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A FEASIBILITY STUDY OF AUXILIARY HVAC SYSTEMS FOR REDUCING IDLING TIME OF LONG HAUL TRUCKS

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ABSTRACT

The feasibility of several alternatives to long-haul truck idling are investigated. Battery Powered systems (BPS) where batteries are charged off the alternator is considered. Moreover, BPSs with various battery types are compared to determine which one would have the greatest impact on the fuel consumption and overall performance. In addition, applicability of thermal energy storage (TES) is studied as a means of cooling instead of a standard compressor air conditioner. Fuel cell powered systems (FCS) are investigated to replace batteries as a means of energy storage source on the truck. It is concluded that the most feasible method for truck idling reduction is BPS featuring lithium ion batteries while, BPS with lead-acid batteries is the cheapest solution.

Keywords: Idle reduction technology; Long haul truck HVAC systems; Feasibility study; Battery powered systems (BPS); Fuel cell powered systems (FCPS); Energy reduction; Thermal energy storage systems (TESS).

INTRODUCTION

Approximately 94% of all freight is moved by diesel power in North America. While the advantages of the diesel engine are clear, diesel fuel is a major contributor to particulate matter (PM). The efficiency of large diesel engines in class 7 or 8 trucks in the highway driving is 40-50% which drops to 1 to 11% during idling time [1, 2]. Drivers keep the engine running mainly to maintain the cabin and/or sleeper heated or cooled overnight [3]. This leads to an excessive fuel consumption (1.9-5.7 l/hr; 6056 l/year per truck), high noise level, and generation of air pollutants (CO: 94.6 kg/year; CO2: 10.4 tonne/year; particle matter: 2.57 kg/year; NOx: 56.7 kg/year per truck) [4]. Therefore, a growing interest exists to reduce the diesel engine idling time due to cabin air conditioning (A/C); this will have a significant impact on reducing fuel consumption and pollutants. Governments have started to restrict the idling time, e.g., the state of California has already banned trucks from idling over five minutes. Similar restrictions are anticipated in other countries.

This idling limitation has caused a major difficulty for truck drivers and created a great demand for new “green” A/C systems that can provide thermal comfort for the cabin and the sleeper berth when the engine is turned off. Thus, several solutions have been suggested to reduce idling time required for cabin A/Cwhich include: i) truck stop electrification (TSE); ii) auxiliary power unit (APU); iii) battery powered systems (BPS); iv) fuel cell powered systems (FCPS); v) solar energy systems (SES); and vi) thermal energy storage systems (TESS). These technologies have been recently reviewed by Lust [2].

Advantages and shortcomings of these technologies are summarized in TABLE 1. The salient parameters that should be considered for determining a practical solution include: cost (capital, operating, and maintenance), extra fuel consumption, weight (the heavier is the system, the lower is the cargo capacity), emission, and, noise level.

Truck stop electrification (TSE) is a stationary terminal that provides power and other services to trucks while their engine is off. TSE connections offer a wide range of services including heated or cooled filtered 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; and high-speed internet access [5, 6]. The two major drawbacks associated with (TSE) are the initial cost for installing the required ducts and systems on the truck and also the limited number of nodes in terms of quantity and location that highly restrict the drivers' flexibility and comfort.

The fuel-fired APU is the most conventional idle-reduction solution and generally consist of a small internal combustion engine, typically rated at 10 kW (13.4 hp). Fuel is supplied from the truck's fuel tanks and when the engine is off the APU will be used to generate the required power for HVAC system [4-6]. APUs' thermal efficiency is high and their fuel consumption which depends on the size of the engine and power load is estimated to be 0.75 – 2.0 L/h (0.2 - 0.5 gal/h) under standard conditions. APUs usually burn diesel; however, systems that runs on propane are also available [5-7]. APUs are flexible and do not impose any restriction on the driver. However, they are heavy, noisy, and lead to extra fuel consumption and emission. To reduce the emission, diesel particulate filters (DPFs) should be installed which is relatively expensive (approximately $3,500).

