ABSTRACT

Title of Document: SYSTEM-LEVEL ANALYSIS AND COMPARISON OF LONG-HAUL TRUCK IDLE-REDUCTION TECHNOLOGIES

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As of January 1, 2008 idling of the main vehicle engine for the purpose of powering sleeper cabin amenities by any truck over 10,000 lbs (4,500 kg) within the borders of the state of California is prohibited unless strict emissions standards are met. In anticipation of tighter idling legislation and rising fuel prices nation-wide, idle-reduction technologies are garnering an increasing market share. These include auxiliary battery-electric power systems, primary vehicle battery systems, truck-stop electrification, diesel-fueled auxiliary power systems, and fuel-fired heaters.

The purpose of this thesis is to provide a concise, detailed compilation of currently-marketed idle-reduction technologies, propose methodologies for evaluation and comparison, develop transient energy system simulations of the most prominent idling alternatives the most suitable commercially available software, create a simple, flexible cost-comparison program, propose future developments and applications, and conduct a critical assessment from the parameters considered which technology has the greatest relative advantage.

SYSTEM-LEVEL ANALYSIS AND COMPARISON OF LONG-HAUL TRUCK IDLE-REDUCTION TECHNOLOGIES

By

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Dedication

This thesis is dedicated to my wife Nicole, who even when the going got tough (and it sure did) had enough faith in me for the both of us.

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I would like to acknowledge with deepest gratitude the contributions of my mentor, Dr. W. Travis Horton, and my advisor, Dr. Reinhard Radermacher.

I would also like to take the opportunity to thank my family for all of their love, support, and patience over this past year.

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1 Background and Literature Review

1.1 Introduction

Vehicles of all types are run at idle to provide power to accessories. The type and power demand of a vehicle's accessories are largely dependent on the function they serve. Class 7 and 8[1] long-haul trucks, also referred to as tractors or heavy-duty trucks, are designed for the transport of goods over long distances. Many are equipped with a sleeper cabin in which the driver lives while on the road. Typically, these types of trucks idle to provide power for cabin climate control; residential-type AC electric loads, also referred to as "hotel loads;" and other miscellaneous equipment.

The two primary objections to idling are made on the grounds of fuel consumption and exhaust gas emissions. The large diesel engine in a class 7 or 8 truck is designed to run at highway speeds and can reach efficiencies in excess of 40%. However, at idle speeds, the engine is comparatively inefficient; on the order of 1 to 11% [1]. On average, the primary diesel engine of a long-haul truck operating at idle consumes 1.9 - 5.7 L (0.5 - 1.5 U.S. gal) of diesel fuel per hour. Idling fuel consumption depends largely on the idle RPM setting, which in turn is dependent on the accessory load. The average total yearly fuel consumption for an idling engine is estimated at 6,056 L

[1] Trucks are categorized by gross vehicle weight rating (GVWR) which includes the base weight of the vehicle as well as the weight of the fuel, cargo, and passengers onboard. Class 7 trucks are defined as weighing 26,001 – 33,000 lbs (11,800 – 15,000 kg). Class 8 trucks are defined as weighing over 33,000 lbs (15,000 kg).

(1,600 gal) per year, per truck [2].[2] As part of a recent campaign to help reduce fuel consumption and exhaust gas emissions levels, the U.S. Environmental Protection Agency (EPA) has created the Smartway Transportation Partnership. A voluntary cooperative agreement between the federal government and a variety of transportation-related manufacturers, the purpose of the program is to establish incentives for fuel efficiency improvements and greenhouse gas emissions reductions. By 2012, this initiative aims to reduce carbon dioxide (CO_2) emissions by 33 - 66 million metric tons and nitrogen oxide (NO_x) emissions by up to 200,000 tons per year. At the same time, the initiative will result in fuel savings of up to 150 million barrels of oil annually [4].

In a related effort, although focused primarily on air quality and related public health issues, many U.S. states have enacted their own anti-idling legislation [5]. The specific restrictions, enforcement schemes, and issuing authorities vary widely across the nation. However, legislation usually restricts the time duration and purpose for which idling is permitted.

The U.S. state of California has historically acted as a sounding board for environmental policy among the individual states and for the federal government. Continuing in this tradition, the state has enacted some of the most restrictive legislation to date. With an economy that trumps that of the majority of the world's

[2] The sample standard deviation for this survey was large: 1,300 gallons per year. However, for the purposes of simple approximation, the mean was deemed a sufficient parameter for distribution description.

most well-developed nations, the impact of anti-idling legislation in a state like California is likely to have a significant impact on the American transportation trucking industry. Its highly-restrictive, detailed legislation could be viewed as the high-water mark in terms of emissions levels for which manufactures must aim.

As of January 1, 2008 title 13, section 2485 of the California Code of Regulations prohibits all vehicles equipped with a model year 2007 or newer diesel engines, weighing over 4,536 kg (10,000 lbs) gross weight from idling longer than five minutes for the purpose of powering a heater, air conditioner or any ancillary equipment during operator sleeping or resting in a sleeper. This regulation applies not only to those vehicles registered in the state, but also to those registered elsewhere, operating within its borders. The exceptions for this regulation are for those engines; auxiliary power systems (APS), also referred to as auxiliary power units (APU); or fuel-fired heaters which meet California tier III emissions standards. To be verified tier III compliant, the technology must achieve at least an 85% or greater reduction in particulate matter (PM) from the current baseline standard or less than 1.34 g/kWh (0.01 g/bhp·hr) emission level. For trucks manufactured prior to 2007, idle-reduction technology must comply with previous California and/or federal emissions standards.

1.1.1 Pathways to Idle-reduction achievement

Prompted by a growing market for a greater number of low-emissions, fuel-efficient alternatives, a variety of idle-reduction technologies have emerged over the last several decades. In general, these technologies can be classified as combustion engine auxiliary power units, battery-powered auxiliary power systems, and a variety of individual components designed to meet a portion of the sleeper compartment heating, cooling, and hotel load requirements.[3] In addition to these mobile systems, truck stop electrification (TSE) has been developed as a stationary alternative to idling, offering operators a power and service connection similar to those found in recreational vehicle (RV) parks for a small hourly fee.

1.1.2 Design Specifications

Prior to discussing the existing idle-reduction technology it is useful to outline the requirements of such technology in terms of the type, magnitude, and duration of power load. It is also beneficial to mention some of the factors that affect acceptance of idle-reduction technology.

Sleeper cabin power demand

In general, long-haul truck sleeper cab power demand can be divided into two types: hotel and accessory loads, and climate control loads. Hotel loads, as previously defined, consist of power drawn by household electronic equipment used in the cabin. In a survey conducted by the University of California, Davis Institute for Transportation Studies (UCD ITS), the frequency (i.e. the ratio of drivers surveyed

[3] The term APU generally refers to a diesel-fired internal combustion engine generator set, and the associated heating, air conditioning, and hotel load power accessories. All other energy systems are here referred to as Auxiliary Power Systems (APSs) to avoid confusion.

who operate a specific type of electronic item onboard to all drivers surveyed), type, and associated power demand of onboard electronics is presented [6]. Similar findings are presented in a 2006 American Transportation Research Institute (ATRI) survey [7]. The total electronic load sums to more than 5 kW, however it can be assumed that not all electronics are used simultaneously. It can further be assumed that hotel loads are generally lower in terms of priority than climate control. For example, during certain periods of the day it may be necessary to prioritize hotel and climate control loads based on available power and driver preference.

In a related paper, researchers at the UCD ITS calculated the electrical power demand of an air conditioning system to be 1.2 kW, with a peak power requirement of 3.6 kW, for a few seconds [8]. The maximum heating load is reported as 2 – 3.5 kW, depending on the ambient conditions and quality of insulation [6]. These estimates are based on the American Trucking Association Technology and Maintenance Council's (ATA TMC) recommended practice 432, which outlines climate control load test criteria.

Main vehicle battery recharging, when provided by the APU, can add an additional 310 W load per battery[4]. Engine block warming is provided by electric resistance in the form of a heating flange, or by engine coolant recirculation. In the case of electric resistance heating, the load is usually powered by the main vehicle batteries, though some idle-reduction systems include it as an additional feature. Typical power demand is approximately 0.5 - 2 kW for a heating flange [8]. Coolant heating

[4] Assuming 14V, 20 amps, and an added 10% for thermal and other losses.

systems are powered either by waste heat from the APU cooling jacket, or by fuel-fired heater. Integrated APU systems do not require extra electrical pump power. Fuel-fired heaters draw a small pump load, typically less than 50 W [40].

1.1.3 Factors Affecting Acceptance

Assuming that each system or component is able to meet the design requirements, the question then becomes one of driver and fleet acceptance. The greater the demonstrated benefit versus cost, the more likely the idle-reduction technology is to be implemented and thus the greater its effectiveness.

The most decisive factor in the implementation of any idle-reduction technology is the associated cost. Particularly for the individual owner/operator, any anti-idling solution, no matter how effective at reducing emissions must also offer a realizable financial benefit. Idle-reduction technology costs include the purchase price of the system or component; a 12% federal excise tax if added as a cost option on a new vehicle; operating costs which depend heavily on fuel prices; and maintenance costs which are dependent on the service interval, part costs (i.e. filters, oil, etc.), and hourly labor rates.

One cost, which is commonly assumed negligible, is the reduction in fuel economy caused by the increase in gross weight. It is estimated that for every 0.45 kg (1 lb) of weight removed from a truck traveling on level highway at 89 km/h (55 mph), fuel economy will increase by 2.55×10^{-5} L/km (6.0×10^{-5} mpg) [9][10]. This equates to

about $1.52 per kg per year ($0.69 per lb per year)[5] assuming an on-highway fuel price of $0.91/L ($3.45/gal). This cost may seem insignificant, but assuming fuel prices continue to rise disproportionate to main engine fuel efficiency, the total can be considerable over the life of the truck. Additionally, this figure does not include the loss of potential profit incurred by payload displacement. Although difficult to quantify and highly dependent on the type of cargo, this cost could easily trump increased fuel consumption costs associated with idle-reduction technology weight. System volume is also a significant concern. Space inside the cabin of the truck, on the rear exterior wall of the sleeper compartment, and along vehicle's chassis between the rear of the cab and the rear wheels, known as the rail, is very limited and therefore highly prized. Even small space displacements for components, ducting, etc. can have a significant negative impact on operator acceptance. According to the U.S. Department of Energy (DOE), the volume of the average APU is 226 - 424 L (8 - 15 ft^3), whereas the ideal volume indicated by truck manufacturers would be 170 - 226 L (6 - 8 ft^3) [3].

Other tertiary factors that may affect idle-reduction technology acceptance and implementation include, but are not limited to, perception of technology as a reflection of imposed standards, idling habits, awareness of idle-reduction technology options, and awareness of financial resources [3]. These factors may be difficult to quantify in terms of design specifications but should be taken into account when comparing idle-reduction technologies.

[5]Calculations assume on-highway fuel price of $0.91 per liter ($3.45 per gallon) and an average annual distance traveled of 193,000 km (120,000 mi).

1.2 Idle-Reduction Technology Review

Long-haul truck auxiliary power systems are comprised of a wide variety of components spanning an equally large number of developing technology areas, each of which is likely worthy of its own rigorous literature review. The scope of this review is therefore limited to the basic operation and specifications of off-the-shelf energy systems and components. Academic contributions as well commercial data, whenever available, are considered. Manufacturers' data is assumed accurate in the absence of independent test data, which is employed for verification purposes whenever available.

The information provided is intended to provide a basis for comparison only. The advantages and disadvantages of each system, component, or technology are weighed against the design specifications and acceptance factors previously outlined.

1.2.1 Truck Stop Electrification

Truck stop electrification (TSE) provides power and other services through connection to a stationary terminal or pedestal, as they are commonly called. TSE connections offer a wide range of services including filtered heated and cooled air; internal and external AC power for hotel loads, block heating, and chilled or frozen transport refrigeration; local and long distance telephone service; satellite television complete with movies on-demand; and high-speed internet access.

There are two basic types of TSE connections: onboard and shore power. Onboard systems require the operator to have all of the equipment onboard the truck (i.e. the climate control unit). Power to operate accessories is provided via an extension cord,

which connects the pedestal to an external terminal on the vehicle. The pedestal connection can also supply other features in addition to power, which are offered for a small increase in hourly service cost (approximately $1.00 per hour without fleet discount plus an additional $1 connection fee per use). With an onboard TSE system, trucks can also be powered while parked during loading and unloading, or anywhere else a 115 VAC connection is available [11].

Shore power systems offer a complete service package without requiring the operator to have any additional equipment onboard the vehicle. Services are provided via a window interface, which includes air ducting; 115 VAC power outlets; Ethernet, television, and phone connections; and a video touch screen which can be used to view movies, browse the internet, and pay the service bill (approximately $2.18 per hour without fleet discount; one hour minimum) [12].

Advantages/disadvantages

Shore power TSE requires a nominal up-front cost for vehicle adaptation. Onboard TSE requires that the vehicle have an electric air conditioning and heating system onboard in addition to a vehicle adaptation kit, which significantly increases the capital costs (approximately $4,000 for a complete climate control unit, installed). However, the larger up-front cost is offset by a lesser hourly service charge. A detailed cost/benefit analysis is conducted in the cost-comparison results section.

Onboard systems are more flexible than shore power systems in terms of where they can hook up to 115 VAC power. However, shore power systems do not displace any cabin space, and do not increase vehicle weight.

From the perspective of the owner/operator, little is required in terms of maintenance for either system, and it can reasonably be assumed that the vehicle adaptation equipment will last the life of the truck.

Other benefits include no emissions certifications concerns for the end-user and better local air quality. In the larger context, the quantity and type of emissions produced as a result of TSE depend on the type of plant servicing the TSE station. However, from an operator's perspective TSE systems are not subject to emissions standards and therefore eliminate the burden of certification. The health benefits not only to truck drivers and truck/rest stop employees, but to nearby residents yielded by idling elimination though not easily quantifiable, are notable.

The primary shortcoming of TSE is the inflexibility associated with a stationary power supply. Between the two largest companies which offer TSE, there are less than 9,000 electrified parking spots available in the U.S. as of September, 2007 [14, 15]. The average number of long-haul trucks on the road each day is estimated at more than 50 times this amount [16]. In view of this disparity, operators seeking a TSE-enabled parking slip must often alter their schedules, which can have a significant impact on delivery schedule, profits, and wages.

1.2.2 Fuel-Fired Auxiliary Power Units

The fuel-fired APU is perhaps the most conventional of idle-reduction solutions. APUs generally consist of a comparatively small internal combustion engine, typically rated at 10 kW (13.4 hp) measured at the output shaft. Fuel is supplied from the truck's fuel tanks. Maximum rated electrical output is generally 4 – 6 kW of 110 VAC power depending on the operating conditions and the efficiency of the APU generator. The majority of APU electrical systems provide an interface for a shore power connection as an extra-cost option. Fuel consumption depends largely on the size of the engine and power load, however average consumption is estimated at 0.75 – 2.0 L/h (0.2 - 0.5 gal/h) under standard conditions. Many APUs come equipped with intelligent control systems that maximize fuel efficiency by operating the APU automatically, only when required. Examples include operating to recharge the main vehicle battery, maintain cabin climate, or for engine block temperature control. APU generator sets, not including the climate control unit, generally weigh 160 - 230 kg (350 - 500 lbs), and have a rail length of 0.46 - 0.76 m (18 - 30 in). Idle-reduction system climate control units typically weight 34 – 45 kg (75 - 100 lbs) and have an average cabin displacement of 85 L (3 ft^3) [17-22, 23].

The vast majority of APUs operate on diesel fuel. However, there is at least one manufacturer that offers a comparably-sized system which runs on propane. The propane is stored in an auxiliary tank mounted to the truck's frame, but can also be connected to a disposable tank, like the kind used to supply gas barbeque grills [22].

One APU manufacturer offers an optional 12 cfm air compressor which is linked to the vehicle's air system providing redundancy for the leveling and pneumatic braking systems. Compressed air is also available for tire inflation and pneumatic power tools. The compressor is belt-driven by the APU engine. No specific product data is available from the manufacturer. However, it can be reasonably assumed that the power requirement is similar to that of a portable air compressor of comparable output: approximately 1.12 kW (1.5 hp) [24].

Climate control

There are a number of climate control system options available among both manufacturers and individual product lines. Air conditioning systems are generally either shaft, belt, or electrically-driven. Heat is provided either via electric resistance or a direct-fired space heating system. Engine and APU jacket coolant recirculation systems, which utilize the truck's OEM driver compartment heating system, are also available. Heating and cooling components will be discussed in greater detail in the energy systems components section.

Emissions

There has been significant research in recent years on emissions control technologies [25]. However, at the time of this writing no manufacturer-endorsed diesel particulate filters (DPFs) are available off the shelf. From an informal telephone survey it is estimated that DPFs will be stand-alone components, to be mounted adjacent the APU (requiring additional rail space), and cost roughly $3,000, installed.

Advantages/disadvantages

In addition to the potential savings over main engine idling, the primary advantage of an APU is autonomy. Given the limited number of parking spaces available in the U.S., long-haul trucks often park along the highway shoulder, at rest stops, truck stops, or myriad other places. Having an onboard energy system allows the operator the flexibility of being able to stop where parking is available[6] with full system operation. Another advantage of the internal combustion engine APU is the proven record of engine technology, the deep market penetration of such technology, and the large number of service stations.

One of the main challenges in the implementation of APU technology is the reduction of emissions. Filtration devices offer promise of future certification, but there is a finite limit to which diesel engines can be "cleaned-up." Some in the truck manufacturing industry believe more and more stringent regulations will be put in place in the future; that the ultimate goal of some legislative bodies is a zero-emissions idling solution. In the near term, the first-cost associated with the purchase of an APU also makes them less attractive to individual owner/operators on a tight budget ($6,000 – $10,000 installed, before FET), especially if a DPF is required, despite their long-term savings potential. Wide-spread implementation is more likely for larger fleets due to availability of investment capital and discount bulk purchase, etc.

[6] Some states regulate the proximity of APU use to densely populated or residential areas

1.2.3 Battery-powered auxiliary power systems

In recent years battery-powered auxiliary power systems (BPAPS) have emerged as a competitive alternative to conventional auxiliary power systems. At the heart of these systems lies a bank of deep-cycle batteries, recharged either by the truck's alternator while driving down the road, or by shore power connection. In addition, electric climate control components can be incorporated for a completely battery-powered energy system.

