The Case for Choosing 3-Phase AC Electric Forklift Trucks Over Vehicles Based on DC Electric, Internal Combustion or Diesel Technologies

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In the early 90's, Jungheinrich was the first company to use static inverters to change the direct current of a forklift truck's battery into 3-phase AC current, opening the door to the many benefits of AC-power (See Sidebar entitled *"Chronology of three-phase AC introduction"*). Today, Jungheinrich installs its proprietary AC technology in all its electric truck categories (counterbalanced models, reach trucks, very narrow aisle vehicles and electric pallet trucks, among others – See Fig. 1). It has now been tested and proven in all areas of the material handling industry.

Three incentives to consider when buying an AC electric truck, as opposed to a DC electric or an internal combustion (IC) vehicle, stand out in particular:

- The potential for a much greater cost savings over the life of the vehicle
- Complete freedom from pollution due to exhaust emissions
- A level of truck performance, productivity and cost-of-load-handled that can match anything available in the world of internal combustion or DC trucks

The Concept of Total Cost of Ownership (TCO)

Many equipment purchasers fail to understand the concept of TCO, instead looking only at the cost of acquisition in making their decision. In reality, TCO is far more relevant to the purchase decision process.

Perhaps the most striking selling point in favor of AC electric trucks is, ironically, also the hardest point to get across to prospective buyers, namely that the total cost of ownership (sometimes also called the total operating cost) over the life of the truck can be *much less* with AC than that with a DC electric or an IC truck.

Factors affecting operating costs of either electric or IC trucks include the following (See Fig. 2, as well):

- Truck performance (pallets moved per hour)
- Energy efficiency (how long the truck can run on one battery charge, or one tank of fuel)
- The cost of fuel or electricity
- Reliability (no work time lost due to truck down-time)
- Cost to maintain, including components like batteries (IC trucks also have batteries), fluids, tires and filters
- Cost of maintaining air quality in the warehouse
- Heating and/or cooling costs

Total Cost of Operation (TCO) as a monetary estimate can help managers evaluate the direct and indirect costs related to the purchase of a capital investment like a forklift truck.

A greater initial price associated with one piece of equipment among several units being considered and compared has to be balanced by consideration of likely repair costs over the life of

Figure 1

the unit, as well as expenses like upgrades. In this way of looking at it, the magnitude of an initial price can be offset by the ensuing series of cost savings realized over the truck's life. At the end of service life, the upfront purchase price of a forklift will be a fraction of the total cost of ownership.

Figure 2: Annual Fuel/Energy and Maintenance Cost Comparison

	LPG/Gas	Diesel	AC	DC
Fuel or Energy Costs	$ 7,050	7,050	940	1,106
Maintenance Cost	$ 4,320	4,320	3,288	3,960

Note: Data assumes approximately 2,500 annual operating hours.

To give a real world example, considering a five year lease (i.e., assuming a five year life cycle), the operation costs of an AC electric truck will be typically just one quarter that of an internal combustion truck. The return on investment for AC vs. IC will usually become attractive between the first and second year of ownership – at some point in that time-period, IC technology costs will surpass the costs of an AC truck (See Fig. 3).

It is true, however, that the initial purchase price of an AC truck will be either moderately higher or substantially higher than for the other technologies, depending on whether the auxiliary equipment – the battery and charger – are included in the price (See Fig. 4). In fact, the biggest difference in the initial cost of an AC system vs. other technologies is not so much due to the truck itself, but to the battery and charger. Electric truck batteries, which are quite large and heavy, are expensive in large part due to the cost of lead in recent years. What's more, two batteries and a charger may be needed at the time of initial purchase.

However, the *adjusted* truck price differential between the initial cost of the various truck technologies (i.e., leaving out the cost of battery and charger for electric vehicles) is perhaps only several thousand dollars.

Jungheinrich has developed a Total Cost of Ownership software program that allows its prospective clients to evaluate and compare on-screen the truck operation costs in dollars for fuel or electrical energy on a state by state basis. Note that in each state, the cost of electricity is different, although, typically it is about one tenth the cost of liquefied natural gas. The price of one 10-gallon tank of LPG varies from $18 to $25. By contrast, the energy cost to recharge the battery once for an electric forklift may be as low as $2.

The Three Leading Forklift Technologies

In the material handling industry, two broad families of forklift trucks exist – electric and internal combustion (IC). Electric trucks comprise both AC and DC motor-based vehicles. IC models include trucks running on technologies based on diesel, LPG (liquefied propane gas), liquid gas diesel or petrol), and CNG (compressed natural gas). IC trucks are also sometimes confusingly referred to as "gas" trucks, but the use of actual gasoline (petrol) vehicles is not that common in material handling – when they are used, they're typically very large trucks employed outdoors.