Although solar energy conversion technology is becoming mature and commercialized, its application for long-haul truck is not feasible as the surface area is limited on a truck and due to low efficiency of existing solar energy conversion systems a large surface area is required [7, 8]. Moreover, a battery pack is required to store the electrical energy which adds to the weight and cost of the system. Despite all these shortcomings, solar energy systems are green and sustainable. As a result, several research groups are investigating their application in trucks for reducing the fuel consumption and emission.

Based on these restrictions, in the present study three alternatives to long haul truck idling are considered for feasibility purposes. These options include BPS, FCPS, and TESS.

PROBLEM STATEMENT

Designing a HVAC system that can maintain the temperature of the truck cabin over a period of up to 16 hours has been considered. Due to the sensitivity of the truck industry and warranty issues, this add-on system should be developed with minimal or no changes to the truck powertrain and wiring system.

Cooling load is different for each truck make and model, and also varies with the time of the day and season. Researchers have employed commercial software to determine the cooling load of various trucks and have reported values between 1.2 *kW* to1.8 *kW* as nominal cooling load [7]. However, as per our industrial partner's, *Cool-It Hi Way Services Inc*. (Abbotsford, Canada), experience, the A/C system capacity can be as high as 2 *kW*.

FEASIBILITY STUDY OF AVAILABLE SOLUTIONS

Battery Powered Systems (BPS)

Battery-powered systems (BPS) have emerged as an alternative to conventional fuel powered systems (FPS) as an idle reduction technology [4]. Replacing the engine and generator of a conventional FPS with a bank of deep-cycle batteries, BPS offer many of the same features such as flexibility without the emissions restrictions or noise of their fuel-fired counterparts [9-11]. Typically, the power source in a BPS is a pack of deep-cycle batteries, recharged either by the truck's alternator while driving, or by a shore power connection. In addition, electrical climate control components (compressors and fans) can be integrated for a completely battery-powered energy system which makes BPS a promising solution for designing standalone systems.

A standalone BPS increases the fuel consumption during the charging phase off the alternator, but eliminates fuel consumption during idling. A schematic of a BPS is shown in FIGURE 1. For this system to work, enough batteries have to be incorporated to supply power for the no-idling time. These batteries can then pack closely together.

TABLE 1: LIST OF POTENTIAL EXISTING HVAC SOLUTIONS FOR IDLING REDUCTION IN LONG-HAUL TRUCKS.

Method	Advantages	Disadvantages
Truck-stop electrification (TSE)	- No extra fuel consumption - No local emission - No need for maintenance	- Capital equipment cost on the truck ~ $4K - Limited number of nodes
Fuel-fired auxiliary power unit (APU)	- Flexible (location and climate)	- Extra weight ~200 kg (0.006L/100Km/1kg) - Expensive ($6K-$10K capital cost) - Noisy
Battery-powered systems (BPS)	- Flexible - No local emission - Quite	- Short battery service life - High installation cost - Performance depends on the ambient temperature - Extra weight ~100 kg
Fuel cell powered systems (FCPS)	- Quite - Clean - High efficiency - No additional diesel fuel consumption	- Expensive - Not fully commercialized yet - Limited availability of the fuel canister - Extra weight
Solar energy systems (SES)	- Clean - Quite - Low maintenance cost - No additional fuel consumption	- Expensive ($4k/truck) - Low efficiency - Requires a battery pack for energy storage - Require large surface area
Thermal energy storage systems (TESS)	- Clean - Quite - Independent of ambient temperature - Low maintenance cost	- Is not a stand-alone system - Extra weight ~200 kg -Expensive - Bulky

Several deep-cycle battery types are available in the market. The most conventional battery chemistry used in the auto industry is the lead acid type which is relatively cheap and safe. However, the major drawback of lead-acid batteries is their low energy density which means bulky and heavy battery packs and a low life time if deep cycled (300-400 cycles). Other high capacity battery chemistries that have been used extensively in hybrid electric vehicle (HEVs) and electric vehicles (EVs) include lithium-ion (Li-ion), nickel–cadmium (Ni-Cd), which can improve the durability and reliability as well as reducing the weight of the required battery pack. The major challenges facing the use of these emerging batteries are their high price and safety concerns especially for li-ion type.