Replacing the engine and generator of a conventional APU with a bank of deep-cycle batteries, BPAPSs offer many of the same features without the emissions restrictions or noise of their fuel-fired counterparts. The number of batteries required depends on the number of electric components, the total system energy demand, and the intended operating environment. The type of battery primarily used in currently available BPAPSs is the group 31 absorbed glass mat (AGM) battery, the next stage in the evolution of the traditional flooded lead-acid battery. Recharging time is generally less than six hours of drive time, depending on the number of batteries, level of depletion, and alternator amperage [27-29].

Recharging the deep-cycle battery bank requires a higher amperage alternator, which can add considerably to the capital cost, depending on the required amperage. Often overlooked or assumed negligible is the decrease in fuel efficiency and increase in vehicle emissions associated with the increased alternator load. A higher amperage alternator places a larger demand on the engine, which in turn burns more fuel and

therefore produces more emissions. The total amount of emissions is presumably less than that of an APU without a DPF, however to state that the use of a BPAPS does not consume any additional fuel or produce any additional emissions is not technically correct.

With the use of a BPAPS, AC hotel load power is provided to the truck's sleeper compartment via a DC to AC inverter. The power output range of currently available inverters varies widely from a few hundred Watts to well beyond the power requirements of a sleeper cabin. DC to AC conversion efficiency at full capacity is generally 80-90% , lower at part-load [66].

Depending largely on the number of batteries used to power the system (roughly 35 kg or 75 lbs per battery), the average weight of a BPAPS is on par with the weight of an APU. Generally, a battery bank containing four batteries takes up less than 0.75 m (30 in) of rail space. More space may be required depending on the total number of batteries and the configuration in which they are mounted. Packaged climate control units displace 64 - 121 L (2.25 - 4.26 ft^3) and are generally mounted in the sleeper cabin underneath the bunk. A split system, which mounts the air conditioning system condenser heat exchanger and fan outside the sleeper cab, takes up even less interior space. Standard packages, which include four batteries and the associated mounting equipment, inverter, climate control unit, and recharging components, cost approximately $6,000, installed.

Advantages/disadvantages

There are a number of advantages a battery system offers over the conventional APU. A completely electric BPAPS (i.e. one that uses an electric resistance heater as opposed to a direct-fired heater), in addition to the health benefits of producing no local emissions, is not subject to emissions regulations. Also, BPAPS are generally quieter, generating noise only from electric motors, fans, etc.

The disadvantages of a battery system include a comparatively short battery service life, decreasing battery performance with number of discharge/recharge cycles and extreme ambient temperatures, finite capacity, shallower market penetration, and a higher level of required operator system knowledge and vigilance. Current deep-cycle battery life is generally accepted as 2-3 years, although this figure depends heavily on conditions under which the battery is used. Deep-cycle batteries also lose some capacity over their service life. Although batteries are designed to operate over large ambient temperature ranges, their capacity and service life can change significantly in extreme temperatures, specifically low ambient temperatures. Due to decreased chemical reactivity at low ambient temperatures, battery capacity is a fraction of what it is at room temperature, thus for regular operation in cold climates, additional batteries may be required to meet energy demands, thus incurring an additional cost. BPAPSs are not as time and road-tested as APUs, and therefore must overcome industry skepticism prior to wide-spread implementation. Battery systems also have a smaller energy storage capacity compared to that of the typical fuel tank at the disposal of an APU. Therefore, operators must manage more carefully their

energy use. For instance, it is recommended that drivers cool their cabins just prior to shutting off the main engine and turning on the BPAPS to avoid the heavy power requirement of cooling a hot sleeper cabin. In a report produced by Schneider National Inc., the required level of operator interaction is inversely proportional to operator acceptance [30]. Operators who followed manufacturers' recommendations were more likely to be satisfied with system operation.

1.2.4 Fuel Cell Systems

One of the most highly anticipated technologies in the development of long-haul truck auxiliary power systems is the fuel cell. With the promise of greatly increased efficiencies over the internal combustion engine, significantly reduced emissions, and quieter operation, fuel cell integration into auxiliary power systems has been studied extensively [6, 45, 67].

Despite considerable effort, there are a number of hurdles remaining which must be cleared before the mass production and marketing of fuel cell APUs is realized. Challenges include, but are not limited to diesel fuel reformation; lack of a hydrogen fuel supply chain; use of expensive and exotic materials; large balance of plant requirements for reforming, and thermal and water management; and slow start-up times, specifically in the case of the solid-oxide fuel cell. It is unclear from the literature and manufacturer's data when these challenges will be overcome. What is clear, however, is that once available on the market, the impact is likely to be significant.

1.2.5 Solar Energy Systems

Solar energy conversion technology has reached the point in its commercial development where it is now being applied to long-haul truck energy systems. One U.S. company currently offers such technology. The system operates by installing a solar photovoltaic panel on the cabin roof and connecting it to the vehicle's main batteries. Each panel can supply 2 amps of current at 18.6 volts, and up to three panels can be installed on a high-roof cab for a total of 111.6 W [31]. The panels provide the most energy between the hours of 12 and 4 p.m., and even produce power under overcast skies [32]. Individual panels have an area of 0.64 m^2 (6.9 ft^2) and weigh 13.6 kg (30 lbs). The manufacturer claims that the panels have no impact on the truck's aerodynamic characteristics.

Each panel costs $1,049, comes in a variety of colors, and can be self-installed. The panel is made of a number of smaller solar strips and thus if one strip is damaged or malfunctions a replacement can be ordered without purchasing an entirely new panel. Warranty life is one year.

Advantages/disadvantages

The primary advantage for a passive energy source such as a solar panel is that no additional fuel is required to recharge the vehicle's main batteries or auxiliary battery bank, if installed, thus no additional pollutants are emitted. The major drawback is system cost versus power output. In this application, the panels are not meant to be the complete idle-reduction solution but rather a means to offset the recharging load

that would otherwise be supplied by the engine or APU. Solar PV panel efficiency is currently too low to cost-effectively replace diesel fuel as the primary energy source for meeting sleeper cab energy demand. However, solar technology is another research area which has received a huge amount of attention and funding in recent years. The day when cabin electricity and HVAC requirements are met with solar panels covering the exterior of the vehicle may be approaching.

1.2.6 Energy Systems Components

The following section includes components which, although they do not meet all the requirements of a complete idle-reduction power system, can be used individually or in conjunction as part of a complete system.

1.2.6.1 Climate Control

A number of APUs provide air conditioning through a standard shaft or belt-driven vapor compression cycle. In these conventional systems, the compressor is contained within the engine/generator housing and the refrigerant lines are run from the APU mount point to the climate control unit, located under the driver's bunk. Available output capacity is advertised as high as 7.6 kW (26,000 Btu/h) or more (although typically on the order of 4.1 kW or 14,000 Btu/h) at a cooling air flow rate of 7.87 – 11.46 m^3/s (278 – 405 cfm). Cabin displacement volume is generally 28 – 42 L (1 – 1.5 ft^3) and units generally weigh less than 13 kg (30 lbs) [19, 33].

Electric air conditioning compressor

Similar to long-proven, packaged residential window air conditioning units, several manufacturers offer complete electric-driven air conditioning systems. There are generally two formats available for air conditioning systems: packaged units or split systems. Packaged units, as the name suggests, contain all system components in a single housing. The advantages of this setup are that they are simpler to install and maintain, less expensive than split systems, and are more efficient as there are no long refrigeration lines through which heat can be transferred. Split systems are typically divided into one section containing the condenser coil and cooling fan, and the other section containing the evaporator coil, compressor, logic module, and blower. The advantages of the split system are that they take up less valuable cabin space, require smaller cutouts through the walls of the truck, and are quieter due to the condenser fan being mounted externally. Cooling capacity generally ranges from 0.9 to 4.1 kW (3,000 to 14,000 Btu/h). The power demand for a 0.9 kW (3,000 Btu/h) capacity system is calculated to be 300 – 350 W by the manufacturer, yielding a coefficient of performance (COP)[7] of 2.6 to 3.0 [27]. The power demand for a 2.9 kW system (10,000 Btu/h) is calculated by the manufacturer to be approximately 1.5 kW yielding a COP of 2.0.

In the previously cited Schneider National Inc. study, it was concluded that two batteries did not supply sufficient capacity to operate the air conditioning system at higher ambient temperatures and that four batteries would be required for peak summer comfort [30].

[7] COP is defined as the cooling power divided by the work input to the compressor.

1.2.6.2 Thermal Storage

Thermal energy storage technology, until recently has not been applied to long-haul trucks in any commercial capacity. However, a small number of manufacturers currently offer an air conditioning system that uses a thermal storage medium, charged while the truck is moving, in conjunction with a small air handling unit to provide cabin space cooling. Once discharged, the thermal storage medium is regenerated by a standard electric-driven vapor compression cycle, which receives power from the truck's alternator via an inverter. Ventilation without cooling is also available via the air handling unit. Available maximum thermal storage capacities range between 5 and 6.15 kWh (17,000 and 21,000 Btu) of energy [34, 35]. A small power draw of 42-100 W is required during discharge to operate the blower and the coolant circulation pump, which can be supplied by the main vehicle batteries. The entire system weighs 140-180 kg (300 – 400 lbs). The external thermal storage and refrigeration unit has a rail length of 0.65 m (26 in) and the air handling unit has a cabin displacement volume of 64 L (2.25 ft^3). Installed costs are generally quoted around $3,800 for an aftermarket product, with a warranty of three years covering parts and labor [34].

Advantages/disadvantages

The low power draw in comparison to conventional air conditioning systems, which can require more than five times the power at similar ambient temperature, is the primary advantage of thermal storage air conditioner systems. However, with a limited cooling capacity per charge, operator vigilance is required. Additionally,

there may not be enough system capacity for some climates in which ambient temperatures regularly climb above 35ºC (95ºF). The system weight is also approximately four times the weight of a comparable electric-driven vapor compression air conditioning system.

1.2.6.3 Evaporative Cooler

In addition to conventional vapor compression air conditioning systems, evaporative air conditioning systems are also available off-the-shelf. From an externally-mounted tank, water is pumped to a roof-mounted unit which contains a fan. This fan forces the evaporation of the tank water, drawing heat from inside the cabin. Especially effective in drier climates (below 60% relative humidity), the manufacturer reports cooling capacity enough to lower cabin temperature by 19ºC (35ºF) while drawing a maximum of 96 W. The system requires little maintenance with the exception of system flushing, annual water filter replacement, and refilling of the water tank, which consumes an average of 2 L/h (0.5 gal/h). The system weighs 57 kg (126 lb) including a full water tank of 32 L (8.5 gal), and the evaporator housing has a total volume of 110 L (3.88 ft^3). The evaporator housing has an aerodynamic appearance, although it is not specified what impact mounting it on the roof of the tractor has on the overall aerodynamic efficiency. The unit costs $1,500 and has a warranty period of two years [36].

Advantages/disadvantages

The advantages of an evaporative air conditioner are that it is simple, requires significantly less electricity than a conventional vapor compression system, and is less expensive to purchase. The drawbacks are that it is less effective in humid climates, requires the driver to monitor the level of water in the reservoir, and may have a detrimental effect on vehicle aerodynamics and therefore fuel efficiency.

1.2.6.4 Direct-fired Heater

According to a recent ATRI study, direct-fired heaters, also called fuel-fired or bunk heaters, are the most widely-employed idle-reduction technology [7]. The systems operate by drawing diesel fuel from the truck's fuel tanks and burning it in a small assembly, usually mounted beneath the bunk providing cabin space heating. A single manufacturer often produces several different series of heating units, designed to meet a range of space heating demands. Smaller units produce approximately 2.2 kW (7,500 Btu/h) on high output setting. Larger unit capacity is upwards of 4 kW (13,650 Btu/h) [37, 38]. Hourly fuel consumption averages 0.1 - 0.28 L/h (0.03 - 0.07 gal/h) depending on the desired heat output. In addition to fuel consumption, a comparatively small amount of DC power is required to operate the blower and logic module. Continuous power demand is typically 8.4 - 33.6 W, with a brief startup draw of 100 W or more. Including power draw and fuel consumption, unit efficiency

averages 78%[8]. Direct-fired heaters are very compact, with the larger units measuring approximately 8 L (0.28 ft^3), with a mass of less than 4.5 kg (9.9 lbs).

Advantages/disadvantages

The advantages of using a direct-fired heater include significant increase in heating efficiency over main engine idling, a small electric draw compared with an electric resistance system, compact size, negligible weight, and perhaps most significantly, direct-fired heaters generally exceed all U.S. federal and state emissions restrictions, including California tier III emissions standards [39]. The disadvantage of a bunk heating system is its cost (approximately $1,200, installed), compared with how much of the total cabin energy requirement it meets: heating only.

1.2.6.5 Electric Resistance Heater

Providing a complete electrified system, many climate control systems incorporate electric resistance heating, which can be powered either by generator or battery. The advantage of an electric resistance system is that it is often built directly into the climate control unit, and uses the same ducting and fans as the air conditioning system, conserving valuable cabin space. Available capacity ranges from 1 kW (3,400 Btu/h) to more than 4 kW (13650 Btu/h) [17, 21, 23, 27, 29]. Electric resistance heaters necessarily have a maximum COP of 1.0.

[8] Assumes the energy density of diesel fuel to be 36.2 MJ/L (LHV)

Advantages/disadvantages

The primary benefits of employing electric resistance heaters are that they can be incorporated directly into the air conditioning housing using the same ducting, and can be powered either by battery or generator. The disadvantages are that they consume a large amount of electricity and require replacement approximately every three years [10].

1.2.6.6 Coolant Recirculation Systems for Engine Block and Cabin Space Heating

Similar in operation to, and often manufactured by the same companies that offer direct-fired space heaters, direct-fired coolant heaters draw fuel from the truck's fuel tanks and transfer the combustion heat to the main engine coolant. The plumbing draws coolant at the rear of the engine block, warms it, and returns it to the intake of the suction side of the engine's water pump [40]. Heater operation is controlled by engine block temperature. When the temperature drops below the set point, the heater automatically turns on to maintain block temperature.

Fuel-fired engine block heaters come in a wide selection of capacities ranging from 4 to 13.2 kW (13.700 to 45,000 Btu/h) measured at maximum output [37, 38]. Hourly fuel consumption at high output is 0.51 L/h (0.13 gal/h) for the smaller units and 1.5 L/h (0.4 gal/h) for the larger units. Power draw ranges between 50 and 85 W at high setting. Smaller heaters can displace 3.6 L (0.13 ft^3) and weigh 2.5 kg (5.5 lbs), while

the larger units displace more than 27.3 L (0.96 ft^3) with a mass of 15 kg (33 lbs) [38].

Along similar lines, one company offers a thermal energy recovery system which continues to circulate engine coolant after the main engine is shut down. Using a 7.5 W (0.01 hp) pump, residual engine heat is carried away via circulating coolant to the truck's OEM heating system, providing up to 3 - 4 hours of space heating, depending on the ambient conditions. The system turns off automatically when coolant temperature drops below 35ºC (95ºF). The system has a two year warranty and costs approximately $600 for the standard model, installed [41].

Also using coolant recirculation, a number of manufacturers offer an engine block warming system for which the heat is supplied by the APU coolant jacket [17, 23]. The system operates by linking the main engine and APU coolant systems. APU coolant pump power is sufficient to circulate coolant throughout the entire system. The advantage of an APU powered system versus a direct-fired coolant heater is that during the colder months of the year it uses heat produced by the APU that would otherwise be discharged to the ambient air. Utilizing this waste heat greatly increases system efficiency. The advantage of a system which uses the coolant system to warm the whole engine block over a system that uses an air intake heater to warm the cylinders is a smaller temperature gradient throughout the engine block. A smaller temperature gradient decreases thermal stress, which would otherwise result in increased wear and tear on the engine.

Advantages/disadvantages

The advantage of a coolant recirculation system is that for a nominal power draw, it takes advantage of residual heat from the main engine that would otherwise be lost to the ambient environment.

The addition of a coolant heater alone does provide engine warming, but most models are not designed to provide space heating. Systems that are designed to use the vehicle's OEM heating system provide advantage by reducing the number of redundant systems. The primary drawback of the recirculation pump is that even in moderately cool temperatures, it may not be able to supply adequate cabin heating for more than a few hours. The disadvantage of a coolant heating system is that it is only required in consistently cold ambient conditions (<-6°C - -12°C), and must be maintained and transported regardless of whether it is required.

2 Objectives

In broad terms, the purpose of this thesis is to develop a foundation of information upon which future contributions can be made to the research area of idle-reduction technology. Aside from general information promulgated in brochures and on-line manuals, specifics on system operation, operating parameters, and materials for example, are largely proprietary. Still, the development of the energy systems which comprise idle-reduction technologies are of logical interest to academia. Especially in a time when many universities are focusing on the advancement of environmentally-responsible/sustainable technologies, the industry holds many opportunities for independent contribution.

The specific objectives of this thesis are as follows:

- To provide a concise, detailed compilation of the major currently-marketed idle-reduction technologies including complete power systems which provide cooling, heating, and power as well as partial systems that provide one or more of these,
- To review available energy simulation software to determine which is most applicable to idle-reduction system simulation,
- To develop transient simulations of the most promising complete energy systems, into which new concepts and technologies can be incorporated,
- To develop methodologies for evaluation and comparison including sleeper cabin load profiles and en route weather variation

- Based on the initial output of these simulations, to propose developments and/or alternatives to current use, areas of future research, and further applications,
- To develop a simple, flexible cost-comparison model through which parametric studies can be conducted comparing several idle-reduction technologies over a range of operating parameters.

3 Approach to Energy System Simulation and Cost-Comparison Modeling

In this section are discussed the methods used in model development and operation, the justification of assumptions, and the equations used in calculating the output values.

3.1 Modeling introduction

For the purposes of this analysis, two types of simulations or programs were developed. A component-based transient simulation was developed using TRNSYS for both a conventional fuel-fired auxiliary power unit and a battery-powered auxiliary power system. The intent of these models is to calculate the fuel consumption, power output, operating hours, and in the case of the APU, exhaust gas emissions over a given time period. The second type of model, an Excel worksheet-based macro, takes a number of product parameters such as the annual operating hours; capital, maintenance, and operating costs; and other economic factors and calculates the lifetime hourly cost, the total cost, and payback period for six prominent idle-reduction technologies and compares them against the idling of the main vehicle engine. Used in conjunction, the transient simulation and worksheet can provide perspective on both the engineering and economic considerations of a particular system.