Figure 3: Total Cost of Ownership Comparison: 2006

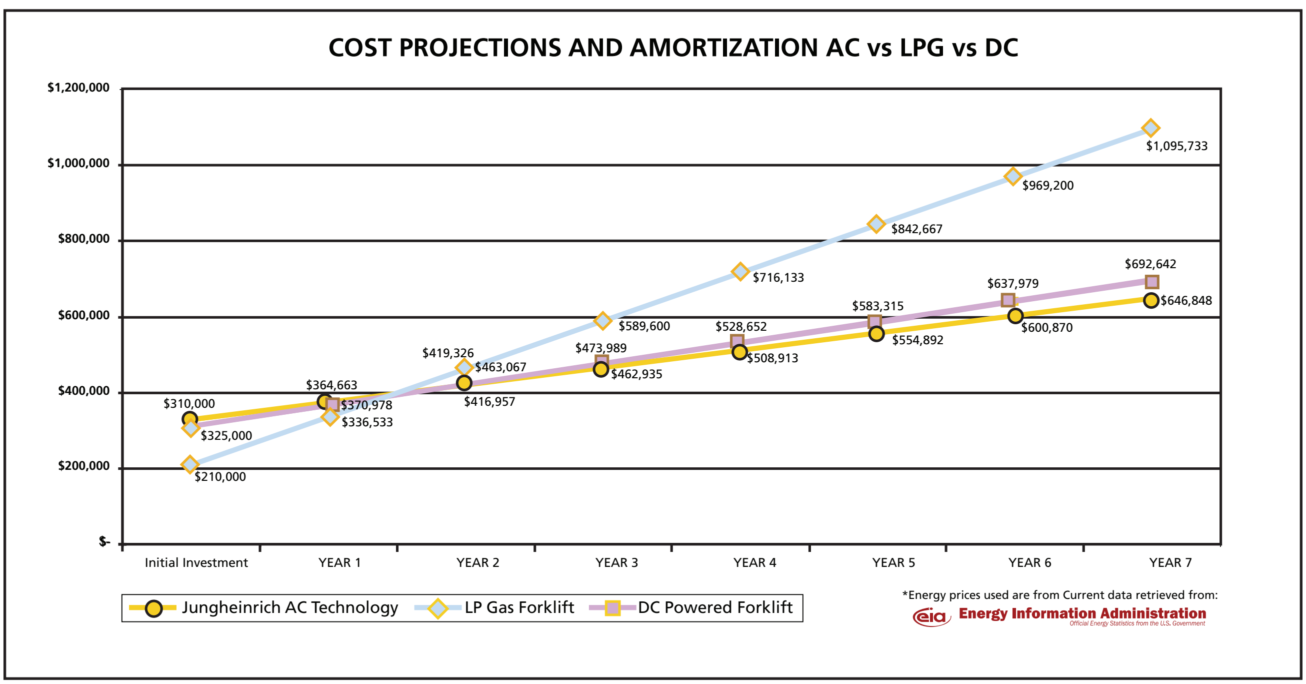

Figure 4: Total Cost of Ownership Comparison: 2007

AC Truck Data

State	Virginia
Truck Type	Jungheinrich EFG425k
No. of Trucks	10
No. of Batteries per AC Truck	1
No. of Chargers	10

Application Data

No. of Effective Hours per Shift	5
No. of Shifts per Day	2
No. of Working Days per Year	250
No. of Hours per Year	2,500

Established AC vs. DC Truck Costs

	Jungheinrich AC Electric Truck	DC Electric Truck
Truck Price	$24,000.00	$23,000.00
Battery Price	$6,000.00	$5,500.00
Charger Price	$2,500.00	$2,500.00
Cost to Recharge per Shift	$2.62	$3.01
Maintenance Cost (per month)	$274.00	$330.00
How Many Batteries per Truck?	1	1

LP Gas or Diesel Truck Costs

LPG Truck Purchase Price	$21,000.00
Monthly IC Truck Maintenance Cost	$360.00
Existing Fuel Cost per Bottle	$20.00
Fuel Cost per Hour (6hrs/bottle)	$3.33

	Jungheinrich Truck (AC 3-phase Technology)	Existing LPG or Diesel Truck	Existing Electric DC Truck
			Extra Battery?
Initial Investment			
Truck(s)	$240,000.00	$210,000.00	$230,000.00
Battery(s)	$60,000.00	n/a	$55,000.00
Charger(s)	$25,000.00	n/a	$25,000.00
Total Investment Cost	**$325,000.00**	**$210,000.00**	**$310,000.00**
Ongoing Costs			
Fuel Cost (per shift per truck)	$2.62	$20.00	$3.01
Fuel Cost (per year)	$13,098.33	$83,333.33	$15,063.09
Maintenance cost (per month per truck)	$274.00	$360.00	$330.00
Maintenance cost (per year)	$32,880.00	$43,200.00	$39,600.00
Total Ongoing Cost	**$45,978.33**	**$126,533.33**	**$54,663.09**
Ongoing Cost Per Truck Per Hour	$1.84	$5.06	$2.19
Total Savings After 5 Years		**$287,774.99?**	**$28,423.75?**

A hypothetical analysis runs as follows: Imagine a purchase deal for ten 5,000 lb. trucks. An individual AC truck may cost $24,000 whereas a DC truck may cost $23,000 and an LPG truck may cost $21,000. But with the AC, a $4,000 battery and a $2,500 charger are also necessary. That adds another $6,500 for AC. For AC, the initial purchase cost can rise to as much as $29,500 however buyers tend to focus far too much on the initial price.

Note: The Jungheinrich full maintenance contract covers tires and brakes as well.