The vapor compression refrigeration cycle is used in BPS and the refrigerant is R-134a. For the present analysis, the isentropic efficiency of the compressor (η_{is}) is estimated to be 0.6(and constant) which is close to values reported by several manufacturers. Our preliminary thermodynamics analysis shows that the required power for running the compressor with 1.75 kW cooling capacity is 624W, considering a constant isentropic efficiency of 60%. The total capacity of the battery pack is calculated for three typical power draws of 0.62 kW, 0.73 kW, and 0.86 kW based on the maximum working period of 16 hours for the auxiliary HVAC system without charging the batteries. To investigate the effect of battery chemistry on the weight of the system five different battery types are considered including: Ni-Cd, Li-ion, Lead acid, nickel metal hydrides (Ni-MH), and Li-polymer. Approximate mass of a battery pack that can provide the required capacity and voltage is calculated for each type of chemistry, based on data from two different manufacturers for each type:

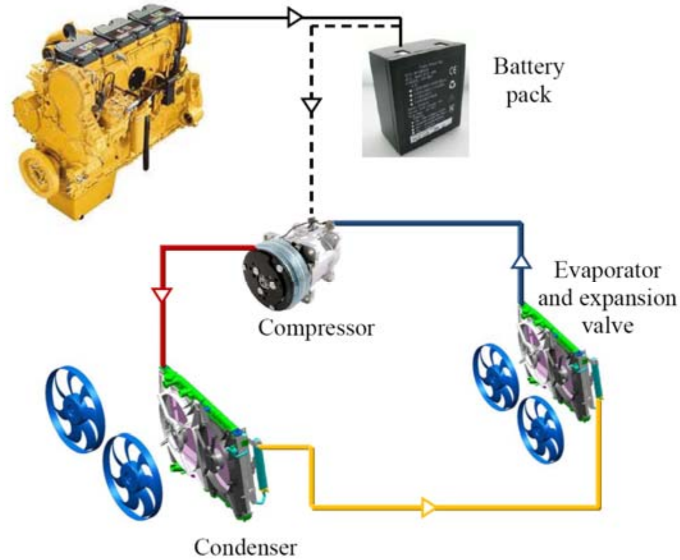

FIGURE 1: SCHEMATIC OF BPAPS FOR TRUCKS; THE SOLID AND DASHED BLACK LINES SHOW DIRECTION OF THE ELECTRICAL POWER TRANSFER WHEN THE ENGINE IS ON AND OFF, RESPECTIVELY.

$$\mathrm{m}_b = \left(\left(\frac{V_{DC}}{\mathrm{V_{cell}}}\right) \times \frac{\left(\frac{(W_{In} \times \mathrm{h})}{(12 \times 0.9)}\right)}{\mathrm{A\ h}} \right) \times m_{cell} \qquad (1)$$

where V_{DC} is the DC voltage of the battery, W_{In} the work required to run the compressor, V_{cell} is the battery voltage for each cell, h is hours of cooling, A is the discharge current of each cell, and m_b and m_{cell} are the mass of the battery and the cells, respectively.

As shown in FIGURE 2 it can be seen that the use of battery chemistries such as Li-ion and Li-polymers can significantly reduce the weight of BPAPU systems. More importantly, these batteries have a longer life time than the traditional counterparts such as lead acid type, with a cycle life in the range of 2000 cycles (at 80% depth of discharge) compared to 500 cycles for lead acid. However, the major drawback is the cost, which is going down with the market maturity.

Thermal Energy Storage Systems (TESS)

Thermal energy storage systems (TESS) accumulate thermal energy (heat/cold) for later use [12]. The heart of a TESS is a thermal storage medium, which can be charged by the truck HVAC system when the engine is running. A schematic of a TESS is shown in **FIGURE 3**. Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat and thermochemical or a combination of these [13, 14]. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change to or from solid to liquid or liquid to gas [15].