3.2 System-level energy model development

Due to the nature of the available information and the scope of the project, a component-based, transient simulation was deemed most appropriate. A number of energy simulation software packages were investigated for use in this analysis. Table 1 provides a list of the software packages considered for simulation.

Software	Description
Aspen	Offers various energy simulation software packages
DOE2	Building energy use and cost analysis software
ESP-r	Building thermal and energy simulation software
Transient System Simulation (TRNSYS)	Transient simulation software for thermal and other systems
Virtual Test Bed (VTB)	Software for prototyping of large-scale, multi-technical dynamic systems

Table 1: Software Packages Considered for Idle-Reduction System Simulation

For reasons including simple graphic-user interface, a well-established support system, international market penetration, the capability to modify or create new components, and the ability to run transient energy system simulations over time periods of more than one year, TRNSYS was ultimately selected.

Figures 1 and 2 illustrate the components used in the APU and BPAPS models, respectively. The following is a brief description of each of the components shown. Components developed specifically for this analysis will be discussed in greater detail in the following sections.

- Type 65d (online plotter): graphs outputs
- Type 33e (psychrometric calculator): calculates humidity ratio from dry bulb temperature and relative humidity
- Type 33c (psychrometric calculator): calculates the relative humidity from the dry bulb temperature and humidity ratio
- CCU (climate control unit): receives input from the thermostat (type 108) and computes cabin HVAC inputs as well as power demand
- Type 55 (summation calculator): performs a number of statistical calculations including summation, integration, mean, standard deviation, and high and low values
- Type 109 – TMY2 (weather data reader): outputs the weather data information from the specified TMY2 input file
- Type 56 (multi-zone building model): calculates cabin energy parameters including temperature, relative humidity, sensible and latent load, etc.
- Type 108 (thermostat): produces an output signal based on the input value relative to the set value (in this case, space temperature relative to set temperature)

- APU (auxiliary power unit): receives power signal from CCU and hotel load forcing function to calculate the power output, fuel requirement, and emissions production
- Gate: selectively allows signals to pass from input to output based on the simulation time
- Type 24 (integrator): integrates input over the time step specified by the control cards
- Type 57 (unit converter): converts values from one unit to another based on user-specified parameters
- Type 21 (simulation time): outputs time-related simulation parameters including hour of the day, day of the week, hour of the year, etc.
- Monday, Tue-Fri, Saturday, Sunday (Type 9 a, generic data-reading components): inputs hotel load profile for the specified day of the week
- Hotel Load (Type 41, forcing function scheduler): applies the appropriate hotel load in accordance with the day of the week
- Inverter: calculates the input power requirement based on the CCU and hotel load demand total
- Battery bank: calculates the fuel required to recharge the battery bank as well as the number of days per year the battery bank capacity is not large enough to meet cabin requirements and by how much in terms of additional batteries required

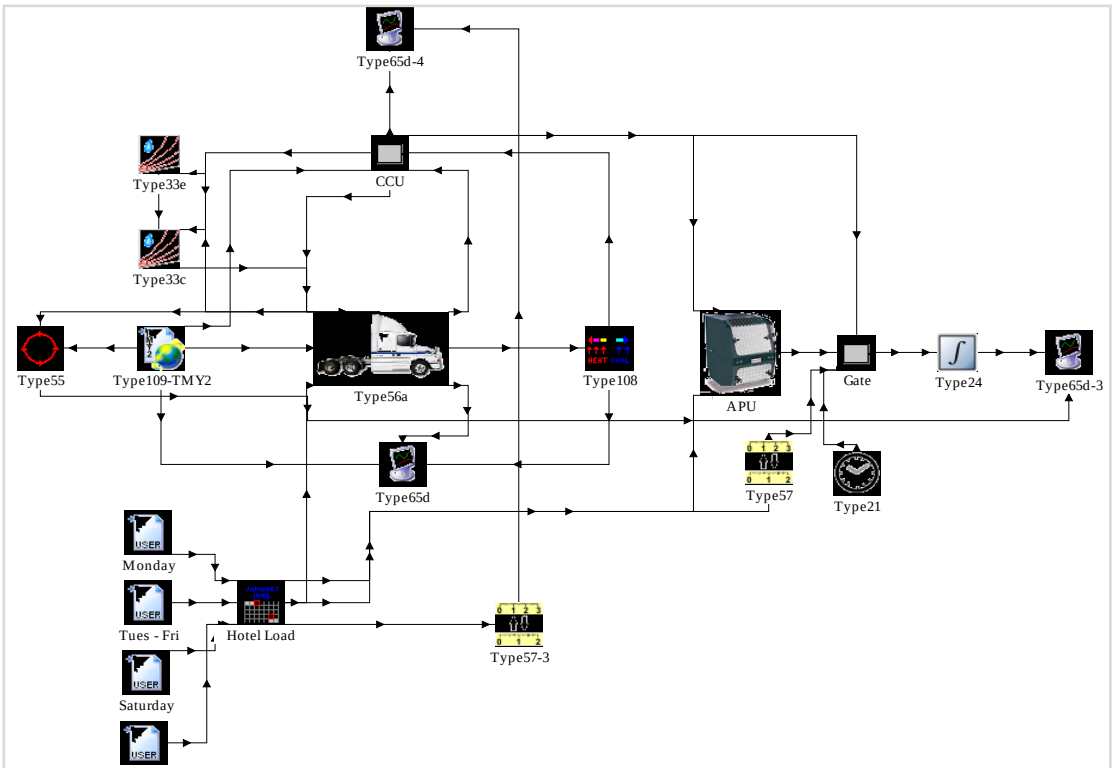

Figure 1: APU Energy System Simulation Schematic

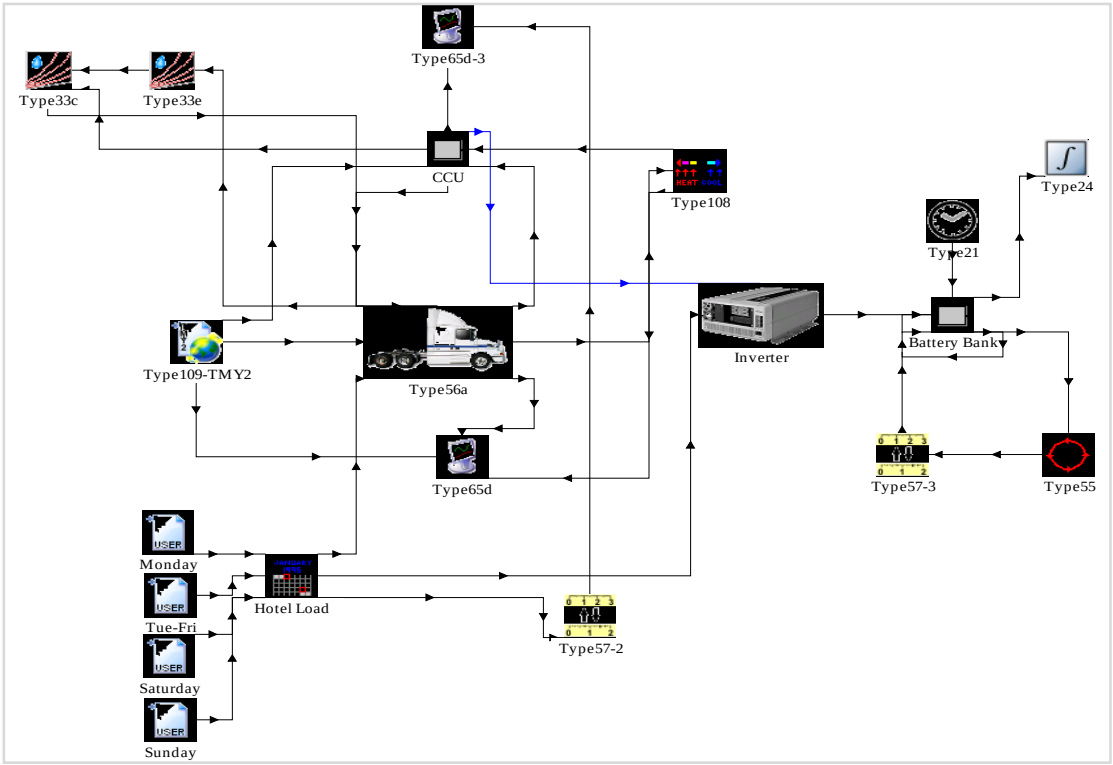

Figure 2: BPAPS Energy System Simulation Schematic

In both models, the inputs from the ambient environment including temperature, relative humidity, and solar gain (type 109), the heat gain from the electrical components used inside the cabin (Hotel Load component), and the heat gain from the occupant are summed by the cabin model (Type 56a). The cabin component is connected to a thermostat (Type 108), which produces an output signal based on the cabin temperature with reference to a set temperature. The signal is then passed to the climate control unit (CCU), which returns the output air temperature, air flow rate, and relative humidity to the cabin. The CCU also calculates the power associated with the required heating or cooling output, which are connected to the power source. The APU model then calculates the output energy, fuel consumption, and quantity of emissions. The battery bank component calculates the additional fuel required to recharge the battery bank on a daily basis.

In the following sections the components common to both systems are discussed, followed by the components unique to each system model.

3.2.1 Common components

3.2.1.1 En route TMY2 weather data

The cabin climate control load profile is based largely upon ambient conditions, which in turn vary greatly with geographic location. Given the great distances over which long-haul trucks travel, it is proposed that the weather data reporting station change to approximate the route of travel. Therefore a forcing function was created which incorporates parameters like the average distance traveled per day and the average number of days spent traveling per year. This function was then used to

simulate the travel of a long-haul truck along the length of freight-significant corridors within the U.S. in an effort to better model the climatic diversity experienced by an actual truck.

Freight-significant corridors are identified by the ATRI as I-5, I-10, I-45, I-65, and I-70 [48]. In this analysis, I-45 was excluded because of the relative climatic homogeneity of East Texas and replaced with I-95, which stretches from Miami, FL to the Canadian border with Maine and thus has a widely ranging climate along its length.

To approximate the ambient conditions a typical long-haul truck would encounter along the corridor, information was obtained pertaining to operator driving habits including average daily distance, average length of haul (defined as the distance between goods pickup and drop off), and the average time spent idling while loading or unloading. The average daily distance can be found in a number of previously cited sources [3, 7, 16, 42, 46]; approximately 400 miles per day. In speaking to representatives from JB Hunt and Schneider National Inc., two of the larger freight transportation companies in the US, the author learned that the average length of haul is approximately 805 – 965 km (500 – 600 mi) [49, 50]. However, operators do not generally remain in their cabs during loading and unloading. Instead, driver rooms are often made available for the operators while they wait. Also, drivers will often pick up or drop off an already loaded trailer, resulting in little to no additional idle time. Given this information, it is assumed that operators do not generally idle during

loading and unloading, thus there is no additional requirement for the use of idle-reduction technology apart from en route rest periods.

The five freight-significant corridors chosen for this analysis are divided into increments averaging approximately 400 miles by interstate-adjacent TMY2[9] weather stations. The forcing function for this analysis assumes the vehicle oscillates between the termini of the corridor for the duration of the year. For example, if an operator were to start in Vancouver, BC on the first day of the year it was assumed that he or she would drive the full length of the corridor to San Diego. Hence, the first morning's ambient conditions correspond to Vancouver, B.C., the first evening and second morning's ambient conditions correspond to Salem, OR, etc. The five routes were divided as follows:

Route	Distance [mi]	Travel Days	Stopover cities						
I-5	1396	3	Vancouver BC	Salem, OR	Sacramento CA	San Diego CA			
I-10	2415	6	San Diego CA	Phoenix, AZ	El Paso TX	San Angelo TX[1]	Houston TX	Mobile AL	Jackson-ville FL
I-65	887	2	Mobile AL	Nashville TN	South Bend IN[1]				
I-70	2153	5	Cedar City UT[1]	Eagle, CO	Goodland KS	Columbia MO	Indian-apolis IN	Baltimore MD[1]	
I-95	1925	5	Miami FL	Jackson-ville FL	Raleigh NC	Phila-delphia PA	Concord NH[1]	Fredric-ton NB	

Table 2: Corridors Selected for Analysis and Stopover Cities

[1] Cities presented are not directly on the corridor. However, TMY2 data was taken from the closest possible reporting station.

[9] TMY2, an acronym which stands for typical meteorological year (second edition), is a standard weather data file collected by some 239 weather stations across the U.S. and its territories. This standard file is interpreted by the TRNSYS type 109 data reader.

To create the mixed TMY2 files corresponding to each corridor, an excel macro was created. The mixed worksheet was then output as a text file, converted to TMY2 format using a FORTRAN executable file, and finally input into TRNSYS using a Type 109 TMY2 weather data reader and processor.

3.2.1.2 AC electrical "hotel" load duty cycle

As there is no standard daily hotel load cycle, one was developed based on a residential electrical load profile using the electronic equipment and power ratings outlined in Grupp, et al. [6]. The proposed load profile complies with the Federal Motor Carrier Safety Administration Hours of Service regulations [51].

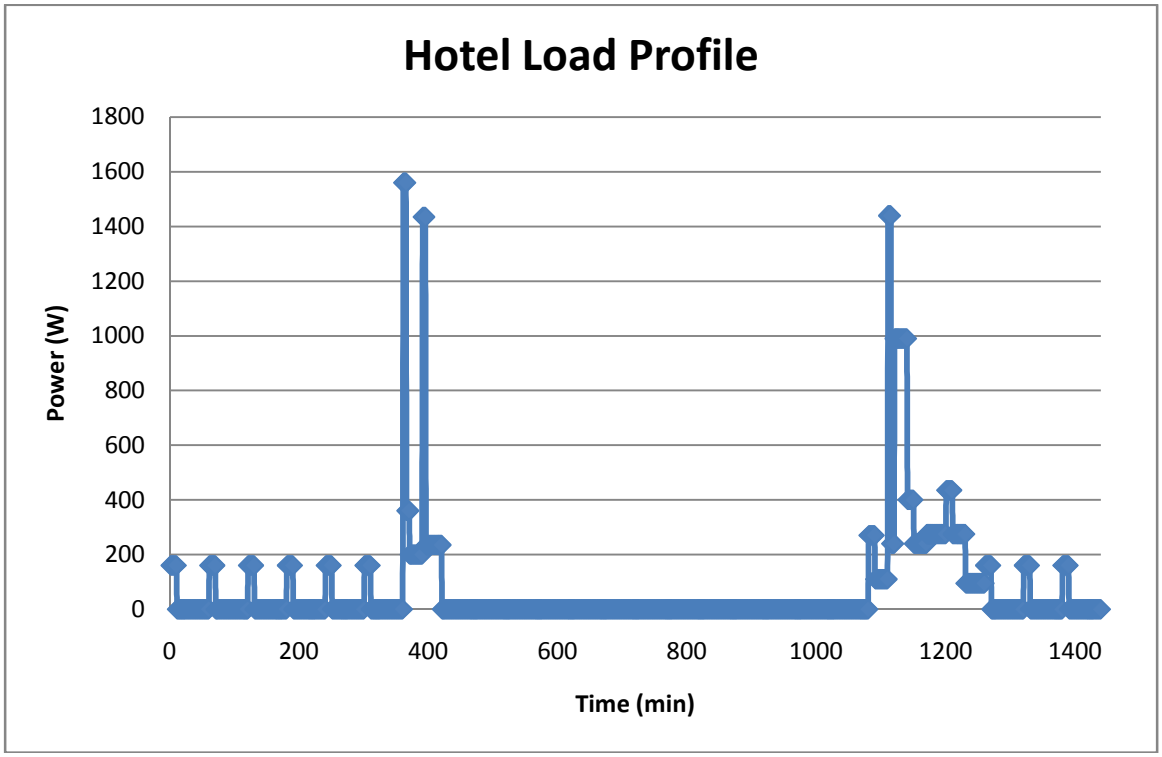

Figure 3: Hotel Load Profile Used in Calculating Idle-reduction System Power Consumption

120 V AC Loads	Present	Power [W]	Schedule	Total time [min]
Entertainment			**Truck runs from 0800 to 1900**	
TV	74%	100	0700-0800, 1930-2130	120
VCR	53%	30	1930-2130	120
Stereo	66%	50	2130-2200	30
DVD Player	*	30		
Game System	*	20		
Communications				
Cell Phone	62%	10	1900-2200	180
Laptop Computer	23%	35	0730-8000, 2030-2200	120
Comfort				
Air Conditioner	-	1200		
Refrigerator	59%	160	Intermittent 13 hrs (10 min on, 50 min off)	140
120V Lamp	46%	100	0700-0800, 1900-2130	210
Microwave	19%	1200	0730-0735,1930-1935	10
Coffee Maker	15%	1200	0700-0705	5
Hot Plate/Crock Pot/Grill	*	750	1940-2000	20
Other*	11%			
Total power demand [kWh]		**1.73**		

Table 3: AC Electric Equipment "Hotel" Load Profile Adapted from Grupp, et al [6].

The daily hotel load cycle, presented in Figure 3 and Table 3, was assumed not to change appreciably from one day to the next. All power consumed within the cabin is assumed to be eventually dissipated as sensible heat although the output is averaged during periods of significant use such as in the morning and early evening. The purpose of averaging the load profile is to keep from inducing a large instantaneous heat load into the cabin without having to consider the thermal capacitance of each piece of equipment, time delay for natural thermal gradient-driven air mixing, etc.

The hotel load profile presented in Figure 3 was developed in an Excel worksheet, saved as a text file, and input into TRNSYS via Type 9a, a generic data reader. In addition, the daily load profile was scheduled via a forcing function scheduling component, Type 41. In essence, the operator begins his or her week on Monday,

sleeps in the cabin Monday evening through Saturday morning, and returns home Saturday evening. Sunday is observed as a day off.

Figure 4 shows the hotel load profile for a work week. As shown, the first section represents the three-hour period in the evening between the time the vehicle is parked and the time when operator goes to sleep. The eight intermittent loads are the refrigerator compressor turning on and off, followed by the one-hour period the next morning when the operator wakes up and prepares for work.