Chronology of Three-phase AC Introduction

The following concise chronology shows the sequence of implementation as Jungheinrich methodically included its pioneering 3-phase AC electric truck technology in its various truck designs over recent years:

1st Generation AC

- 1996 – 4-Wheel Electric Sit-Downs
- 1997 – Systems Trucks
- 1998 – Order Pickers

2nd Generation AC

- 1999 – 4-Wheel Electric Sit-Downs
- 1999 – Reach Trucks
- 2000 – Large 4-Wheel Electric Sit-Downs
- 2000 – Systems Trucks

3rd Generation AC

- 2001 – Walkies
- 2002 – 4-Wheel Electric Sit-Downs
- 2002 – Walkie-Riders
- 2002 – Systems Trucks
- 2003 – 3-Wheel Electric Sit-Downs
- 2003 – Large 4-Wheel Electric Sit-Downs
- 2006 – US Reach Trucks

Trends, Niches, and Market Shares

A trend to increasingly narrower aisles in warehouses and distribution centers reflects the need to store more goods in the same amount of space than in the past – i.e., to get a much higher degree of space or "cube utilization." In addition to aisles shrinking, storage racks are being raised higher. This means the forklift working in these evolving environments must maneuver in smaller areas and lift loads higher.

Trucks not only have to negotiate narrow aisles, they also have to be able to turn within tight spaces like the inside of half-full trailers where stacked goods reduce maneuvering space. In response, materials handling vehicle manufacturers are now making forklift trucks more compact. AC electric trucks designed specifically for the narrow aisle environment are now serving areas where counterbalanced trucks cannot go.

Electrics largely own the pallet truck and narrow aisle sectors because that environment is typically indoors and often in a regulated area as well, like one containing refrigerators, freezers, etc., in grocery and food distribution centers. These are arenas where exhaust emissions in confined spaces would be a problem.

Thus, electrics excel at working around medical and food products (they largely dominate the grocery industry), and in enclosed areas where toxic emissions like carbon monoxide would be a concern. Another strong niche for electrics is working around explosives and chemicals.

Looking strictly at the market for sit-down counterbalanced forklifts – the type of forklift that is perhaps most familiar – approx. 26% of the 140,366 total number of that type of vehicle in use are electric. The remainder of the total are internal combustion models (LPG, diesel, petrol, etc.), with LPG trucks owning the majority of that share.

In addition, as of 2007, almost 80% of the trucks in electrics' 26%-share of the total market pie are now based on AC drive control. The remaining approx. 20% of electrics are derivatives of various DC technologies. Arriving at a precise breakdown of DC vs. AC in this sector is difficult because some trucks contain a mix of technologies – for example, they use AC drive control but DC hydraulic control.

Jungheinrich designs all its sit-down electric trucks for indoor/outdoor use. Historically, creation of this dual capability was motivated by the warehousing environments in Europe, where many of the semi trailers are side-loaded – with side openings accessible through a tarp or sliding doors in the truck, as opposed to the case in the U.S., where virtually all trailers are rear-loaded.

Voltage Levels Used in Electric Trucks Today

Electric warehousing vehicles, both AC and DC, are based on a range of voltages (e.g. 24V, 36V, 48V and 80V). Some applications don't require a great deal of power. For example, most Class 3 trucks (walkies, walkie-stackers and walkie-riders – see Sidebar entitled *"Brief Overview of the Various Classes of Industrial Lift-Trucks"*) operate on 24V power, considered a low voltage. Smaller trucks like these often (although not always) only have to transport lighter loads, have limited hydraulic functions requiring lower amperage, and work in areas where top speeds are not important.

With a relatively low voltage *and* a lower amperage, power output is low. On the other hand, a higher voltage in a truck's electrical system means the ability to achieve higher levels of performance. For example, an 80V system, as opposed to, say, a 36V system, permits higher levels of acceleration and torque.

In general, any current flow entails some heat radiating from conductors due to Joule (I2R) heating. Thus, the low current of a higher voltage system means relatively lower heat losses. In a forklift truck, the single biggest enemy of energy efficient operation is buildup of heat that cannot be dissipated quickly. Heat buildup not only harms electronic components, it also creates greater electrical resistance in wiring and cables, making it more difficult for a battery to push amps through the conductors – the electrical resistance has been increased. A rising heat level in conductors means a greater amperage draw is needed to compensate for this increased resistance, which in turn creates even more heat – a slippery slope.

Battery and Charging Systems

Forklift batteries come in all shapes and sizes. A typical forklift battery's dimensions and weight can vary widely depending on the truck, but in the case of the 5000 lb. electric sit-down, it's approx. 40 inches wide by 32 inches high, by 34 inches front-to-back and it weighs around 3200 lbs. A forklift battery must *continually* provide power for vehicle systems (the 3 main system motors – drive, steering, and load-lift), so its physical size and energy capacity must be large. Also, the heavy battery in a forklift truck contributes a substantial amount of the truck's counterweight.

How often a battery charge or change-out becomes necessary on an electric truck depends on how it is used. In a 3-shift operation, a battery will definitely need to be changed-out after three shifts of work – physically removed and replaced by a fresh one. With the lead acid battery technology present in today's forklifts, if the energy in the battery becomes depleted, it takes a long time to put the energy back into it correctly. In fact, it's common in the material handling industry to refer to the "8-8-8 rule," which means that it takes about 8 hours to deplete a battery working on the job, 8 hours to charge it back up, and another 8 hours to allow the battery to sufficiently cool.

