reduction of Total PM Emissions with PEM APU