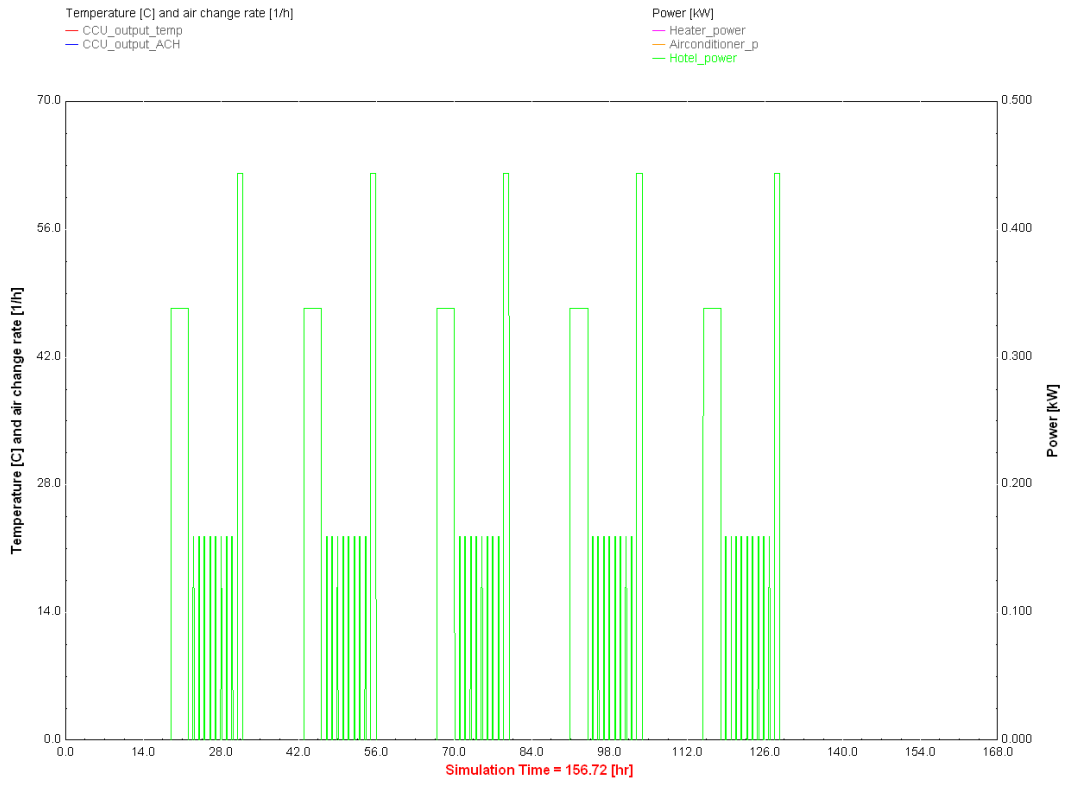

Figure 4: AC Electronic Equipment "Hotel" Load Profile for an Entire Week as Produced in TRNSYS.

3.2.1.3 Long-haul truck sleeper cabin (type 56)

The sleeper cabin model used in this analysis was constructed in TRNBuild, part of the TRNSYS software suite, using cabin schematics and insulation data obtained from a major vehicle manufacturer [52]. The model was then compared against the available academic literature [6] as well as the capacity of currently-marketed CCUs [17-24].

As previously addressed, long-haul truck sleeper cabins are available in a number of different size configurations from low roof models with a cabin ceiling height of approximately 1.65 m (65 in) to high roof models with a ceiling height of 2.6 m (102 in). The majority of cabins are approximately 2.43 m (96 in) wide. For this analysis, a high roof configuration was employed for the purpose of investigating the worst-case-scenario in terms of heating and cooling requirements. To decrease the heating and cooling requirements, offer privacy, and block out any incident light coming through the windshield and side-view windows, sleeper cab trucks are equipped with a heavy curtain which, when drawn separates the driver's compartment from the sleeper. Table 4 lists the dimensions taken directly or estimated from the cab schematics.

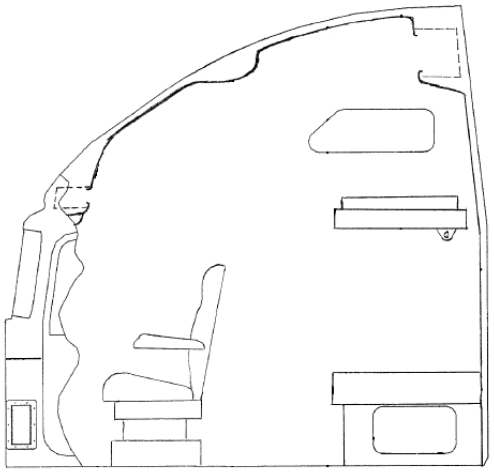

Figure 5: High Roof Long-haul Truck Sleeper Cabin

Driver's Compartment			
Wall	**wall area (m^2)**	**window area (m^2)**	**U-value (W/m^2-K)**
Forward	4.27	1.67	1.20
Driver	1.59	0.68	1.20
Passenger	1.59	0.68	1.20
Curtain	5.26		5.67
Roof	2.23		0.69
Floor	1.98		1.20
Volume (m^3)	3.88		
Cabin			
Curtain	5.26		5.67
Driver	4.51	0.19	1.20
Passenger	4.51	0.19	1.20
Aft	6.32		1.20
Roof	4.58		0.69
Floor	4.46		1.20
Volume (m^3)	11.00		

Table 4: Cabin Dimensions and Insulation U-values used in Analysis

The TRNBuild parameters are input into TRNSYS via the Type 56 multi-zone building component. The building model is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node. The greatly simplified energy balance is calculated using the following equation [53]:

$$\dot{Q}_{internal} = \sum \dot{Q} = \dot{Q}_{conv,\ surface} + \dot{Q}_{conv,\ infiltration} + \dot{Q}_{conv,\ ventilation} + \dot{Q}_{conv,\ adjacent\ space} + \dot{Q}_{conv,\ internal} + \dot{Q}_{radiation,\ solar} \quad (1)$$

At the node, the heat flux is summed including inputs from the wall surfaces, infiltration (from both ambient and adjacent spaces), ventilation, and internal convective gains such as the operator, electronic equipment, and lighting. The convective heat flux is given by the flowing expression:

$$\dot{Q}_{conv,\ surface} = \sum_{surfaces} UA(T_{ambient} - T_{internal}) \quad (2)$$

In equation 2, U is the inverse of the equivalent thermal resistance of all wall materials and A is the area of each respective wall. Both values were taken from cabin schematics [52] and listed in Table 4. The infiltration heat gain is given by the following expression:

$$\dot{Q}_{conv,\ infiltration} = \dot{V}_{infiltration}\rho C_P(T_{ambient} - T_{internal}) \quad (3)$$

Here, $\dot{V}$ is the time rate of change of the volume of infiltrated air, ρ is the average density of the infiltrating air, and C_P is the average specific heat of the infiltrating air. Due to the high level of air-tightness of new vehicles, the infiltration load was considered negligible in comparison to the ventilation load, calculated using the following expression:

$$\dot{Q}_{conv,\ ventilation} = \dot{V}_{ventilation}\rho C_P(T_{ambient} - T_{internal}) \quad (4)$$

In the above expression, $\dot{V}$ is the time rate of change of the volume of ventilated air, ρ is the average density of the infiltrating air, and C_P is the average specific heat of the ventilation air. The majority of the climate control units surveyed, specifically the one selected for modeling does not use ambient makeup air. Thus, there is no ventilation load that does not come from the operator opening the vehicle doors or rolling down the windows. To otherwise account for a ventilation requirement, the occupancy-based ASHRAE standard of 0.0035 m^3/s (7.5 cfm) was used [54]. The heat flux from the unconditioned driver's compartment is calculated using the following expression:

$$\dot{Q}_{conv,\ adjacent\ space} = UA(T_{driver's\ compartment} - T_{sleeper\ cabin}) \quad (5)$$

Here, the U-value is the thermal resistance of the curtain separating the two spaces, and A is the area of the curtain.

One challenge encountered in using a model that was designed for buildings (assumed stationary) is modeling mobile systems with varying compass orientations and surrounding environments. Solar gains are dependent upon the thermal characteristics of the incident surface, incident angle, shading effects, etc. Not being able to reasonably estimate the parked orientation of the tractor at a given stop or the attenuation of solar gains the roof is considered a horizontal surface, and the only surface through which solar loads are considered.

3.2.1.4 Climate control unit

The CCU contains both the electric resistance heater and the vapor compression air conditioning system. Both systems use common ducting and fans and are typically mounted beneath the bunk in the sleeper berth. The CCU component receives the operating signal from the thermostat (type 108) and using temperature inputs from ambient (type 109) and cabin sensors (type 56), outputs heating or cooling temperature, air flow rate, and relative humidity values to the cabin as well as the power demand by the CCU, which is input to the power source.

Electric resistance heater

The 115 VAC electric heating system has a dual-stage heating element producing 1,000 W (3,400 Btu/h) on low setting and 2,000 W (6,800 Btu/h) on high setting. The blower fan is also variable speed, requiring 162 W on the low setting and 240 W on high [29]. The low and high heating stages are activated separately by the thermostat (type 108) at 18°C and 16°C, respectively.

Electric-driven vapor compression air conditioning system

The air-conditioning portion of the CCU component is modeled using a 10-coefficient curve fit to calculate system capacity and power consumption [55]. To this a constant speed evaporator fan was added as an additional power draw; the same fan used by the heater [56]. The inputs to the component are the control signal from the thermostat, cabin temperature, and ambient temperature. The parameters of the model are the minimum and maximum evaporator refrigerant-side inlet temperature, the minimum and maximum compressor air-side inlet temperature, and the approach temperature $T_{approach}$. The model calculates the unit capacity $\dot{Q}_{AC\,unit}$, power consumption rate $P_{AC\,unit}$, compressor air-side inlet temperature T_C, and evaporator temperature T_E from the cabin temperature and the approach temperature using the following expressions:

$$\dot{Q}_{AC\,unit} = C_1 + C_2T_E + C_4T_E^2 + C_7T_E^3 + (C_3 + C_5T_E + C_8T_E^2)T_C + (C_6 + C_9T_E)T_C^2 + C_1T_E^3 \quad (6)$$

$$P_{AC\,unit} = C_1 + C_2T_E + C_4T_E^2 + C_7T_E^3 + (C_3 + C_5T_E + C_8T_E^2)T_C + (C_6 + C_9T_E)T_C^2 + C_1T_E^3 + P_{fan} \quad (7)$$

$$T_E = T_{cabin} - T_{approach} \quad (8)$$

$$T_C = T_{ambient} \quad (9)$$

The air conditioning unit calculations are predicated on the assumption that the cabin temperature is regulated to within a small temperature band while the truck is being driven, and therefore, when the cabin climate control system is used following main engine shutdown the cabin is already fairly well climate controlled, thus it does not need to be "pulled down" from a high temperature. With the previous assumption it

is concluded that a constant approach temperature of 11.1°C (20°F) is a reasonable approximation.

In TRNSYS, specifically for the multi-zone building model (type 56), heating and cooling loads are connected as ventilation loads with the output temperature, volumetric flow rate, and relative humidity as inputs. The following methodology was used to calculate the input values:

The volumetric flow rate of the climate control unit was taken from manufacturer's data as approximately 0.094 m^3/s and 0.189 m^3/s (200 cfm and 400 cfm) for the low and high settings of the electric resistance heater, respectively, and 0.189 m^3/s (400 cfm) for the air conditioning unit [29,55,56]. The number of air changes per hour was calculated by the following expression:

$$ACH = \frac{\dot{V}_{CCU}}{V_{cabin}} \tag{10}$$

In equation 10, ACH is the air changes per hour, $\dot{V}$ is the volumetric flow rate, and V_{cabin} is the cabin volume [54].

The CCU output temperature was calculated using the following expression:

$$T_{output} = \frac{\dot{Q}_{capacity}}{\dot{V}\rho C_p} + T_{inlet} \quad (11)$$

Here, $\dot{Q}_{capacity}$ is the cooling or heating capacity of the system, $\dot{V}$ is the volumetric flow rate, ρ is the air density, and C_p is the constant pressure specific heat capacity of air [57]. For heating calculations, the cabin humidity ratio is assumed constant; therefore the entire heating capacity $\dot{Q}_{capacity}$ is used for sensible heating. For cooling calculations, however, discerning the proportion of the capacity used for sensible versus latent cooling is not as straight-forward. Because the CCU does not use outside air, the difference between the CCU inlet and outlet temperature is relatively small; on the order of 10 – 15°C (18 – 27°C). Because of this relatively small temperature difference, coupled with the desire to avoid a significant increase in the computation time and complexity required to model the sensible and latent cooling followed by sensible reheating process, it was proposed to use a constant sensible heat ratio (SHR). To do so, an average SHR had to be calculated, ostensibly based on a standard convention. Using the ASHRAE Unitary Air-conditioning and Air-source Heat Pump Equipment Standard temperatures [58] the sensible heat ratio is calculated using the following expressions:

$$\dot{Q}_{sensible} = \dot{V}_{CCU}\rho C_p(T_{high} - T_{standard}) \quad (12)$$

Equation 12 was used to calculate the sensible load for which $\dot{V}_{CCU}$ is the volumetric flow rate of the CCU, ρ and C_p are the density and specific heat capacity of air, and

T_{high} and $T_{standard}$ are 35°C (95°F) and 26.7°C (80°C), respectively. The following expression was used to calculate the latent load:

$$\dot{Q}_{latent} = h_{fg}\dot{V}_{ventilation}\rho(\omega_1 - \omega_2) + \dot{Q}_{latent,\ occupant} \quad (13)$$

Here, h_{fg} is the latent heat of vaporization of water, $\dot{V}_{ventilation}$ is the ventilation volumetric flow rate, ρ is the density of the ventilation air, ω_1 and ω_2 are the humidity ratio of the inlet and outlet air, respectively, and $\dot{Q}_{latent,\ occupant}$ is the latent gain of the occupant; 40 W for a quiet, seated person, according to TRNSYS. The SHR is calculated via the following expression:

$$SHR = \frac{Q_{sensible}}{Q_{total}} = \frac{Q_{sensible}}{Q_{latent}+Q_{sensible}} \quad (14)$$

From the above values, the SHR was calculated to be 0.97, implying that almost the entire capacity of the climate control system is used for sensible cooling. This conclusion is also supported by the fact that there is no mention of reheating (required to increase dry-bulb temperature after the latent load has been removed) or humidity concerns in the product literature.

The relative humidity was calculated using the psychrometric component (type 33). The temperature and relative humidity at the inlet of the climate control unit were input into type 33, yielding the humidity ratio. As justified above, the humidity ratio was assumed constant. The CCU output temperature and previously calculated humidity ratio were then used to calculate the relative humidity at the CCU outlet.

3.2.2 Power sources

In the preceding section, components common to both the APU and BPAPS simulations were discussed. The following sections describe the differences between the two system models: primarily the components that simulate the power sources for each system.

3.2.2.1 Fuel-fired Auxiliary Power Unit (APU)

As much as possible, the APU used in this analysis was based on one particular product [23]. This product was chosen because of the quality and amount of information available. Also, its characteristics are near the average of those surveyed in terms of power output, fuel consumption, weight, capital cost, service interval, etc. However, when supplementary information was required it was taken from other system brochures and manuals for products of similar power output, features, etc.

The selected APU operates at constant RPM and power output regardless of generator load. The rated generator output at a constant engine rotation speed of 2,400 RPM is listed as 35 amps at 120 VAC. The product literature does not specify whether or not the current and voltage values are RMS values. Assuming they are, the average generator power output was calculated to be 4.2 kW. From the engine spec sheet, using GetData® graph digitizing software, the instantaneous fuel consumption at 2,400 RPM was observed to be 262 g/kW·h [59] or 2.28 L/h[10].

[10] The specific fuel consumption, 262 g/kW·h (0.578 lb/ kW·h), is multiplied by the brake specific horsepower output per hour, 7.4 kW·h, and multiplied by the density of diesel fuel 849.0 g/L (7.709 lb/gal) [60], yielding 2.28 L/h.

As a brief aside, from an energy efficiency and fuel consumption standpoint, an APU that does not modulate power to follow the imposed load is not ideal. Although it is unclear from inspection of the product brochures and owner's manuals of the APUs surveyed in this study, a number of systems appear to "load-follow." However, specific information regarding engine power output versus fuel consumption could not be obtained.

The majority of currently marketed APUs feature both manual and automatic start and shutdown. This particular model features three automatic modes: comfort monitor, timer, and cold weather watch. Comfort mode uses thermal priority to control the APU. Any time the cabin temperature goes 2°C above or below the set temperature the APU starts and the HVAC system operates until that temperature is reached or for 15 minutes, whichever is longer. Timer mode, as the name implies, schedules startup and shutdown via a user-set timer. Cold weather watch mode automatically starts the APU for a specified time when the ambient temperature drops below a specified value to ensure the APU and main engine do not get so cold that they will not start. This mode is used by APUs with block heating capabilities. The model created for this analysis operates on timer mode from 7 – 8 a.m. and 7 – 10 p.m., and comfort mode between the hours of 10 p.m. and 7 a.m.

In addition to calculating power and fuel values, the model was also written to calculate the emissions produced during APU operation. The emissions data was taken from the CARB emissions certification of the engine used in the APU [61].

Specifically, the emissions gasses considered are the non-methane hydrocarbons plus oxides of nitrogen (NMHC +NO_x) (6.2 g/kW·h), carbon dioxide (3.5 g/kW·h), and particulate matter (0.24 g/kW·h) and are calculated as a function of brake horsepower output. The quantity and composition of the exhaust varies greatly with a number of factors including ambient temperature, fuel composition, and engine component temperature. The calculations made from these values are meant only to be a gross estimation; a starting point for reference.

In addition to the APU component, there is also a component referred to as a "gate" in the APU model. The function of the gate is to block the output from the APU to the summation component during times when the APU is modeled as not operating (i.e. prior to 7 p.m. on Monday, between 8 a.m. and 7 p.m. on Tuesday through Friday, and after 8 a.m. on Saturday) as the program calculates values for all output parameters for each minute of the year.