Batteries need to cool after charging to allow battery acid to settle and sulfate properly. Also, any heat remaining in a battery after charging makes it harder for it to push current through circuitry, meaning that energy has to be wasted in the added work. What's more, if a battery is insufficiently cooled down on a repeated basis, its useful life will be shortened.

New battery technology now coming on stream is shortening the 8-8-8 rule times. For example, new fast-charging technology allows a company to charge a 750 AH (amp hour) battery partially during breaks in a shift, and then at lunch or at shift's end fully charge it up in approx. an hour and a half. However, although this represents a significant improvement, there's a limit in how far this technology can be taken. For example, such fast charging technology still requires a weekly 24 hour 'equalizing charge'.

Electric Braking and Energy Regeneration

AC electric technology allows precise and aggressive electric braking in which mechanical friction from a physical brake is not used as the sole means of slowing or stopping the truck. Because it reduces wear on the truck's conventional brake components, electric braking can lower operating costs over the life of the truck.

Jungheinrich designs its trucks in such a way that electrical braking constitutes the actual working or "service" brake, the primary method for slowing the vehicle, as opposed to activation of the physical brake by the driver's foot on the brake pedal. In this way, brake wear and heat build-up are greatly diminished, unlike in systems where the hydraulically operated brake is constantly being applied. Although a Jungheinrich truck still possesses a hydraulic brake system, it's considered an emergency or auxiliary braking system.

Jungheinrich's form of electric braking leads to more precise positioning. Truck speed precisely corresponds to the degree of travel of the accelerator pedal and won't vary unpredictably, even on ramps. There's no need for the operator to constantly switch a foot back and forth between accelerator and brake pedals in such situations.

Electrical braking occurs primarily with the release or easing up of the accelerator pedal and during changes of direction (e.g., going into reverse following a forward motion, and vice versa). The controller senses a request to stop or slow down and creates a counter-electric force (back emf) in the motor. Essentially, this turns the drive motor into a generator and sends amps in the opposite direction back toward the battery for regeneration. Regeneration can also take place during load lowering on certain Jungheinrich trucks – certain order pickers and high-lift narrow aisle trucks.

With these modes of regeneration working as a truck carries out its normal tasks, a great deal of otherwise wasted potential energy can be, under ideal circumstances, fed back to the battery on a continual basis. Trucks can achieve more working cycles per charge and users can sometimes even reduce the size of their charging stations or battery exchange areas. It is not out of the question to get two shifts work from a truck with just one charge.

Energy regeneration is technically possible in both AC and DC trucks. In each, the process serves to top off a battery "on the run" and extend the time between charges, though regeneration is not intended to be an outright substitute for a full battery charge. However, the characteristics of an AC system allow for a much more potent regeneration, more energy transferal back to the battery.

One problem with a DC truck is a characteristic hitch or hesitation in forward motion when it changes direction, due to the difficulty in carrying out energy regeneration all the way down to zero miles per hour. It goes into a "neutral phase" or a "plugging phase" at approx. half a mile per hour, which can produce a hesitation when the truck changes direction.

By contrast, an AC truck can electrically brake and regenerate battery charge all the way down to zero mph, giving it essentially "infinite" speed control. The ability of an AC truck to regenerate down to 0 mph allows for a very smooth direction change, which becomes evident in a smoother operation and more productive shuttling overall. In addition, Jungheinrich's method of aggressive regenerative braking allows for a more

CAN-Bus Signal Exchange System in Electric Trucks

CAN-Bus (Controller Area Network) is a robust serial bus for connecting electronic control units in industrial environments, including those on vehicles like forklift trucks used in the material handling arena. It replaces bulky wiring harnesses, and is designed to be especially impervious to electromagnetic noise.

An open bus system, CAN-Bus manages all operating functions on a material handling vehicle, providing a simplified point of information exchange between the motor drive control, hydraulics, steering, operator controls, visual displays, and the computer control and service unit. Every individual component of a truck's electronic system constantly reports its operating condition to other components, and simultaneously receives their data.

Most new designs built today use a CAN-Bus-based communications protocol, since it offers some advantages over RS-232 and other, earlier protocols. Perhaps the most significant advantage over older protocols is the reduction of wiring. CAN-Bus uses the same wire to send different signals, whereas in the past a separate wire was used for each signal. Thus, the bus saves space, weight and wiring cost. It's also a much quicker form of communication protocol. Signals arrive at their destination quicker and get distributed quicker. In addition to reducing the amount of expensive cabling on the truck, CAN-Bus can often help to facilitate a diagnostic check using a laptop computer – even remotely over a dial-up phone line. Service can thereby be dramatically simplified.

level battery discharge rate during peak battery draw periods, resulting in longer battery run-times.)

Available only on certain models (i.e. not on sit down electric trucks), regeneration via load lowering can actually be more efficient at charging the battery than electric braking, since the downward motion of alowering cab or load is more stable and smooth compared to the choppy motion of starting and stopping.

Possible Drawbacks to Electric Trucks

A possible drawback to use of electric trucks not encountered with internal combustion trucks is the necessity of handling and servicing large, heavy batteries. Although an IC truck still needs a starter battery, it's relatively small, whereas with electric trucks a substantial warehouse facility for battery changing and charging can be required in a large operation. In addition, it takes much less effort to change out a propane tank than a 3200 lb. battery.