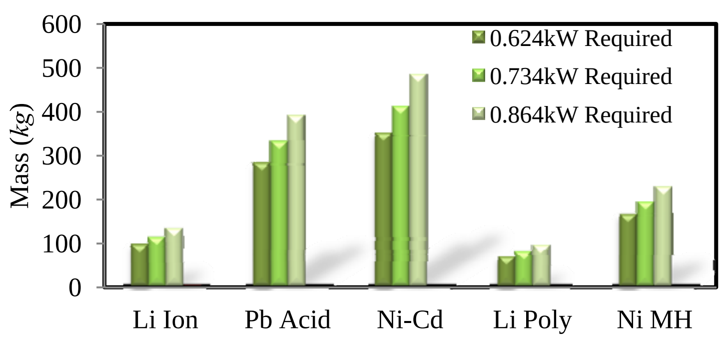

FIGURE 2: EFFECT OF BATTERY CHEMISTRY ON THE WEIGHT OF THE SYSTEM.

Among the above mentioned thermal heat storage techniques, latent heat thermal energy storage is particularly attractive due to its capacity to provide high-energy storage density at constant temperature corresponding to the phase transition temperature of phase change material (PCM). Phase change can transition between the following form: solid–solid, solid–liquid, solid–gas, liquid–gas. PCM's can store 5–14 times more heat per unit volume than sensible storage materials such as liquid water, masonry, or rock [12, 16].

Currently, thermal energy storage technology is not common for long-haul trucks in any commercial capacity. However, a small number of manufacturers offer an air conditioning system that uses a thermal storage medium, charged while the truck is running, in conjunction with a small air handling unit to provide cabin space cooling. While the engine is running, the thermal storage medium is regenerated by a standard electric-driven vapour compression cycle, which receives power from the truck's alternator via an inverter. Once the truck engine is no longer running, a small electric blower running off the truck battery passes cabin air through the cold TES system to reduce its temperature and ventilate the cabin.

We modeled ten different commercially available PCMs [16] to determine the weight and the size of the TES system that would work as an auxiliary HVAC system for trucks. Similar to BPAPS, a cooling load of 1.75 kW was considered in the analysis. Moreover, the PCM bed should be able to maintain the cabin temperature in the 20-26 ^oC range for 16 hours. The mass of the TESS needed for providing the cabin cooling load is calculated as:

$$m_I = \frac{Q_L \times h \times 3600}{H_f \times 1000} \qquad (2)$$

where:

$$Q_L = \frac{(E_{water} + E_{cabin} + m_I \times H_f)}{hr_{freeze} \times 3600} \qquad (3)$$

Here Q_L is the cooling load of the cabin, H_f is the heat of fusion, m_I is the mass of ice, E_{water} is the energy required to cool the water to 0 degrees, E_{cabin} is the energy required to cool the cabin, and hr_{freeze} is the hours to freeze the water.

The calculated mass and the relevant information of the PCMs are listed in TABLE 2. It can be seen that the weight of the TES is directly related to its heat of fusion. Therefore, water based TES is the lightest. The minimum weight of a TES that meets the cooling requirements is more than 300 kg which is much heavier than the battery pack in BPAPS.

Overall, one can state that the application of TES can be promising for reducing fuel consumption in trucks, but there are several hurdles that should be overcome to commercialize this solution. Further, TESS can be used in combination with vapor compression systems in order to optimize the fuel consumption and/or to alleviate the peak loads.

Fuel Cell Powered Systems (FCPSs)

Fuel cells have a great potential as a "green" energy conversion system for reducing the truck idling time. They would replace the battery pack of a BPS. Polymer membrane electrode fuel cells (PEMFCs) have emerged as promising power sources in the automotive industry and portable, and stationary electronic applications [17, 18]. PEMFCS complete an electrochemical reaction and combine hydrogen with oxygen to produce water, releasing heat and electricity as by products that can be used for a variety of applications [19, 20].

TABLE 2: SUMMARY OF THE PROPERTIES OF THE TESS WITH A 1.75 *KW* COOLING LOAD USING TEN DIFFERENT PCMS.