3.2.2.2 Battery-powered auxiliary power system (BPAPS)

The computational operation of the battery bank is as follows: if the total energy required by the CCU and cabin hotel loads does not exceed the capacity of the battery bank, the component calculates the additional fuel consumption required to recharge the battery bank. If the combined electrical load is greater than the capacity of the battery bank, the component calculates the fuel that would be required to replace the entire capacity of the battery bank and the day is "flagged." A flag indicates that the number of batteries currently in use is insufficient to meet cabin power requirements.

The flag also shows how many additional batteries would be required to meet the cabin energy demand (i.e. fewer batteries for temperate climates, more batteries for more extreme climates).

As stated in the market review section in chapter 1, in comparing a battery-powered system to other idle-reduction technologies, the fuel additional fuel consumed by the main engine in providing the energy necessary to recharge the battery bank must be taken into account. Without access to such information (if alternator load versus fuel consumption is even evaluated by manufacturers) the following methodology was used to approximate the fuel consumption value associated with operating a BPAPS.

The average fuel consumption for a long-haul truck is approximately 2.55 km/L (6 mpg) or 3.9 L/100 km to use the European convention for fuel economy [16]. The average highway speed is approximately 88.5 km/h (55 mph). In fact, many fleet tractors are governed to 96.9 km/h (60 mph). Assuming the energy density of diesel fuel is approximately 36.2 MJ/L [60], the energy flow to the engine is calculated to be 347 kW.

The additional power that the engine must produce to in order to recharge the battery bank is approximated by the following expression:

$$P_{engine,\ additonal} = (a_{rated} - a_{base})(V_{System})/(\eta_{engine} * \eta_{alternator} * \eta_{battery}) \quad (15)$$

In equation 15, a_{rated} is the rated amperage of the truck's alternator, a_{base} is the average base load on the alternator used to run vehicle electronics, V_{system} is the system voltage, and η_{engine}, $\eta_{alternator}$, and $\eta_{battery}$ are the engine, alternator, and battery recharge efficiencies, respectively.

The battery recharge efficiency is a function of the state of charge (SOC). The charging efficiency decreases the closer to it is to fully charged, especially for batteries that are only discharged to 30% of their capacity before recharged [62]. In this analysis, of the 660 amp·h available in the battery bank, regular discharge is typically less than 200 amp·h, so charging efficiency considerations of this sort are germane to this analysis. Again, using the GetData® graph digitizing software, the linear curve fit yielded the following:

$$\eta_{battery} = -1.452 * SOC + 1.871 \tag{16}$$

$$SOC = \frac{E_{bank\ capacity} - E_{disharge}}{E_{bank\ capacity}} \tag{17}$$

Below *SOC* of 0.6, the charging efficiency is assumed to be approximately 100%. Above 0.6, the efficiency is calculated using equation 16 up to an *SOC* of 1.0 (no discharge).

For example, an alternator rated at 185 amps is recommended for banks systems of up to six batteries, which is generally enough energy capacity to meet cabin

requirements in moderate climates. Assuming a base load of 110 amps[11], an engine efficiency of 40% [1], an alternator efficiency of 65% [8], and a battery recharge efficiency of 75%, the engine must consume an equivalent of 4.6 kW of fuel to provide 900 W of battery recharging power for a 12 VDC system.

Assuming a linear relationship between power output and fuel consumption, at least over small variations, the following expression is used to approximate the associated decrease in fuel economy:

$$FE_{reduced} = E_{flow}/(E_{flow} + E_{flow+additional\ load}) * FE \tag{18}$$

To continue with the previous example, the reduction in fuel economy caused by the increased alternator load $FE_{reduction}$ is equal to 0.04 km/L to yield a reduced fuel economy of 2.51 km/L. Finally, to calculate the fuel consumed in recharging the battery bank the following expression was used:

$$V_{fuel} = \left(\frac{1}{FE_{reduced}} - \frac{1}{FE}\right) * \frac{E_{total\ required\ to\ recharge}}{P_{per\ hour\ charging\ capacity\ of\ the\ alternator}} * S_{highway} \tag{19}$$

In equation 19, the first term on the right-hand side of the equal sign represents the additional fuel volume per unit distance, the second represents the total amount of

[11]The alternator base load was estimated from the literature assuming a 185 amp alternator is recommended for a bank of 4, 110A-h batteries. Recharging time is stated at 6-8 hours. Assuming 7 hours to recharge at 20 amps per battery, the base load was estimated to be 110 amps.

time the alternator must produce the recharging power level, and the third term is the highway speed of the vehicle. Given the previously calculated information, and assuming an energy deficit of 4 kWh is needed recharge the battery bank, the fuel consumption amounts to 2.52 L (0.665 gal).

Once calculated, the values output from the TRNSYS simulations are entered into the appropriate cells in the macro-enabled worksheet described in the following section.

3.3 Cost comparison model

The cost comparison model was originally developed as a stand-alone program for estimating the cost savings between idle-reduction technologies. However, using the preceding models to refine estimates of operating hours and fuel consumption, it was employed as a second stage in the comparison process, adding an economic perspective to the energy analysis.

3.3.1 Cost comparison model development

Considering every permutation of possible components within an idle-reduction system would not provide a relevant or useful comparison (i.e. it would not be effective in terms of cost, space, or weight to install an APU with a thermal storage air conditioner and a direct-fired heater). For the purpose of identifying the least-cost option among the prominent competing technologies an Excel macro-based calculation program was developed and six system configurations were chosen. For the same reasons they were ultimately selected for transient simulation development, the APU and BPAPS were included in the cost comparison: they are the primary competing complete energy systems in terms of cooling, heating, and power. A direct-fired heater and thermal storage air conditioning system were included in the analysis although neither can be compared directly to the APU or BPAPS because they are not complete power systems. The partial systems are also not directly comparable to one another because they meet different requirements, and are merely included for reference. Additionally, the direct-fired heater was selected because it is the most widely implemented idle alternative [7]. The thermal storage air conditioning system was selected as the most promising current alternative to

conventional air conditioning systems. Although TSE infrastructure is still in the developing stages, it is widely considered in the literature. Therefore, it was also considered in the cost comparison.

3.3.2 Sensitivity Analysis

Considering the large numbers of miles, operating hours, and the overall timeline of this comparison, small changes in certain types of costs can have a significant impact on the total cost and potentially which technology is the least cost option for a given set of parameters. For this reason, a sensitivity analysis was conducted. Each variable was increased by 10% and the resultant impact on the output variables was analyzed.

The variables having the most significant impact on hourly cost and payback period were the equipment costs (2.7%), annual operating hours (4.6%), current price per gallon (1.1%), main engine highway fuel economy (1.7%)[12]. Equipment costs vary significantly with the number of units purchased, geographic region, time of year, purchasing source, etc. To address this, at least three price quotes were obtained for each system over as wide a geographic region as was possible. It should be noted however, that cost information was quoted for a single unit, including installation costs. Fleet prices could be considerably less due to bulk purchase and simultaneous, multi-unit installation. Annual operating hours, addressed previously, have been shown to vary significantly with respect to operator behavior, fleet operating

[12] Because each technology may be more or less sensitive to a given control variable, the sensitivity analysis was used primarily for trend analysis. Values presented are averaged for all technologies for lifetime hourly cost. The variables not mentioned averaged less than 1% sensitivity.

procedures, geographic location, etc [2]. For this reason, a parametric study involving a range of operating hours is included in the results section. Fuel price also has a strong influence on the cost/benefit of idle-reduction technology. According to the U.S. Energy Information Administration (EIA), the average, on-highway price of diesel fuel was $0.76 per liter ($2.88 per gallon) in 2007. Prices are expected to increase to an average $0.91 per liter ($3.45 per gallon) in 2008 and drop to $0.85 per liter ($3.22 per gallon) in 2009 [47]. Despite the projected drop in on-highway diesel prices next year, it can be reasonably assumed that the overall trend of diesel prices will continue to increase. Due to price projection uncertainty, the rise in fuel cost was accounted for using an annual cost escalation rate and a parametric study with respect to this variable is also contained in the results section. The highway fuel economy of a long-haul truck can vary with a great number of factors. However, the average value is agreed upon to within a reasonably narrow range by a number of sources [2, 7, 16, 42]. Therefore, 2.55 km/L (6 mpg) is taken as the average vehicle fuel economy without variation.

Idle-reduction system service life also has a considerable impact on the cost of ownership. However, publicly available information on expected service life is extremely limited. Third-party information was used whenever available to discern the expected life of a system. When unavailable, equipment was assumed to last the length of ownership.

3.3.3 Nomenclature

The following variables were used in cost-comparison calculations.

AD	Annual Distance
AE	Alternator Efficiency
ALE	Alternator Load on Engine
AOD	Annual Operating Days
AP	Alternator Penalty
API	Alternator Penalty Index
APU	Auxiliary Power Unit
BLA	Base Load Amperage
BPAPS	Battery Powered Auxiliary Power System
CC	Capital Cost (including component replacement)
CVC	Cumulative Variable Cost (idle-reduction technology)
DBO	Distance Between Overhauls
DCH	Daily Charging Hours
DFH	Direct-Fired Heater
DTO	Days To Overhaul
DTO_I	Days To Overhaul, Idling
ECVC	Engine Cumulative Variable Cost
EE	Engine Efficiency (highway)
EMY_I	Effective Miles per Year Idling
EVC	Engine Variable Cost (annual)
FE	Fuel Economy
HEO	Hourly Engine Output
HFC_E	Hourly Fuel Consumption, Engine
HMD	Hourly Maintenance Degradation (charge)
HS	Highway Speed
IMPD	Idling preventative Maintenance cost Per Day
LHV	Lower Heating Value (fuel energy density)
PMSC	Preventative Maintenance Service Charge
PPG	Price Per Gallon
RAA	Rated Alternator Amperage
OHCPY	Overhaul Charge Per Year
OHCPY_I	Overhaul Charge Per Year, Idling
OB	Onboard (TSE)
SP	Shore Power (TSE)
SV	System Voltage
TS	Thermal Storage Air Conditioning System
VC	Variable Cost (annual, idle-reduction technology)
W	Weight
WP	Weight Penalty
WPI	Weight Penalty Index
Y	Year (current)

3.3.4 Calculations

In general, the cost-comparison macro calculates the operating and maintenance costs for each year. To this, it adds a weight penalty derived from transporting the added payload as well as an alternator penalty as previously discussed. These variable costs are continually summed, making adjustments for monetary inflation, as well as fuel, service, and labor cost escalation. In addition to these variable costs, the model adds the capital costs associated with initial purchase and component replacement over the lifetime of the system. The cost of components replaced after initial purchase are also adjusted for inflation.

The expression used to calculate the operating costs is as follows:

OC = HSC * AOH + CF * AOD + HFC_E * AOH * PPG + HFC_A * AOH * PPG + HFC_H * AOH * PPG * HDP / 100# (20)

The first term to the right of the equal sign in equation 20 is the service charge costs associated with TSE. The second term is the initial connection fee charged by onboard TSE purveyors. The third term is the main engine fuel cost per hour. The fourth term is the APU fuel cost per hour. The fifth term is the fuel cost for the direct-fired heater, adjusted for the number of annual heating days.

The maintenance cost for each system and/or component is tallied as a function of operating hours using the following expression:

SMC = AOH / SSI * SPMC * INF ^ (Y - 1) (21)

In other words, the annual system maintenance cost is equal to the number of times per year the maintenance must be performed, multiplied by the servicing cost, adjusted for inflation.

The cost savings associated with main engine idle avoidance are calculated using the ATA TMC RP 1108. However, instead of applying an hourly savings to each idle-reduction technology, the costs are included as a penalty against the baseline case of main engine idling. Equation 22 is used to calculate the idling preventative maintenance costs per day (IPMC/D) [10]:

$$IPMC / D = \frac{PMSC}{43} - \frac{PMSC}{62} \quad (22)$$

PMSC is the preventative maintenance service charge. The assumed interval without considering idling is 62 days; considering idling, the interval is reduced to 43. This is based on an oil change interval of 40,200 km (25,000 mi) and an average daily travel distance of 650 km (400 mi). TMC RP 1108 assumes $100 per oil change. However, this figure is provided from a fleet perspective, and may also be outdated. The current cost of PM servicing is near four times that amount for an individual owner/operator including an average of 3.5 hours of labor and $100 in parts and fees. This results in a significantly higher hourly penalty.

TMC RP 1108 also provides a method for calculating idling overhaul costs per day by calculating the effective miles per day idling:

$$EMY\_I = FE * AOH * HFC\_E \quad (23)$$

Here, the effective additional miles per year due to idling is a function of the fuel economy, the annual operating hours, and the hourly fuel consumption of the idling engine. In the following expressions the distance to overhaul is calculated for the idling case using the effective idling miles, equation 24, and also for the non-idling case, equation 25:

$$DTO\_I = DBO / (AD + EMY\_I) \quad (24)$$

$$DTO = DBO / AD \quad (25)$$

The overhaul charge per year of the idling and non-idling case is calculated using the following expressions:

$$OHCPY\_I = OHC / DTO\_I \quad (26)$$

$$OHCPY = OHC / DTO \quad (27)$$

The idling overhaul cost per hour is calculated using equation 28:

HMD = (OHCPY_I - OHCPY) / AOH (28)

Similar to the idling preventative maintenance costs per day, TMC RP 1108 assumes a $5,000 overhaul charge is incurred every 805,000 km (500,000 mi). Again, this figure is from a fleet maintenance perspective. From an owner/operator's point of view overhaul costs regularly exceed $10,000. Additionally, technology implemented since the publication of TMC RP 1108 in 2003 has pushed the overhaul life of most engines beyond 805,000 km (500,000 mi) to more than 1,207,000 km (750,000 mi).

The weight penalty is calculated using a fuel efficiency degradation versus weight index [9, 10]. Using GetData© graph digitizing software, a second order polynomial curve was fit yielding a weight to fuel efficiency degradation correlation of:

$$WPI = 3 * 10^{-10} * SW^2 - 6 * 10^{-5} * SW \quad (29)$$

Here, WPI is the weight penalty index and SW is additional system weight added by the idle-reduction technology. The cost of the weight penalty is approximated using equation 30:

$$WP = AD * PPG * \left(\frac{1}{FE} - \frac{1}{FE + WPI} \right) \quad (30)$$

In the above expression, WP is the weight penalty, AD is the annual driving distance of the vehicle, PPG is the price per gallon of fuel, and FE is the on-highway fuel

economy. The alternator penalty is calculated using the same method as discussed in the approach section; however the fuel amount is multiplied by the current price per unit of fuel to yield the cost.

After all of the variable costs are calculated for the total number of years of ownership, the fixed costs, including the capital and component replacement costs are added to yield the lifetime total cost. This figure is divided by the total number of idling hours to give the lifetime hourly cost. The payback period is calculated using the following expression:

If $ECVC - CVC \geq CC$ then

$$P = \left(\frac{CC - (ECVC - CVC)}{EVC - VC} \right) + Y \tag{31}$$

In equation 31, ECVC is the engine cumulative variable cost, CVC is the idle-reduction technology cumulative variable cost, CC is the capital cost, which includes component replacement due to service life expiration, EVC is the current year engine variable cost, and VC is the current year idle-reduction technology variable cost. In other words, if the variable costs accumulated by running the main engine less the cumulated variable costs of employing the idle-reduction technology are greater than the capital costs associated with purchasing the idle-reduction technology, the payback period is calculated using equation 30.

4 Results and Discussion

Because there was no test data from which to build the models developed in this analysis, validation cannot be performed in the strictest sense. However, the model results can be compared to other studies as well as manufacturer's data in order to support the contention that the model behavior is representative of the energy systems they were created to simulate.

4.1 Energy system results

Both the APU and BPAPS models were run in TRNSYS for each of the five freight-significant corridors described in the approach section for a time period of 50 weeks. At six working days per week, this equates to 300 driving days per year, followed by two week's vacation over the last half of the month of December. The results are as follows.

4.1.1 APU simulation results

Table 5 shows the total annual system operating time and fuel consumption for both systems and for each of the five selected interstates.

Route	Operating Time [h]	Fuel Consumption (APU) [L]	Fuel Consumption (BPAPS) [L]
I-5	1,504.69	3,388.70	278.16
I-10	1,501.60	3,399.60	284.48
I-65	1,533.42	3,472.00	295.15
I-70	1,599.24	3,620.82	314.08
I-95	1,545.65	3,499.80	297.90

Table 5: Results for the APU and BPAPS Simulations for Each of the Five Freight-significant Corridors

As shown, the average annual fuel consumption over the five routes is 3,476 L (918 gal). The majority of the APU market literature places hourly fuel consumption at 0.75 - 1.13 L/h (0.2 - 0.3 gal/h). However, this figure may be slightly misleading. For APUs with constant output, including the one modeled in this analysis, this average figure takes into account APU cycling during automatic mode. This is supported by the specific fuel consumption being nearly twice the advertised value, 2.28 L/h (0.60 gal/h). For this analysis, the hourly fuel consumption is calculated to be 0.89 L/h (0.24 gal/h)[13], which agrees well with the manufacturer's data.

The average annual operating time for all five routes is 1,536 hours, which lies between the survey results for average annual idling time of the ATRI (1,456 hours) and UCD ITS (1,744 hours), and below the Argonne study estimates (1,830 hours for the base case). The UCD ITS study also notes that the standard deviation of their data was quite large, on the order of 1,400 hours per year [2].

Although annual idling time[14] and annual operating hours[15] are not technically equivalent, they should be of the same order of magnitude. The difference between the two definitions comes from the automatic scheduling feature and ease of starting of the APU relative to the main engine. To use this analysis as an example, of the

[13] The daily operating hours, 13, multiplied by the annual operating days, 300, equals the total annual operating hours, 3,900. The total annual fuel consumption, 3,476 L, divided by this number yields the time-averaged fuel consumption, 0.89 L/h; the value provided by manufacturers.

[14]The average number of hours per year a long-haul truck would spend with the engine running at idle to power cabin electricity and climate control loads.

[15] The average number of hours an idle-reduction system would operate to meet the cabin electricity and climate control loads.