Note, however, that time-saving battery change-out devices do exist today. In addition, there are truck applications where it isn't necessary to change the battery, or at least where it doesn't have to be done often. For example, a Jungheinrich design emphasis is to maximize energy efficiency, which results in a charge life of 15-20% and sometimes as much as 30% more from the same battery than when using competitors' models.

Internal combustion trucks may also hold a slight advantage over electric trucks when it comes to the specialized tasks of pushing and towing. Pushing a load with either type of electric truck, AC or DC, for a lengthy period of time can raise motor heat levels, since current draw rises substantially. From time to time, most forklifts have to push a load into a tight spot or reposition it, but with electrics the push duration must be kept short to avoid damaging motor components due to arcing and burning from high current draws. This is especially true with DC motors, which can seize up in a stalled push situation. AC induction motors are less susceptible to this condition.

AC Motor

The number of motors in an electric truck varies. Some models have two drive motors, some do not have a steering motor, and some (narrow aisle trucks) have multiple hydraulic motors. Taking Jungheinrich's EFG 425 5000 lb-rated sit-down truck as a representative vehicle, three separate main system motors are present: A 23 kW load-lift motor, a 14.5 kW AC traction (drive) motor, and a .5 kW brushless power steering motor.

All sit-down electric trucks today have power steering and the vast majority have a form of hydraulic power steering. However, most electric trucks don't use an AC motor for this system, since power steering doesn't require much power, and because an AC motor would require a complex controller, which makes a system more costly and uses up limited space. A basic DC motor does not have to be controlled – it can be turned on and off with a contactor, so it's simpler. Thus, for reasons of cost and space savings, steering is almost always handled by a DC motor. Some trucks do not have a separate power steering motor, but use the main hydraulic motor to power the steering function, as well.

On the other hand, while a power steering motor typically needs a very low but very consistent amount of power, a drive motor's power requirements are not consistent. For example, the amount of power needed to propel an empty truck down an aisle when it is already running at six miles per hour is relatively small, but the power needed when the truck has to drive up a ramp with a full load from a dead stop is much higher.

Most AC motors used in material handling vehicles are induction motors, with no current being transferred from a rotor or armature to a stator or field windings. Instead, current is electromagnetically-induced in the armature. Thus, an AC induction motor eliminates the need for parts that represent a substantial portion of a DC motor – carbon brushes, springs, and, in some cases, contactors, components which work together to physically transfer the current from the stationary part of the motor to the rotating part. Although the absence of these items does not mean AC motors will never break down, it does mean that they require no regularly scheduled maintenance, unlike a DC motor.

With fewer moving parts to wear, users of AC trucks see an increase in truck efficiency, productivity and reliability. Moreover, because an AC induction motor dispenses with the commutator, it is able, in the same envelope of space available to a DC motor, to provide more power. Put another way, for the same size "motor volume" as in a DC motor, the user of AC gets a bigger energy generator. It is sometimes said that inherent to an AC system is better use of the "power envelope." It also offers more precise control of speed, loaded and unloaded.

AC induction motors offer many specific advantages over shunt-wound or series-wound DC motors, while still offering greater power. Here's a summary:

1. Simpler design, reducing motor cost
2. More power output per cubic inch of motor (an AC motor can pack the same punch as a larger DC motor)
3. Lower need for maintenance, given the elimination of the primary wear items of a DC motor – the carbon brushes and springs
4. Cooler motor operating temperatures, resulting in less energy losses and a more efficient operation, with much less chance of heat damage to wiring and other electrical components
5. Designers can position an AC motor in a more remote location of the truck chassis since it rarely has to be accessed for maintenance. This may contribute to an improved overall truck design (e.g. a smaller truck body).
6. It is easier to build a sealed AC motor than a sealed DC motor, given the absence of commutation components. This means much less dust and water ingress, and permits trucks to be used outdoors.

A Closer Look at the Issues of Motor Enclosure and Operating Temperature in AC vs. DC

The material handling equipment industry uses an easy-to-use figure of merit called the "Ingress Protection" (or IP) rating to evaluate the enclosures of electrical devices for the level of environmental protection or sealing they offer against entry of dust, moisture and chemicals that may disrupt device operation (See Fig. 5). The higher the IP number, the greater the protection – an IP rating of 0 means no protection. IP ratings have been adopted by the European Committee for Electro-technical Standardization (the specification is fully described in Document IEC/EN 60529).

The issue of ingress protection often has implications not only for the motor but also the associated connectors, cables and the motor controller, each of which item can have its own IP rating. Most of Jungheinrich motors, controllers and related circuitry items are all rated to a minimum IP level of 54 (note, for example, that in the designation IP54, the first digit refers to dust and particulate protection, and the second digit, to protection from sprayed water). Some components on Jungheinrich's trucks destined for outdoor use are rated to a level of IP65, considered extremely high. The ratings for equipment from other forklift manufacturers can be IP23 or less.

An AC induction motor doesn't necessarily have to be sealed. It can be designed to be as "open" as a DC motor – the degree of enclosure needed depends on the application the motor will see. Since the inside of the AC motor does not typically need to be ventilated for cooling, it can be readily enclosed per IP54.