Number	PCM	PCM set point	Heat of fusion (*kJ/kg*)	Total PCM mass (*kg*)
1	Water	0	334	303
2	Thermasorb 43	6	163	621
3	TH-4	-4	286	354
4	STL-3	-3	328	309
5	SN03	-3	328	309
6	ClimSel C 7	7	130	779
7	RT5	9	205	494
8	ClimSel C 15	15	130	779
9	E7	7	120	844
10	E13	13	140	723

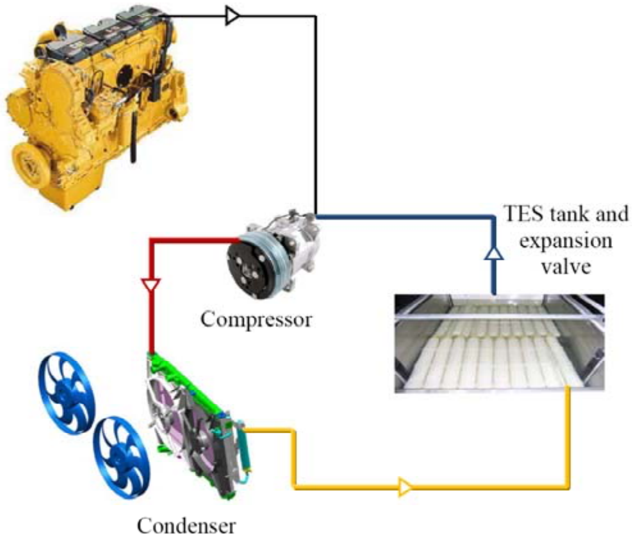

FIGURE 3: SCHEMATIC OF A TES SYSTEM FOR TRUCKS; THE SOLID LINE SHOWS THE DIRECTION OF POWER TRANSPORT WHEN THE ENGINE IS ON.

For the targeted application, however, a subcategory of PEMFCs, called direct methanol fuel cells (DMFCs),is emerging as methanol is easy-to-transport and energy-dense yet a reasonably stable liquid at all environmental conditions [17]. While batteries of a BPS should be recharged when the engine is running, for a FCS fuel cartridge should be replaced. Thus, FCSs are green idle reduction technology with no extra fuel consumption. However, depending on the fuel cartridge distribution, its replacement can be expensive and a hassle for the driver.

FEASIBILITY COMPARISON

The important factors in determining the applicability of each of the abovementioned technologies include: i) cost (capital, operating, and maintenance), ii) extra fuel consumption, iii) weight, iv) emission, and v)noise level.

The total weight of a system is a key parameter for long-haul trucks. In particular, long haul trucks have a threshold weight that they cannot exceed, when weighing in. This includes everything that they carry, the APU and their cargo as well. Any additional weight due to use of idle reduction system is a reduction in cargo capacity of the truck which leads to a lost revenue.

Lust [4] stated that the extra fuel consumed in *L/100km* is 0.06 per *Kg* of extra weight added to the vehicle. The weight of a typical BPS and TESS with the cooling capacity of 1.75 *kW* is calculated using Eqs. (1)-(3). The extra fuel consumption associated with BPS with various battery chemistries, water-based TESS, and a FCS is shown in FIGURE 4.

In addition, the extra fuel consumption due to the extra load off the alternator is estimated using the value of .99 *L*/100*km* per *kW* proposed by MacDonald and Douglas [21]. To calculate the required power for charging the battery pack of a BPS and the water-based TESS, the compressor input power is calculated by assuming an isentropic efficiency of 0.6.The results are shown in FIGURE 4. It should be noted that the fuel cells do not require any charging from the alternator since they use fuel cartridges (methanol).

It can be seen that the extra fuel consumption associated with any of the idle reduction technologies is much lower than the total fuel saving resulted by eliminating truck idling. This means that all of the studied solutions could be used as they significantly reduce the fuel consumption and consequently the engine emissions. FIGURE 4 suggests that BPSs with li-ion batteries have the best performance. It should be noted that in case of FCPSs, continuous fuel cartridge replacement that can add to the operating cost and their flexibility can limit their success.