3,900 hours the APU was turned on in automatic mode[16], it operated just 1,537 hours. Because the main engine does not turn on and off based on cabin power and HVAC requirements, it must remain idling when the operator wishes to enjoy these features. This implies that a deliberate choice is made as to when the operator operates the engine at idle; a choice he or she no longer needs to make because of idle-reduction technologies like the APU. However, in order to compare the idle-reduction technologies against the baseline, there must be a common time value. In the case of the idling engine, idling hours are equivalent to operating hours. Therefore in the comparison to follow, all technologies will be compared with respect to idling hours. The APU will use the actual fuel consumption rates calculated using the previous simulation, 2.28 L/h (0.6 gal/h) as opposed to the time-averaged values provided in the product literature, 0.75 – 1.14 L/h (0.2 – 0.3 gal/h).

With regards to a route to route comparison, the highest number of idle-reduction system operating hours were accumulated along I-70. The lowest system operating time was accrued along I-10. This disparity can be explained by the difference in route climate. I-70, running from Utah to Maryland, is both higher in average altitude and higher in latitude than I-10, which is the most southerly east-west interstate traversing the US. This contention is supported by the monthly average values shown in Figure 6. I-10 has the highest average temperature of all five routes, whereas I-70 has the lowest average monthly temperature for the majority of the year. I-5, 65, and 95 run north to south, and therefore have a more temperate average climate. In other

[16] The annual operating hours are calculated by multiplying the number of hours per day the APU is operating, either running or in automatic mode, 13, by the number of working days in the year, 300.

words, the weather extreme at one end is balanced by the temperate weather at the other.

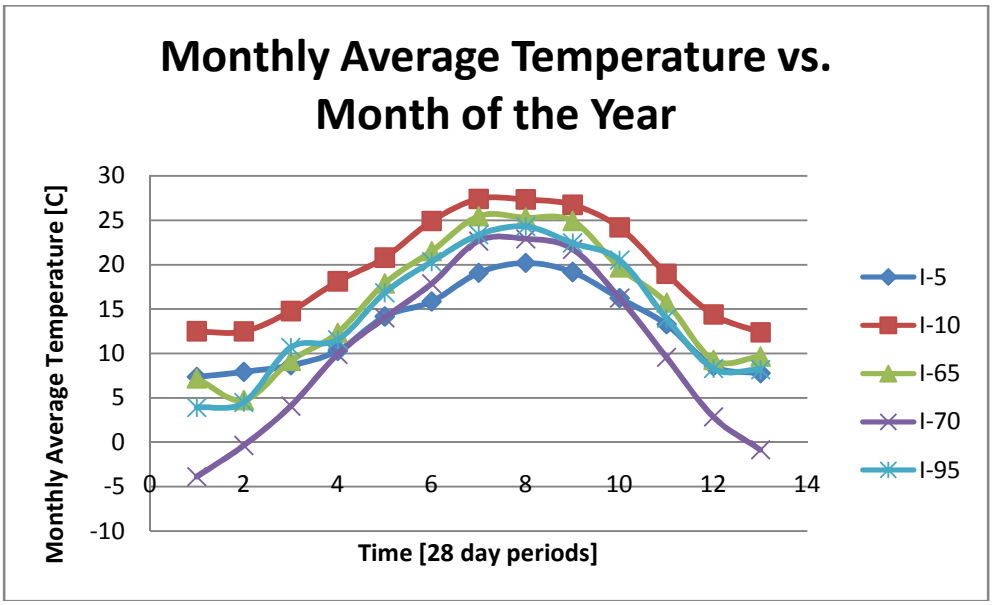

Figure 6: Average Monthly Ambient Temperature Along Each of the Five Freight-significant Corridors of the US

As shown more distinctly in Figure 7, the heating requirement has a much more significant impact on the operating hours and therefore the fuel consumption than the cooling requirement. This is due largely to the rigid daily schedule of the simulated truck. In the late fall and winter, the coldest part of the day occurs at night, when the APU or BPAPS is used to meet the cabin energy requirements. However, in the summer, the hottest part of the day occurs at mid-day or in early afternoon when the vehicle's engine is used to meet the driver compartment cooling requirements.

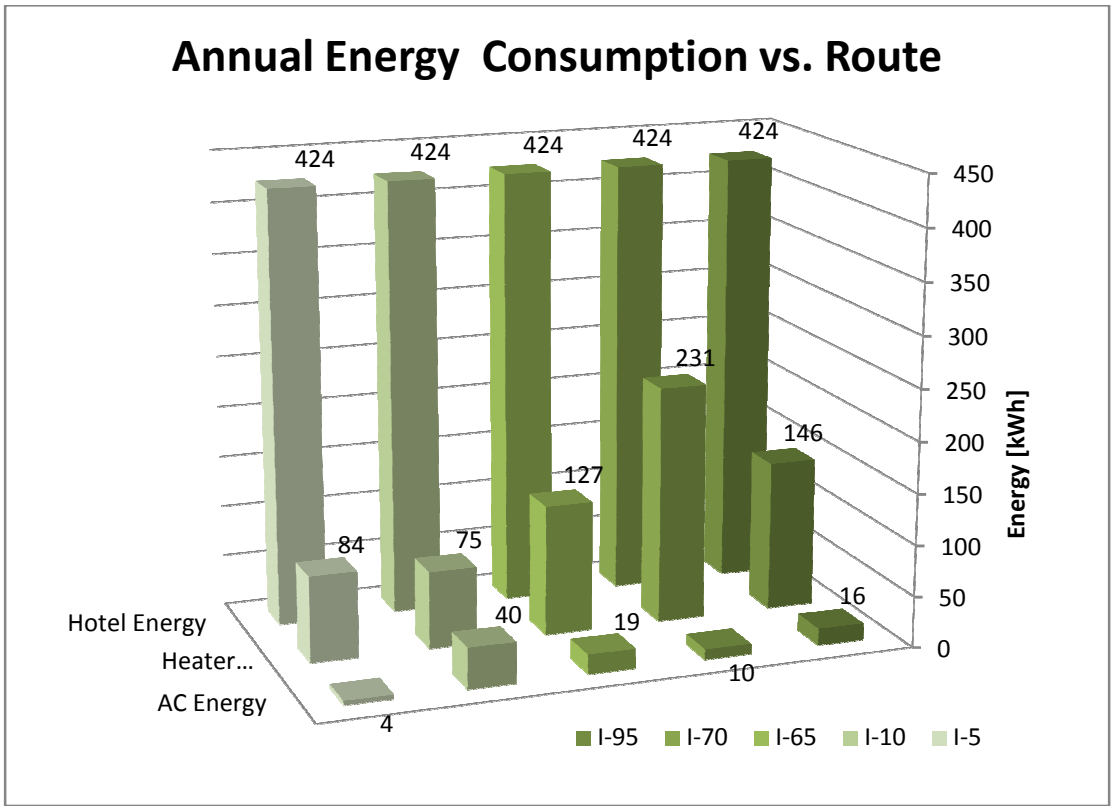

Figure 7: Annual Energy Consumption of Each of the Three Types of Energy Consumers: the Air Conditioner, Heater, and Cabin Electrical Loads

Figure 8 shows the annual estimated exhaust gas emissions for an APU not equipped with a particulate filter. As the emissions levels are directly proportional to the energy output, the model of the truck traversing I-70 produced the most emissions; the truck traversing I-5, the least. Because there is no emissions data available corresponding to the additional exhaust gas produced in recharging the battery bank, the two systems cannot be compared in terms of "fuel-tank-to-outlet" environmental impact. However, as mentioned in the approach chapter, the emissions values displayed in Figure 7 are offered as a starting point for later refinement.

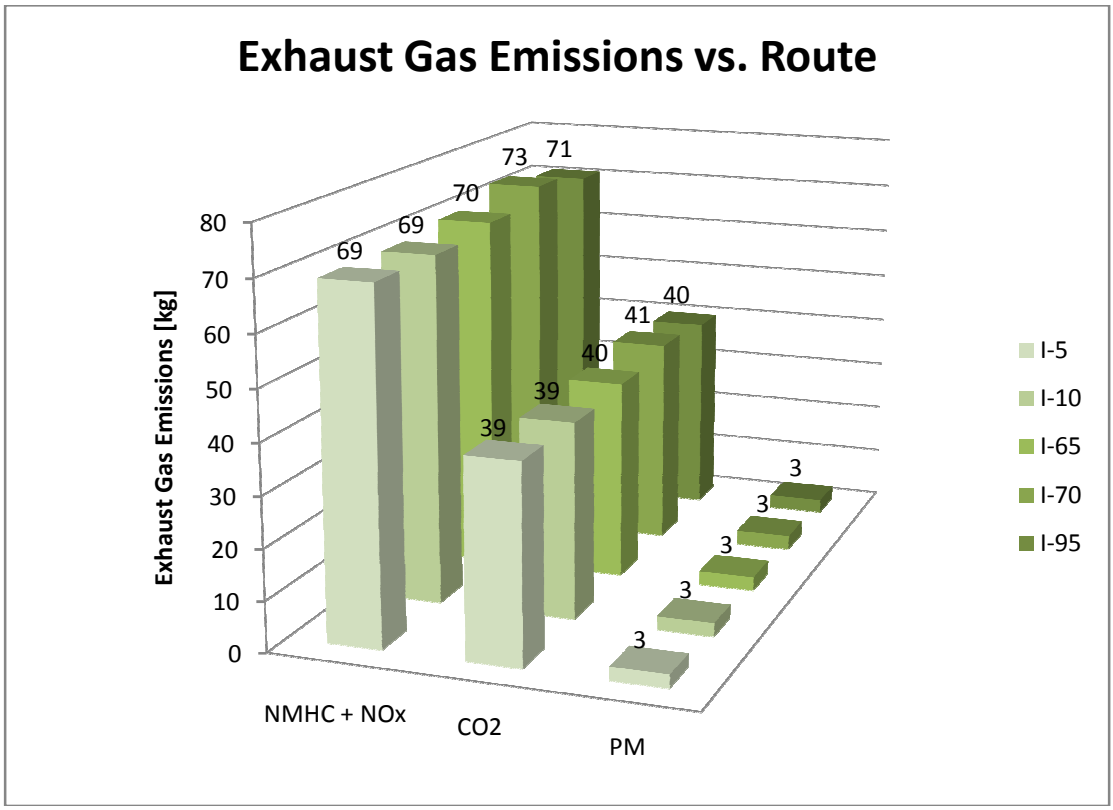

Figure 8: Emissions Levels of Non-methane Hydrocarbons Plus Oxides of Nitrogen, Carbon Dioxide, and Particulate Matter for Each of the Five Freight-significant Corridors.

4.1.2 BPAPS simulation results

Figure 9 shows a significant fuel savings of the BPAPS over the APU. For this disparity there are two related explanations. First, the battery charging system only produces the energy required to recharge the battery bank, whereas the APU produces much more energy than the cabin load requires.

The second is the higher efficiency with which the main engine generates electricity compared to the APU. As stated in the approach section, if the engine produces power at 40% efficiency, the alternator produces electricity at 65% efficiency, and the battery bank recharges at near 75% average efficiency the overall fuel to electricity

conversion efficiency of the truck is approximately 21.0%. In comparison, the APU consumes fuel at a rate of 2.28 L/h (0.59 gal/h) (equating to a fuel energy flow of 22,963 W[17]), and produces 4,200 W of electricity. This yields a full-load fuel to electricity conversion efficiency of 18.3%, which is on par with most engines of its size. However, if only 1.6 kW of power is required by the cabin (as would be the case during the evening with the heater operating on the low setting, for example), the efficiency drops to 7.0%.

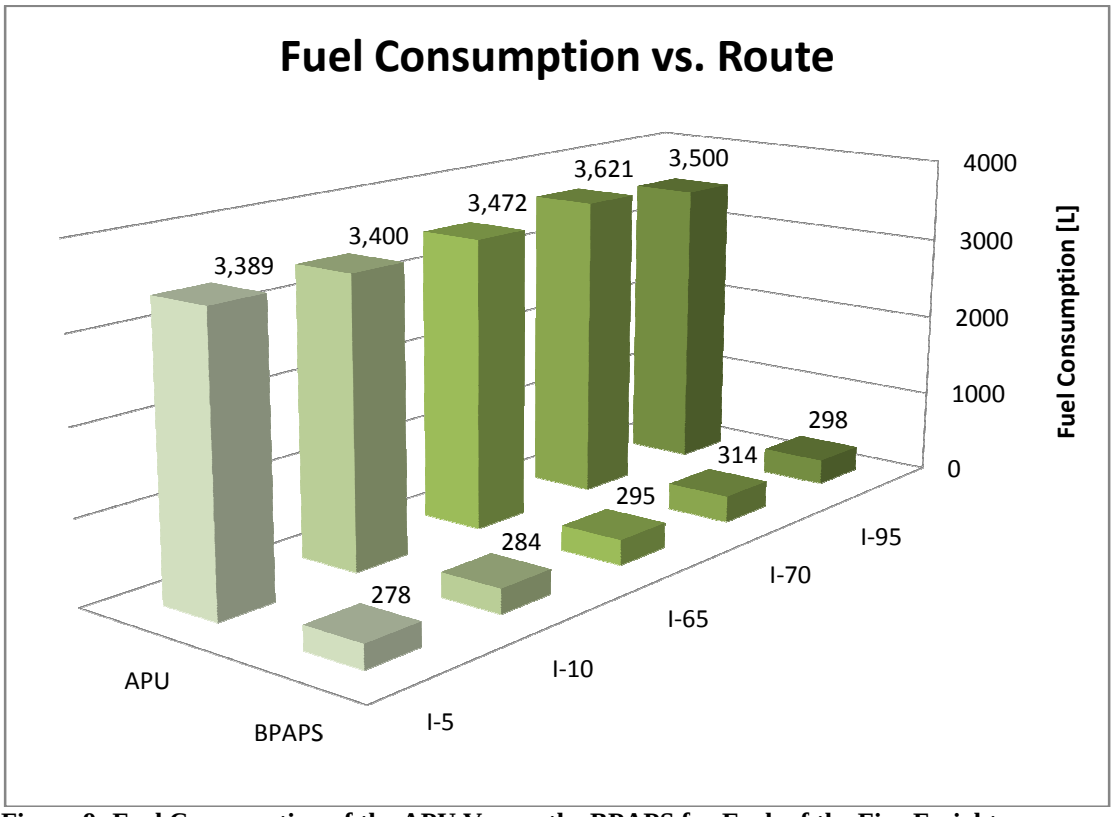

Figure 9: Fuel Consumption of the APU Versus the BPAPS for Each of the Five Freight-Significant Corridors.

[17] 0.262 kg/kWh multiplied by the break horsepower hours (BHPh), 7.4 kWh, and divided by the average density of diesel fuel, 0.849 kg/L, equals 2.28 L/h. This value multiplied by the energy density of fuel, 36.2 MJ/L, equals 22,963 W.

4.2 Cost comparison

Using the calculated values from the APU and BPAPS simulations for operating hours (1,536) and fuel consumption (3,476 L for the APU and 294 L for the BPAPS), a cost comparison was conducted showing the relative advantage of each of the selected idle-reduction technologies in terms of lifetime cost per hour, total cost, and payback period. As mentioned previously, variables like fuel price, annual operating hours, and years of ownership can have a significant impact on the comparative costs of an idle-reduction system. A simple parametric study is provided to demonstrate the impact of these parameters on the lifetime hourly cost and payback period.

4.3 Assumptions

The following are the assumptions made for the calculations used in this analysis:

- Price inflation is 3% per year on all components, services, and service charges
- All equipment installed at the time of purchase and subject to 12% FET
- Service life is equal to the life of the study unless shown to be shorter [10]
- The average vehicle operates for 300 days per year [2, 42, 43]
- Main engine fuel consumption at idle is 3.79 L/hr (1 gal/h) [2,42]
- The DFH hourly fuel consumption is 0.19 L/h (0.05 gal/h) [37, 38]
- The average number of heating days per year is 96 [7, 42]
- The average number of cooling days per year is 120 [7]
- The periodic service interval for an APU is 1,000 hrs [17-21, 23, 24, 44]

- The relationship between increased weight and decreased fuel economy is described by a second-order polynomial curve fit even at small increments (< 1% of gross weight)
- The total annual distance traveled is 193,000 km (120,000 mi) the majority of which is on-highway [2, 7, 16]
- The average fuel economy of truck is 2.55 L/km or 39.2 L/100km (6 mpg) [2, 16, 42]
- The average trucks alternator efficiency is 65% [8]
- Main engine efficiency is 40% at highway speeds [45]
- Recharging efficiency is 75% as estimated in previous section for an average SOC of 0.75 [62]
- Average highway speed is 89 km/h (55 mph) [2, 16]
- Lower Heating Value for diesel fuel is 36 .2 MJ/L (130,000 Btu/gal)
- The base electrical amperage for the truck is 110 amps. This figure is estimated from the additional alternator capacity required for a BPAPS and advertised battery charging times as described in the preceding section.

Capital and service costs, hourly labor rates, and installation hours were attained via an informal market survey conducted by telephone and compared against third party information when available [10, 42, 46]. See appendix A for more information including a detailed view of the worksheet variables and cost values.

4.4 Results

Input	Engine	OB TSE	SP TSE	APU	BPAPS	DFH	TS
Number of Years (Y)	4	4	4	4	4	4	4
Lifetime hourly cost ($/hr)	$4.44	$1.92	$2.35	$4.44	$1.78	$0.36	$0.90
Lifetime cost ($)	$32,000	$13,827	$16,949	$27,271	$10,933	$2,223	$5,975
Actual payback (yr)	N/A	1.1	0.0	-	1.4	0.2	0.7
Input	**Engine**	**OB TSE**	**SP TSE**	**APU**	**BPAPS**	**DFH**	**TS**
Number of Years (Y)	7	7	7	7	7	7	7
Lifetime hourly cost ($/hr)	$6.67	$1.88	$2.83	$4.19	$1.43	$0.28	$0.64
Lifetime cost ($)	$84,002	$23,698	$35,636	$45,057	$15,366	$3,044	$7,771
Actual payback (yr)	N/A	1.1	0.0	4.7	1.4	0.2	0.7

Table 6: Cost Comparison Baseline Engine Idling, Onboard Truck Stop Electrification, Shore Power Truck Stop Electrification, Fuel-fired Auxiliary Power Unit, Battery-powered Auxiliary Power Unit, Direct-fired Heater, and Thermal Storage Air Conditioning System

Using the listed assumptions, Table 6 shows the lifetime hourly cost, lifetime cost, and payback period for each of the idle reduction technologies. The years of ownership used in this calculation, four and seven, correspond to the average length of fleet ownership and individual ownership, respectively [7, 42].