That means it is possible to operate AC trucks in hostile environments, indoors or outdoors. In general, Jungheinrich's trucks are all designed for both indoor and outdoor use and its IP ratings are always at the top of the design scale, achieved with the careful selection of all related electrical components.

Regarding operating temperature, AC motors generally run much cooler than their DC counterparts rated at the same power output. The process of energy regeneration, whether taking place in an AC or DC system, tends to send increased amperage through a motor. Since a DC motor inherently runs hotter than an AC motor anyway, this extra current tends to heat it up even more. By contrast, an AC motor-based system permits a more aggressive energy regeneration without incurring an unacceptable heat penalty.

On the other hand, most of the heat in an AC system is generated in its controller – the black box that converts DC input power to 3-phase AC output power. Many AC and DC systems, therefore, need some sort of forced air cooling, but in DC systems, much of the emphasis is placed on cooling the motor, while in AC systems it's on cooling the controller. In general, the cooler any electrical system runs, the more efficiently it works.

Controllers

Every electric truck controller, DC or AC, contains some sort of a logic unit, or logic card. It's often called a "vehicle manager" or simply the "logics" and it can communicate with electrical devices throughout the truck via a communication protocol such as RS232 or CAN bus (see sidebar entitled "CAN bus signal exchange system in electric trucks).

Sometimes it's built-in to the black box, and sometimes it's a separate unit. Control systems for both DC and AC trucks today have mostly gravitated to a black box concept. Here, the system is not serviceable within the box, so maintenance personnel simply replace it when it becomes necessary.

One of the advantages to DC has traditionally been a simpler electrical control system. In a DC truck, a controller simply switches voltage on and off to vary the overall power and translate it into faster or slower speeds, based on the operator's use of the accelerator pedal or hydraulic controls. AC con-trollers must perform switching too, but also have to take DC power from a battery and convert it to 3-phase AC power, via inverters. The added complexity involved in this task necessitates more components than in a DC controller, and more complicated logics. In addition, since an AC system sends 3 phases of power (i.e., three phases of current) to the motors in an electric truck, it requires 3 power cables.

It should be pointed out that newer generation DC controllers are, themselves, becoming more complex electronically. Even so, generally speaking an AC electrical system (motor and controller taken together) is more complicated than a DC system.

Performance: AC vs. DC

Superior power and torque performance, motor simplicity and a potential for more aggressive energy regeneration during braking are three key attributes that set AC apart from DC.

AC is inherently more energy-efficient than DC, by eliminating the losses attributed to the commutation process, all else being equal. And, given the same amount of input power, motor size and battery voltage in an AC truck as in a DC model, the AC vehicle can develop more output power, better acceleration and deceleration, and more torque – both low-end and high-end torque.

Within the past decade, a German engineering consortium developed what's known as a Standard Cycle to emulate the real world demands placed on a forklift truck in work situations, in terms of load lifting and lowering, ramp usage and acceleration, both loaded and unloaded. Also known as a VDI cycle, it allows all forklift manufacturers to measure and compare their vehicles on the same basis in terms of performance.

Jungheinrich's energy usage tests have shown that its truck families can perform the standard cycle repeatedly, on a single battery charge, for over 12 hours in some cases. This means that often a Jungheinrich electric truck will be able to be operated for two shifts on the same charge.

AC also offers very precise speed control, useful at the higher speeds where torque in a DC system is typically minimized. Speeds are more consistent in a loaded vs. unloaded condition, too. Surprisingly, speed is not considered as important in forklifts as some of the other performance parameters, such as acceleration, power output, low-end and high-end torque, braking ability, maneuverability, gradient (ramp) negotiation, and level of maintenance and servicing required.

A forklift is limited as to speed since it often operates in rela-tively small, congested areas and must carry very heavy loads for relatively short distances. In addition, a forklift truck is obligated to meet certain braking specifications that limit its speed. What is essential under those working conditions is a truck that is able to handle loads at a high level of acceleration, which in turn demands high levels of low-end torque – i.e., torque developed at low motor RPMs.

Figure 5: IP (Ingress Protection) Ratings

	Protection from solid objects or materials		Protection from liquids
0	No protection	0	No protection
1	Protection against solid objects up to 1.97” (50 mm)	1	Protection against vertically falling drops of water
2	Protection against solid objects up to 0.5” (12 mm)	2	Protection against direct sprays of water up to 15” from the vertical
3	Protection against solid objects up to 0.1” (2.5 mm)	3	Protection against direct sprays of water up to 60” from vertical
4	Protection against solid objects up to 0.04” (1 mm)	4	Protection against water sprayed from all directions. Limited ingress permitted
5	Protection against dust limited ingress	5	Protection against low pressure jets of water from all directions. Limited ingress permitted
6	Totally protected against dust	6	Protection against low pressure jets of water from all directions. Limited ingress permitted
		7	Protection against the effect of immersion between 5.9” and 39.4” (15cm and 1m)
		8	Protection against long periods of immersion under pressure

Brief Overview of the Various Classes of Industrial Lift Trucks

The forklift truck industry is regulated by a trade association known as the Industrial Truck Association (ITA). It breaks down all powered lift trucks sold into five general classes:

Class 1: Electric counterbalanced trucks. This class comprises 4-wheel sit-down electric trucks, 3-wheel sit down electric trucks, and stand-up counterbalanced trucks. Class 1 trucks are all electric.