As for the approximate capital cost of each system available on the market, BPS offers the lowest costing system just under 3,000$ [22]. This is substantially lower than that of the TES system which is over 8,000$ [23]. At the time of this study, there are no FCPS in the market. For this reason, one can compare the prices of the energy storage mediums, since the air conditioning unit will be the same for all systems and thus have the same base cost. The additional costs will come from the different energy storage mediums. The price of the lead acid batteries used in the BPS is lower than the Li-ion, making the system using the lead acid cheaper to produce. With four batteries used, the price is approximately 668$. The shells used for the TES system can be purchased individually, and have a relatively low cost at 30$ per bed [24]. It takes 20 tubes to gather enough ice, the total price is approximately 600$. This is comparable to the BPS system. However, a second A/C system is needed to freeze the PCM, nearly doubling the overall system cost. The FCPS main drawback is their need to be refuelled with new canisters. This is offset by the fact that fuel cells do not need to be charged off the alternator, which normally causes extra costs in fuel consumption. The fuel cartridges last for 16 full parking cycles idling for 16 hours at a time. Since it takes ten fuel cells to generate enough current to power the A/C, it costs approximately 350$ to recharge the fuel cell system.

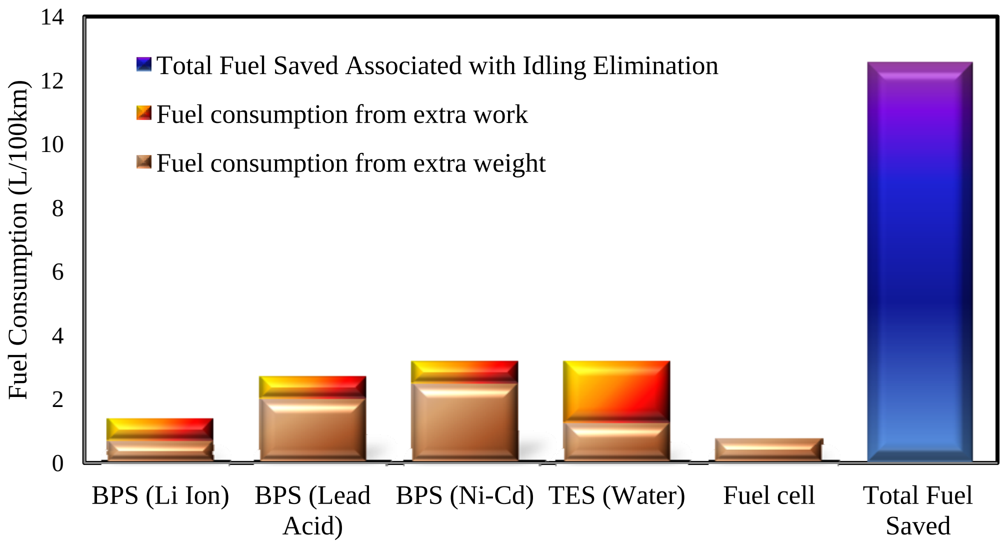

FIGURE 4: THE EXTRA FUEL CONSUMPTION ASSOCIATED WITH EACH IDLE REDUCTION TECHNOLOGY.

CONCLUSIONS

A feasibility study has been carried out to investigate the potential use of various available technologies including battery power, thermal energy storage, and fuel cell systems to reduce fuel consumption and emission caused by idling in long-haul trucks.

Weight, cost, and the total fuel saving associated with each technology, for a nominal cooling capacity of 1.75 *kW*, have been determined. Our analysis has shown that FCS is the greenest system but BPS is the most feasible method for reducing the idling time in long-haul trucks. Lithium-ion based batteries reduce the system weight significantly while adding to the capital cost. TES systems are heavy and cannot be used as standalone systems. However, TES systems are practical for delivery or referral trucks and also to alleviate peak loads in niche applications. The present analysis is important for designers working on new idle reducing technologies for trucks.

LIST OF ABBREVIATIONS AND VARIABLES

PM	Particular matter
BPS	Battery powered System
E_{water}	Energy to freeze water (*kJ*)
E_{cabin}	Energy to cool cabin (*kJ*)
h	Hours to cool
hr_{freeze}	Number of hours to freeze (h)
H_f	Heat of fusion (*kJ/kg*)
m_I	Mass of ice (*kg*)
m_b	Mass of batteries (*kg*)
m_{cell}	Mass of battery Cell
PCM	Phase change material
Q_L	Cooling load (*Ton*)
W_{in}	Work Input (*kW*)
W_{in}	Work Input (*kW*)
TES	Thermal energy storage

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