Over the period of fleet ownership, Table 6 shows the hourly cost of purchasing, operating, and maintaining an APU is nearly equivalent to that of the primary engine. This is due primarily to the relatively small difference in fuel economy, 3.79 L/h (1.0 gal/h) versus 2.28 L/h (0.6 gal/h), matched with the high capital cost of purchasing the APU. Over the lifetime of individual ownership, the APU cost per hour drops with respect to the baseline as the effect of reduced fuel consumption “washes out” the high capital cost of the APU. Figure 5 also shows that at these parameters, fleet purchases would not surpass the payback period for an APU.

The remaining technologies all have payback periods less than the timeline of fleet ownership. It is interesting to note that even with relative high capital cost the

BPAPS provides a quick return on investment because of its relative low fuel consumption with respect to the baseline. Also interesting is the difference between onboard and shore power TSE over the two lengths of ownership. As shown, with a 3% annual service charge escalation rate, shore power TSE increases while onboard decreases due to the decreasing effect of the initial equipment purchase cost.

As shown in Figure 10, over the lifetime of fleet ownership, at low annual operating hours, the APU is actually more expensive to operate on an hourly basis than the main engine, regulations aside. However, as operating hours increase, the cost per hour decreases as the impact of purchase price decreases. Onboard TSE and the BPAPS are also more expensive than shore power TSE, initially.

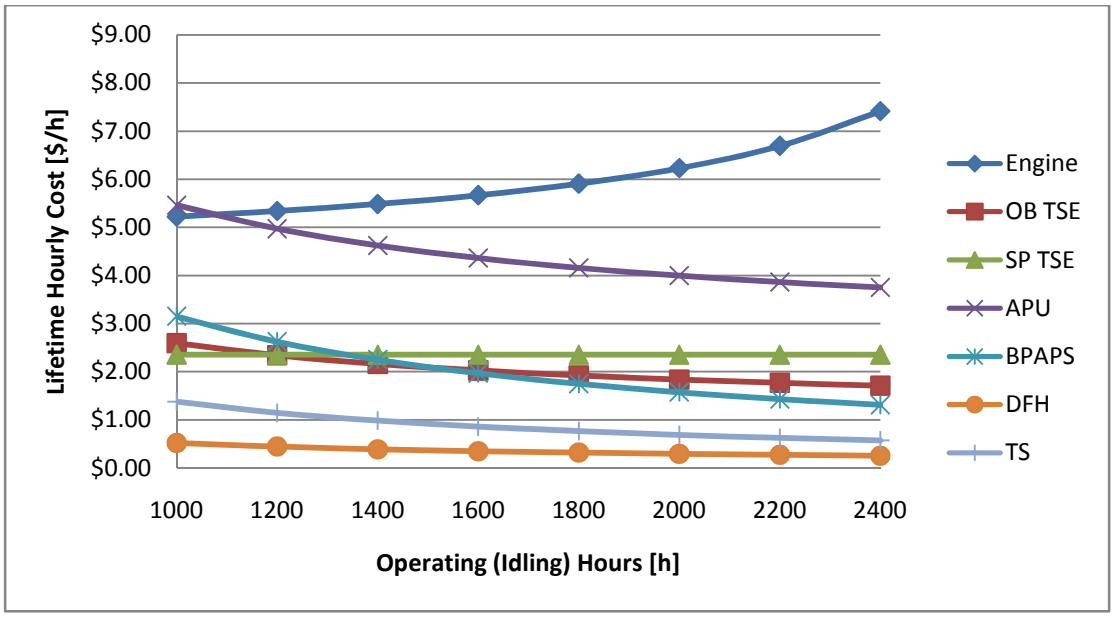

Figure 10: Operating Time Versus Lifetime Hourly Cost Over Four Years of Ownership

Echoing Figure 10, Figure 11 describes the period of individual ownership. In terms of the mobile, complete energy systems, the APU remains more expensive per operating hour relative to the BPAPS. In the range of operating hours calculated previously in this analysis, onboard TSE has near equivalent cost per hour relative to the BPAPS, assuming enough electrified parking spaces were available to meet operator demand.

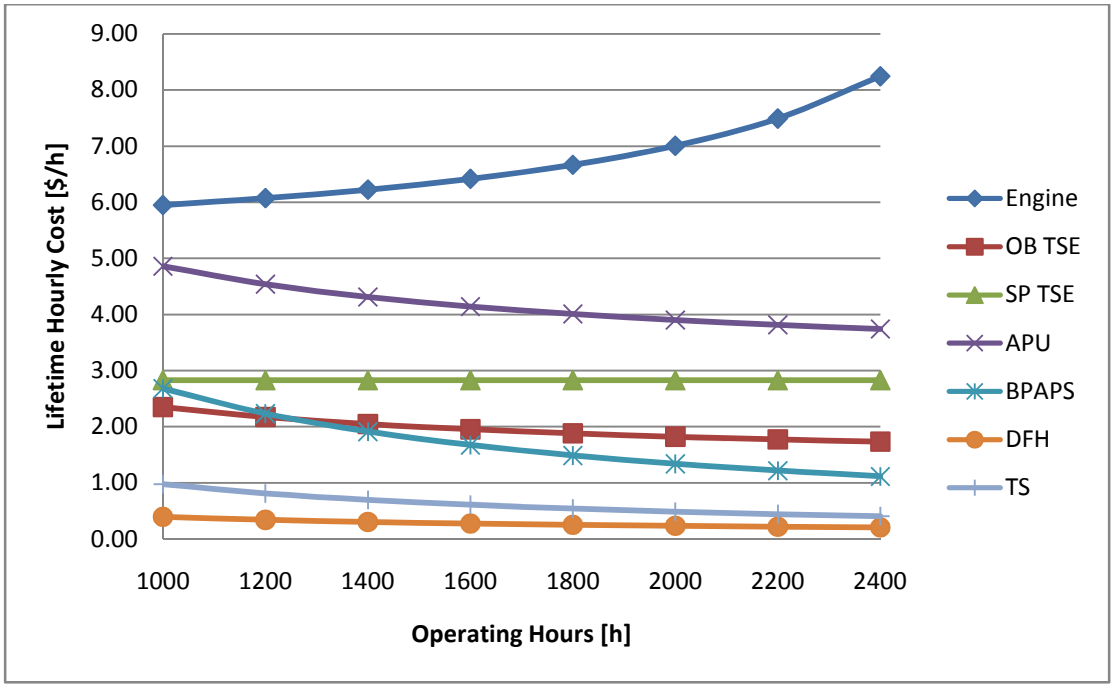

Figure 11: Lifetime Hourly Cost Versus Annual Operating Hours for the Period of Individual Ownership (7 Years)

Figures 12 and 13 display the effect of fuel price escalation rate on lifetime hourly cost for the timelines of fleet and individual ownership, respectively. Again, because of its more sizeable fuel requirement, the APU is affected to a greater extent by the rising price of fuel, though not as much as the baseline.

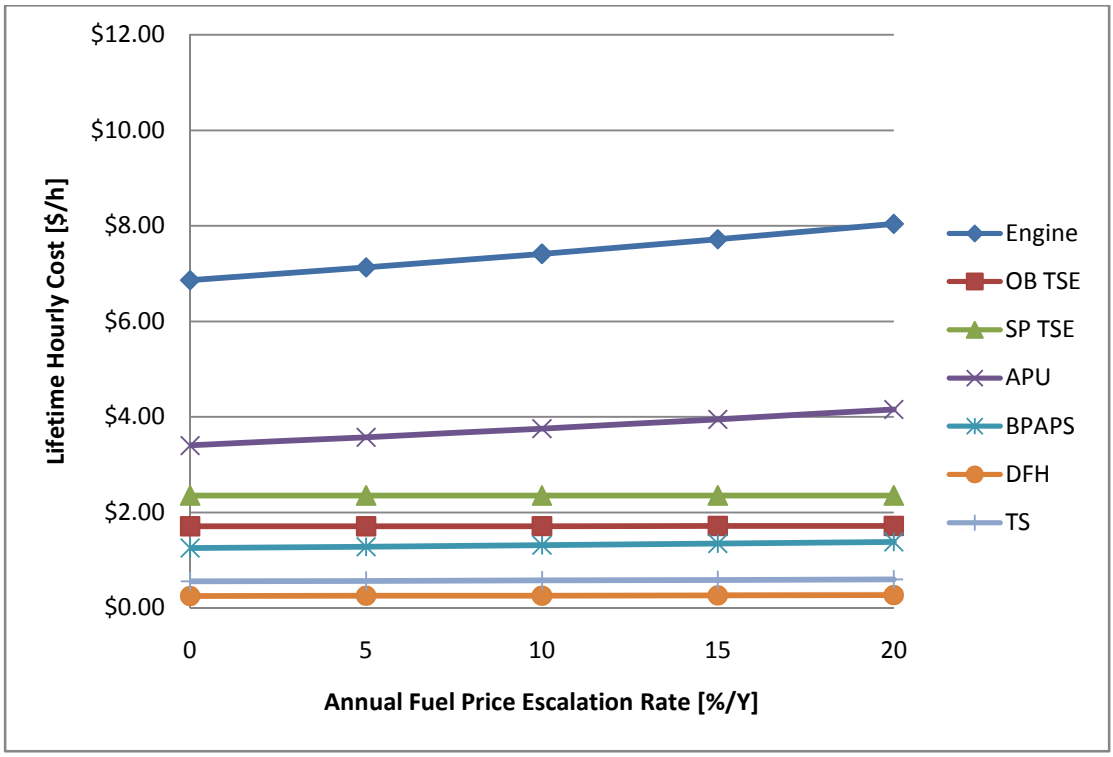

Figure 12: Lifetime Hourly Cost Versus Fuel Price Escalation Rate for an Ownership Period of Four Years

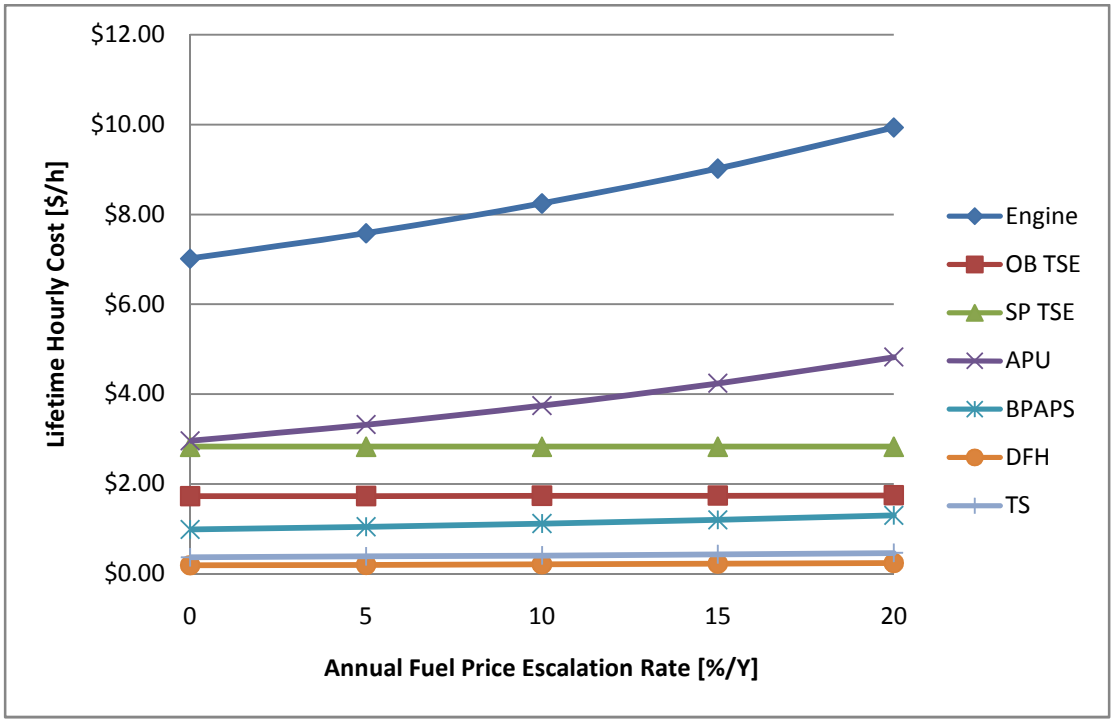

Figure 13: Lifetime Hourly Fuel Cost Versus Fuel Price Escalation Rate Over a Seven Year Ownership Period

As shown in Figure 14, the payback period is highly dependent on the number of annual operating hours. Specifically, technologies with high fuel consumption rates are impacted to a greater extent by operating hours than those with low or no fuel consumption rates.

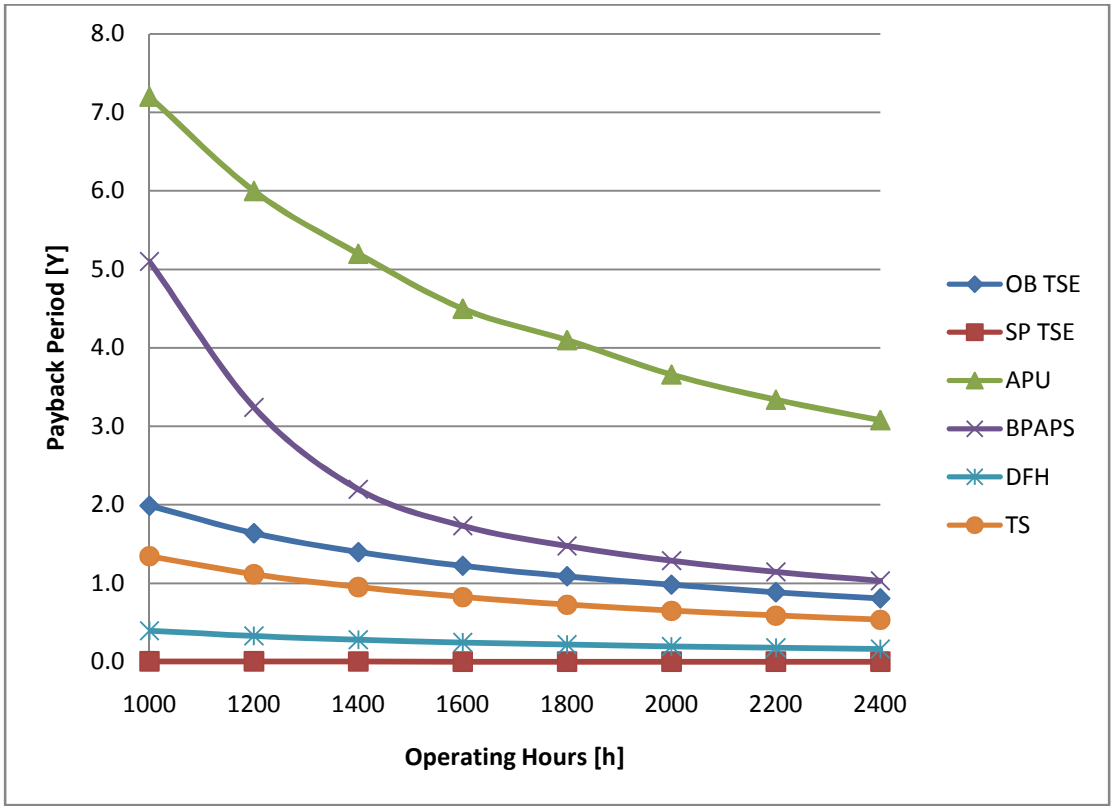

Figure 14: Payback Period Versus Operating Hours

By contrast, with the exception of the APU, Figure 15 shows little change in the payback period with respect to escalating fuel prices. As fuel prices increase, the advantage of the APU over the idling engine makes a greater impact, driving down the payback period, although it is to a lesser extent compared with the impact of operating hours. Onboard and shore power TSE are not directly affected by escalating fuel costs, although surcharge rates could increase if the plant that supplies

energy to the terminals is powered by fossil fuels. The direct-fired heater, BPAPS, and thermal storage air conditioner decrease only slightly.

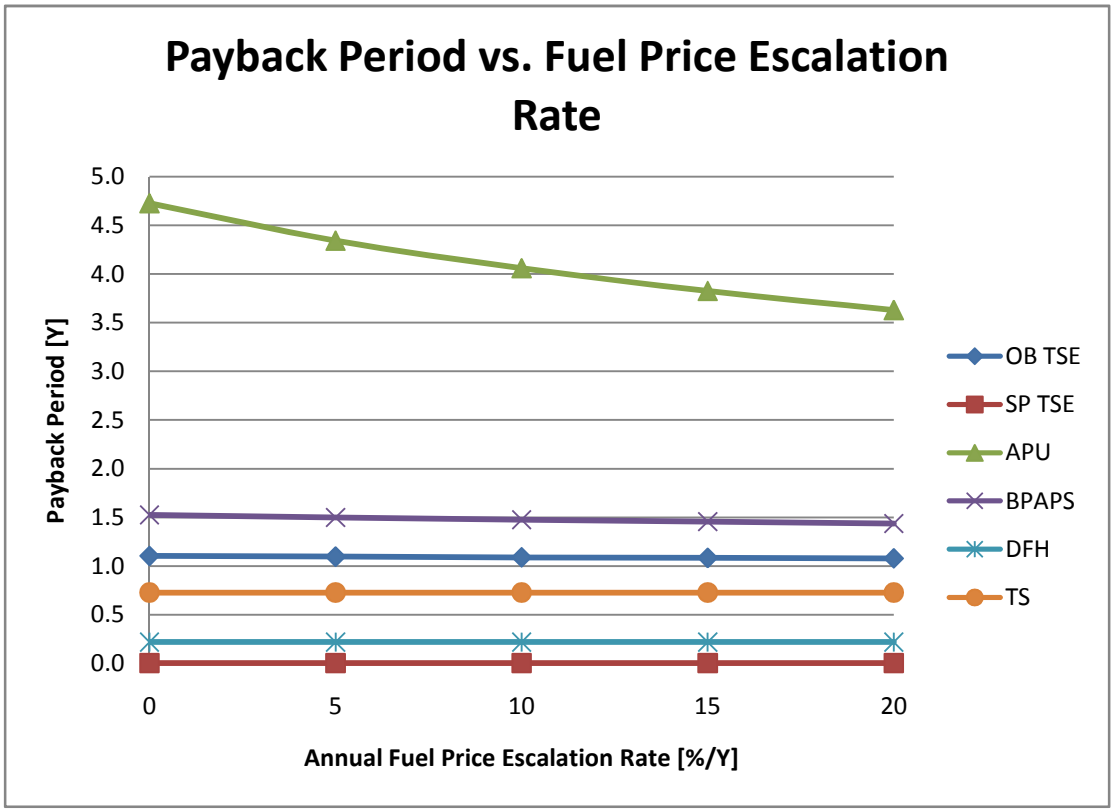

Figure 15: Payback Period Versus Annual Fuel Price Escalation Rate

4.5 Proposed model improvements

The purpose of the simulations developed in this analysis is to approximate current system operation, discern which idle-reduction technology has the most promise for wide-spread implementation, and provide a platform upon which future system improvements can be tested. The following section outlines possible future improvements to the models as well as areas for further research.