Distinguishing the type of tires used on trucks is a way to further specify members of the class. The U.S. standard is a cushion tire design (hard rubber, low profile), as opposed to the solid pneumatic (super-elastic) design. The pneumatic tire category includes both air-filled and solid pneumatics as standard. Jungheinrich offers cushion tires as an option and most 'cushion' trucks offer solid pneumatic tires and air filled tires as an option.

Class 1 electric pneumatic style trucks are also differentiated (though not by the ITA) as to where the battery is positioned inside the vehicle. For example, Jungheinrich puts the battery within the wheelbase of the truck (i.e., between the front and rear axles) to achieve a lower center of gravity and, therefore, more stability. However, on many other cushion trucks, the battery sits over the rear axle, which results in a shorter truck, but one with a higher vertical load center than the Jungheinrich approach.

Class 2: Narrow aisle trucks: This class includes reach trucks, man-up order pickers, and a sub-category known as VNA (very narrow aisle) trucks. The latter includes 4-way trucks, multi-directional trucks, turret trucks and combi trucks (both man-up and man-down versions). VNA trucks perform very high lifts and work in very narrow aisles, and allow operators to pick loads or put loads away, or both. All Class 2 trucks are electric.

Class 3: Walkie or pedestrian forklift trucks. All of these vehicles are electric driven. This class includes walk-behind trucks and walkie rider trucks, as well as walk-behind high-lift trucks – stackers that allow the transport of loads with a walk-behind operator, but that also lift loads to heights up to approx. 15 feet. The latter can be said to be a combination of a walkie and a reach truck.

Class 4: Internal combustion trucks with cushion tires.

Class 5: Internal combustion trucks with pneumatic tires – although most of the pneumatic tires in this class are air-filled, as opposed to the super-elastic pneumatic tires described in Class 1.

As a result, the emphasis in forklift design has traditionally been on engineering for better torque and power, not on making trucks significantly faster. Even so, however, AC truck travel speeds can be as much as 10% higher than DC vehicle speeds, and lift speeds might be as much as 15% higher. On a DC system, loaded travel speeds are often moderately lower than unloaded travel speeds, and loaded lift speeds can be measurably lower than unloaded lift speeds (sometimes as much as 50% lower). With AC, the gap between loaded and unloaded speeds is typically much lower (i.e., in that context, travel speeds loaded and unloaded are about the same).

Typically, a well-designed AC system can achieve better productivity than a similar DC system and has potential to offer better energy efficiency, although not necessarily at the same time. For example, Jungheinrich's EFG 220 series unit has been measured as being over 15% more energy efficient and over 15% more productive than several families of tested competitive trucks, based on the same work cycle.

Torque and Ramps

An AC truck offers excellent torque at both low and high RPMs. This dual ability is almost impossible to achieve with the older style DC motor known as a series-wound motor, although it's somewhat easier to achieve with a newer style DC motor called a "separately excited" motor. A large DC motor can offer quite a bit of torque at low speeds, but in general it's much easier to get both high-end and low-end torque with AC. The substantial torque that AC offers even at high speeds is essential in a forklift because it means there will be no annoying torque gaps and no speed drop-off, even in rigorous applications.

Torque is essential for good performance on ramps, and with its excellent low end torque 3-phase AC offers better ramp usage than DC, allowing for the greater possibility of momentary ramp hold (an anti-rollback feature), and more importantly, precise speed control on the ramp in either direction, with/without load.

This makes it easy to creep down a grade in complete control. When an AC truck is going down an incline, it will descend at a controlled rate depending on how much the operator steps on or off the accelerator pedal. As such, the truck has very precise control of speed, with no required use of the physical brake to slow down.

Speed control on a ramp related to how the controller manages current and sends it to the motor. At very low motor RPMs, a DC motor, in order to creep down a ramp, needs an abundance of amperage to develop the torque needed. In attempting to supply the needed torque, it can overheat.

AC Technically Compared to Internal Combustion

When compared to internal combustion systems, the performance of AC trucks in parameters such as acceleration, ability to negotiate a grade, speed control on ramps, load lift ability, and braking are today quite competitive. Until recently, IC forklift users found it difficult to find electric trucks that had the same or better levels of performance as IC, which was seen as the only available choice for indoor and outdoor use. AC technology has demonstrated a proven ability in recent years to match the performance of IC trucks in these criteria, and in some cases, even surpass them.

Today, some AC trucks can go as fast, get up a 20% grade as fast, and accelerate to top speed as quickly as a comparable IC truck. In fact, a review of the spec sheet for Jungheinrich's 5000 lb electric counterbalanced truck shows that it has actually eclipsed the performance specifications of most internal combustion trucks.

Pollution: A Major Problem for IC Trucks

A serious drawback to the use of internal combustion trucks in indoors material handling environments is the presence of polluting engine emissions: carbon monoxide (CO), various compounds of nitrogen and oxygen that contribute to creation of smog (lumped under the umbrella term, NOx), hydrocarbons of various kinds (HCs), as well as particulates, soot and odors (See Fig. 6).