4.5.1 Further development of cabin AC electrical "hotel" load duty cycle

As mentioned in the approach section, the hotel load cycle for this model was developed in the spirit of a residential electrical load cycle, using electronic equipment and their respective power ratings from published literature. A considerable effort was made to acquire some feedback on the proposed duty cycle, though the pursuit was ultimately unsuccessful. An improvement on this approach would be to survey the habits of long-haul truck operators with respect to their type of electronic equipment and power use to further refine the load cycle. Even input from a handful of operators would be beneficial. The impression of the author is that the actual energy demand for hotel loads is probably smaller than the amount represented in this analysis. Product literature suggests some of the more energy-intensive electronic components listed in the surveys used to create the duty cycle [6, 7] are available in smaller, more efficient models [63, 64]. It is also more likely that the electronic equipment presented in this analysis is used less frequently than represented; the television and DVD player are most likely not used by the average

operator five nights a week, as an example. For these reasons, feedback from the industry would be beneficial in making the model more realistic.

4.5.2 Further development of route weather files and operator schedule

Another instance in which industry feedback would be beneficial is with respect to operator driving habits. Also outlined in the approach section, the TMY2 weather files used in this analysis are a mix of en route weather data along five of the most freight-significant interstate corridors in the US. The purpose creating these files was to better approximate the climatic diversity experienced by a long-haul truck more reasonably than simply using the weather data for a single reporting station.

However, modern fleets use GPS to track their trucks. Actual data describing trip lengths, overnight stops, working hours, etc. would contribute enormously to the accuracy of the model. A component model could be developed to input the GPS coordinates of the vehicle at any given time, find the nearest TMY2 reporting station, and output the ambient conditions to the cabin model. As shown in the previous section, assuming similar hotel load requirements, ambient conditions play the most significant role in the energy consumption of the sleeper cab equipped truck.

Also, although long-haul trucks regularly traversing the country serve the purpose in this analysis of demonstrating the variation of energy requirements with geographic region, this behavior is not necessarily representative of the average operator. For instance, regional fleets would generally purchase idle-reduction equipment most

suited to the climate their drivers encounter most frequently. This information could aid in tailoring future models and research efforts towards a more specific technology or energy requirement.

Also pertaining to operator driving schedules, this model has a rigid driving schedule; 8 a.m. to 7 p.m. six days a week. Anyone who has driven on an interstate after 7 p.m. can attest that even the majority of truck drivers do not obey this schedule. With the considerable impact time of day has on the climate control load a model featuring some flexibility with respect to driving schedule would likely be more accurate.

4.5.3 Improvements to the APU component

Obtaining appropriate information to model an APU that is designed to operate at part-load is the first step in APU component improvement. A load-following APU would certainly compare more favorably with other idle-reduction technology and provide an interesting comparison against non-load-following models.

As it stands, the current APU component simply "senses" when there is an electrical or climate control load, and calculates the fuel consumption and emissions. However, it does not take into account temperature or altitude considerations which can have a considerable effect on power output and exhaust gas emissions levels. Having dynamometer and emissions data for a similarly-sized engine would contribute greatly to the accuracy of the model. Also, test data describing the temperature and mass flow rate of the coolant and exhaust systems would provide valuable

information for use in the design of waste heat utilization technologies such as fuel warming in cold weather.

Similarly, as mentioned in the first chapter, several APUs feature main engine block warming systems. The current APU model does not have this feature, although adding it would increase the accuracy of those systems which do have “cold weather watch” automatic control functionality.

4.5.4 Improvements to the battery bank component

Like the output capacity of the APU, the battery bank capacity is also highly susceptible to fluctuations in ambient temperature; losing as much as half the available capacity as temperatures fall from room temperature to freezing and below. A battery’s charge capacity is also greatly impacted by the number of discharge/recharge cycles it endures and the rate at which it is discharged. The current BPAPS model does not take any of these considerations into account. Including these calculations will not only increase the accuracy of the model, but also provide a better picture of how many batteries are required given the ambient conditions in which the truck is intended to operate. The inclusion of temperature dependent capacity calculations would also facilitate the addition of a battery compartment climate control unit, outlined in greater detail in the proposed system improvements section.

At the current moment, the battery bank component program is written on an energy basis (i.e. the rate of discharge is not taken into account, only the energy removed and replaced). A more accurate component model would include the discharge and charge rate calculations to facilitate total capacity calculations mentioned in the above paragraph.

Perhaps the improvement with the greatest impact with respect to the BPAPS model, would be main engine test data for a truck engine describing the fuel consumption rate and exhaust gas emissions production with respect to power output. Such data could be used to verify the alternator penalty expressions used to calculate the fuel consumption as a function of increased alternator output. The emissions data could be used to compare the APU and BPAPS with respect to the total amount of exhaust gas material produced.

4.6 Proposed system improvements

As demonstrated by this analysis, system improvements that would have the greatest impact can be generally ascribed to two related categories: decreasing cabin energy requirements and utilizing engine and APU waste heat. The suggested improvements could be developed and tested using the preceding models to determine feasibility in further research efforts.

4.6.1 Increase insulation thermal resistance

One of the simplest methods of reducing cabin power demand is to increase the insulation thermal resistance. As late as five to ten years ago, sleeper cabin trucks were built with U-values of 5.7 – 3.8 $W/m^2 \cdot K$ (R1 – R1.5). The cab used in this analysis was based on a sleeper cab with insulation values of 1.2 $W/m^2 \cdot K$ (R4.6). Increasing the thermal resistance would further reduce the cabin heating and cooling load, reducing the size of the climate control unit, and thus the size of the APU or battery bank required to power it. For example, using the TRNSYS model developed in this analysis, increasing the insulation value to 0.56 $W/m^2 \cdot K$ (R10) would reduce the thermal load requirement for the month of January along I-70, the coldest route of those surveyed, from 158 kWh of heat to 112.5 kWh. This is approximately a 30% energy savings during the coldest months of the year.

The truck manufacturing industry appears to be moving this direction. Several manufacturers are increasing their base model insulation and offering premium insulation packages at additional cost. The National Renewable Energy Laboratory

(NREL) is also looking into methods of efficient thermal management, which include increasing cab insulation, using IR reflective materials on the exterior, implementing advanced window glazes and shading, and utilizing waste heat sources from the vehicle for climate control [65].

4.6.2 Utilize APU waste heat for cabin forced-air heating

One of the most obvious ways to increase system efficiency is to take advantage of the waste heat being produced by the APU. At less than 20% fuel to electric conversion efficiency, there is plenty of waste heat to use. To a limited extent, waste heat utilization is already available in the form of the integrated coolant loop between the main engine and the APU, allowing engine coolant warmed by the APU to maintain engine block temperature in extreme cold conditions. However, jacket heat makes up approximately half of the waste heat produced during APU operation. APU exhaust gas could be directed through a heat exchanger, and the heat removed could be used for cabin climate control. This would be especially attractive for units that are designed to modulate their output power. An intelligent control system could be employed to switch from electrical to thermal control priority as needed to power cabin loads or maintain cabin temperature as required. If the APU has to run regardless to power the heating system, be it electrical resistance or forced-air, providing energy equal to the requirement is a sure way to increase system efficiency.

4.6.3 Integrate battery systems with coolant recirculation pumps

Integrating two technologies that are currently on the market may also provide a simple solution to reducing cabin power requirements. As shown in this analysis, decreasing the heating energy requirement is one of the most effective ways of reducing the overall energy requirement. If the heating load can be displaced through the use of a coolant recirculation pump, even if the residual engine heat cannot meet the heat load for more than a few hours, it could significantly reduce the energy demand on the battery. This may also allow fewer batteries to be used, saving capital investment, weight, and possibly fuel.

4.6.4 Thermal storage fuel heater

The waste heat, either from the APU or the main engine, could be used to regenerate a phase-change material-encased thermal storage fuel tank. In addition to engine starting in cold ambient conditions, one of the major complaints of the trucking industry is congealed diesel fuel. Currently the fuel is thinned with other petroleum products that are often more expensive and/or less energy dense than no. 2 diesel fuel.

Regenerated with waste heat recovered from the engine exhaust system or the APU, the thermal storage medium surrounding a double-walled fuel tank could provide enough warmth over the course of the shutdown period to keep the fuel from congealing. This concept could be employed along with a small fuel circulation pump to keep desorbed solids from blocking the fuel lines between the engine and the fuel tanks.

4.6.5 Thermal storage battery compartment

Another instance in which engine waste heat could be used is in regenerating a thermal storage medium surrounding the battery bank compartment. As previously discussed, cold ambient temperatures have a significant degrading effect on the capacity of the battery bank. Maintaining compartment temperature near room temperature would maintain battery capacity in cold ambient conditions.

Similar to the previously suggestion, heat from the main engine exhaust could be diverted to via a small heat exchanger and used to regenerate a phase change material (PCM). The PCM would be sandwiched in between a double walled battery compartment. Once the engine was shut down, the PCM would change from liquid to solid, releasing the heat of crystallization into the battery compartment, maintaining the space temperature above freezing. Once in use, the batteries may produce enough internal heat to maintain a larger percentage of their total room temperature capacity. Such a system would add both weight and cost to the system overall. However, it such a configuration allowed the system to meet the cabin energy demand with fewer batteries, the increased costs of a thermal storage system may be offset by purchasing, hauling, and regularly replacing fewer batteries.

4.7 Future research

The Center for Environmental Energy Engineering at the University of Maryland has several on-going projects relating to cooling, heating, and power (CHP) and fuel cell technologies. Coincidentally, these are the two research areas which hold the most promise for idle-reduction technology development.

As outlined in the previous section, lessons learned from CHP research in terms of waste heat utilization could be applied to long-haul truck auxiliary power systems. The design and testing of an APU in conjunction with a waste heat forced-air heating system, operated by a control algorithm designed to switch between thermal and electrical load priority may offer significant system efficiency increases and fuel savings as a result. In recent years, small-scale waste heat driven cooling technologies have also received a considerable amount of attention. In combination with advancements made at Maryland with regards to compact heat exchanger design and optimization, development of small, mobile heat-driven cooling may prove feasible.

Also, as U.S. industries consider alternative fuel technology more seriously, it may be a worthwhile endeavor to investigate idle-reduction technology adaptation to some of the more prominent renewable fuel alternatives. Considering both APU and DFH technologies, a test facility could be constructed to investigate the operating parameters of idle-reduction technologies that are fueled with alternative and renewable fuels.

Another area of interest to the university is solar systems, at the heart of which are banks of deep-cycle batteries. Investigating the capacity dependence on ambient and life-cycle conditions would be of interest to both solar residential and idle-reduction systems researchers. The development of correlations describing this interaction would have a high value to future model development and has the potential for frequent citation.

As mentioned in the first chapter, fuel cell technology has the potential to provide a great increase in auxiliary power unit system efficiency. Further increasing system efficiency by utilizing the waste heat produced directly from the fuel cell, specifically the high temperature fuel cells such as SOFCs, or as a product of the reforming process is a subject area not widely considered in the literature. With the university's strong background in fuel cell development, the investigation of waste heat utilization methods for both mobile and stationary energy systems would be a natural progression.

5 Conclusions

The purpose of this thesis was to investigate the driving forces behind anti-idling legislation, to compile a detailed and concise summary of idle-reduction technologies, to develop a transient simulation of the most promising of these technologies which would enable the user to calculate the pertinent operating parameters of those systems, and to develop a program that would offer the user the ability to compare the selected technologies against other prominent energy systems in economic terms.

The following list is a summary of the findings and contributions of this thesis:

- Market review featuring a brief description system operation, physical specifications, cost, and advantages and disadvantages relative to other systems
- Proposed hotel load duty cycle developed from survey information, variable the day of the week, and in compliance with hours of service requirements
- Proposed methodology for simulating truck movement with respect to ambient conditions
- TMY2 files created for five of the most freight-significant interstate corridors in the US
- TRNSYS simulation of a long-haul truck sleeper cab, the loads for which are met by an APU
- TRNSYS simulation of a long-haul truck sleeper cab, the loads for which are met by a BPAPS
- TRNSYS simulations yielded the following results:

  - 1,537 average annual operating hours for idle reduction system operating along the selected routes
  - An annual average fuel consumption of 3,476 L (917 gal) for a constant-output APU
  - An annual average fuel consumption of 294 L (78 gal) in recharging the six deep-cycle lead-acid batteries used in the BPAPS
- Cost-comparison worksheet which incorporates six idle-reduction technologies including onboard and shore power TSE, and APU, a BPAPS, a direct-fired heater, and a thermal storage air conditioning unit, compared against the costs associated with the idling of the truck's main engine
- Cost-comparison calculations yielded the following results:
  - The BPAPS is the least-cost option in terms of complete energy systems (those that produce heating, cooling, and power) by $2.66 per hour over the short-term and $2.76 over the long-term compared with the APU
  - The BPAPS has a payback period of 1.4 years
  - Over the short-term, the APU does not surpass its payback period. However, over the long-term, the APU does offer a savings benefit compared with idling of the main engine, having a payback period of 4.7 years
  - Annual operating hours have a greater impact on lifetime hourly cost, lifetime cost, and payback period than annual fuel price escalation rate

- Despite significantly higher first cost, beyond approximately three years of ownership onboard TSE costs less per hour than shore power TSE assuming equal service charge escalation rates
- The direct-fired heater and thermal storage air conditioner both have payback periods much less than one year. Neither are affected as greatly as the other technologies surveyed with respect to annual operating hours or annual fuel price escalation rate

- Future research opportunities include:
  - Development of an APU waste heat-powered forced-air heating system in conjunction with a control system which selects thermal or electrical priority depending on cab requirements
  - Development of waste heat-driven cooling technologies for mobile applications
  - Investigation of alternative fuel use with idle-reduction technologies
  - Development of battery system correlations which take into account ambient and life-cycle conditions for use in solar PV systems as well as idle-reduction systems
  - Fuel cell waste heat utilization for both mobile and stationary applications

Using the metrics defined in this thesis, the BPAPS appears to be the best choice in terms of cost for complete energy systems. However, the selection of one idle-reduction technology over another depends on a number of factors previously discussed in this thesis. Which technology a trucking fleet, regional transport company, or owner/operator selects ultimately depends on the relative weight of those factors, largely particular to the situation of the purchaser.

Appendix A

Input	Engine	OB TSE	SP TSE	APU	BPAPS	DFH	TS
Inflation rate (%)	3	3	3	3	3	3	3
Number of Years (Y)	7	7	7	7	7	7	7
Equipment Costs, Installed ($)		$4,000.00	$10.00	$9,000.00	$6,000.00	$1,200.00	$3,800.00
Federal Excise Tax (%)		12		12	12	12	12
Hourly Labor Rate ($/hr)	$80.00	$80.00		$80.00	$80.00	$80.00	$80.00
Labor Hours (hr)							
#1 Component Replacement Cost ($)		$125.00		$125.00	$125.00		
#1 Component Replacement Labor Hours (hr)							
#1 Component Service Life (hr)	12,600	5,400	12,600	4,608	4,608	12,600	12,600
#2 Component Replacement Cost ($)					$1,500.00		
#2 Component Replacement Labor Hours (hr)					0.0		
#2 Component Service Life (hr)					3,840		
Annual Operating Days (d/yr)	300	300	300	300	300	96	120
Annual Idling Hours (hr/yr)	1,800	1,800	1,800	1,536	1,536	1,800	1,800
Current Price Per Gallon ($/gal)	$3.45	$3.45	$3.45	$3.45	$3.45	$3.45	$3.45
Escalation Rate (%)	10	10	10	10	10	10	10
Baseline Fuel Consumption (gal/hr)		1	1	1	1	1	1
Hourly Fuel Consumption, Engine (gal/hr)	1						
Preventative Maintenance Service Charge ($)	$480.00						
Preventative Maintenance Service Interval (mi)	25,000						
Overhaul Charge ($)	$10,000.00						
Distance Between Overhauls (mi)	750,000						
Hourly Fuel Consumption, APU (gal/hr)				0.6			
Hourly Fuel Consumption, Heater (gal/hr)						0.05	
Heating Day Percentage (%)						32	
System Service Interval (hr)				1000		1,800	
System Periodic Maintenance Charge ($)				$125.00		$110.00	
Component Service Interval (hr)							
Component Periodic Maintenance Charge ($)							
Hourly Service Charge ($/hr)		$1.00	$2.18				
Service Charge Escalation Rate (%)		3	3				
Connection Fee ($)		$1.00					
System Weight (lbs)		75		470	375	8	326
Annual Distance (mi/yr)	120,000	120,000	120,000	120,000	120,000	120,000	120,000
Fuel Economy (mi/gal)	6	6	6	6	6	6	6
Rated Alternator Amperage (amps)					185		165
System Voltage (V)					12		12
Alternator Efficiency (%)					65		65
Highway Engine Efficiency (%)					40		40
Daily Charging Hours (hr/d)					6		1.33
Highway Speed (mi/hr)					55		55
Lifetime hourly cost ($/hr)	$6.67	$1.88	$2.83	$4.19	$1.43	$0.25	$0.54
Lifetime cost ($)	$84,001.94	$23,698.38	$35,635.83	$45,056.82	$15,366.46	$3,181.88	$7,770.53
Actual payback (yr)	N/A	1.1	0.0	4.7	1.4	0.2	0.7

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