Carbon monoxide (CO) is poisonous to humans. NOx emissions are undesirable since they are considered greenhouse gases and thought to harm the ozone layer, contribute to formation of acid rain, and even to aggravate asthmatic conditions. Produced primarily from the combustion of fossil fuels, at least six oxides of nitrogen exist. Many of the emissions reduction initiatives today are directed at reducing NOx compounds, in particular, because of their impact on the environment.

The main approach to suppressing pollutants on internal combustion trucks is the use of a catalytic converter. However, often-times a fix to the problems of modern technology does not come cheap, and catalytic converters are no exception. They are an expensive add-on to a truck and take up valuable space inside the truck chassis.

What's more, although LPG trucks equipped with a 3-way catalytic converter do have lower NOx emissions, the problem is never eliminated completely unless electric vehicles are used. Also, 3-way catalytic converters only work effectively to reduce NOx emissions from LPG and fuel-gas engines; they offer no benefit with diesel engines. In fact, diesel forklifts are dying out in popularity because it's so difficult to economically eliminate NOx emissions from them, or bring their emissions to an acceptable and compliant level.

If the engine emissions of a truck running on LPG are measured, the carbon monoxide (CO) content will be found to be only about 10% that of automobiles or fuel-gas vehicles – including lift trucks. For that reason, internal combustion trucks used indoors are generally LPG trucks, not diesels.

All IC trucks pollute the air to some degree, sometimes substantially. Excluding gasoline vehicles, the IC trucks considered the worst polluters when not fitted with a catalytic converter are those based on LPG technology. However, that is no longer true once a 3-way catalytic converter is used. Running at full power (as opposed to idle engine speeds), an LPG truck with a 3-way converter gives off less CO than Diesel.

Discussion of Catalytic Converter Technology

A catalytic converter is an insulated reaction chamber containing a finely-divided form of precious metals like platinum and iridium, which serves as a catalyst for chemical reactions that will cleanse exhaust gasses of pollutants.

Figure 6: General Comparison of Three Technologies

	LPG/Gas	Diesel	AC
Emissions:			
Carbon Monoxide	100%	Lower	0%
Hydrocarbons	100%	Lower	0%
NOx	100%	Higher	0%
Particulates	0%	Higher	0%
Odor	100%	Higher	0%
Life Cycle	100%	150%-200%	150-200% (Batt. 50%)
Engine Efficiency	100%	135%	200%-300%
Initial Investment Costs	100%	105%	156% (w/batt. & charger)
Fuel/Energy Costs	100%	90%-110%	10%-20%
Use Indoors	Limited	Limited	Unlimited

In the above table, fuel gas/LPG has been used as a baseline. For LPG, the futures are always shown as 100% since it's essentially being compared to itself. All other figures represent a percentage of the expected value for an LPG truck. For example, CO emissions are somewhat lower and engine efficiency somewhat higher on a diesel truck than on an LPG, but the electric efficiency is substantially higher and CO emissions are zero percent of the LPG figure, i.e., electric runs "clean."

Notes: 1. With all of the emissions reduction initiatives on IC trucks, vehicles of this type need ever more complicated diagnostics and sensoring components.
2. This table uses fuel gas/LPG as the basis for comparison.

In application, the gas is sent through the converter along with excess air so that pollutants react with the catalyzing agents and are converted to safe products, like carbon dioxide, water vapor and (in some cases) nitrogen.

There are two main types of catalytic converters: A two-way (sometimes called an "oxidation converter") and, and a three-way. Two-way converters see application on diesel engines. They reduce HC and CO emissions, and can do a good job of suppressing soot and diesel odor, but they are ineffective at reducing NOx -- which is a big emissions concern since it is a greenhouse gas.

Three-way converters can remove all three of the main pollutants simultaneously, including NOx, although they work at 100% efficiency only if the converter is operated at a point that is neither overly oxidizing nor overly reducing. Since the early '80s, 3-way catalytic converters have been the mainstay of emissions control systems in North American LPG forklift trucks.

It should be mentioned that catalytic converters have several drawbacks. For example, both types can become "poisoned," meaning catalytic activity declines due to buildup of contaminants like lead and phosphorus, as well as by exposure to overly high temperatures. In addition, it has been estimated that catalytic converters account for up to 50% of total nitrous oxide emissions to the atmosphere. While the relatively low concentrations of N2O involved here are not toxic to humans, the compound is still considered a greenhouse gas. In fact, some estimates hold that it accounts for about 7% of the overall Greenhouse Effect.

Thus, while on a local level, catalytic converters fitted onto IC forklift trucks may have cut down on toxic emissions and smog, they may also have added to the problem of global warming.

CARB and Its Influence Throughout the Industry

A number of Federal and state agencies are responsible for issuing regulations on engine emissions, whether from LPG, diesel or gasoline engines. In the U.S., overall responsibility for this regulation lies with the EPA (U.S. Environmental Protection Agency). Statewise, standards set by organizations like the California Air Resources Board (CARB) and other state bodies regulate the emissions of NOx, particulate matter and soot, carbon monoxide (CO) and volatile hydrocarbons, in accordance with Congressional legislation.

The California legislature has invested CARB with aggressive powers to set policy, devise and enforce emissions regulations, and levy fines and penalties as a way of punishing violators and simultaneously earning revenues to fund itself. The Board has a reputation for setting extremely tough standards for air quality, with its stated goals including attaining and maintaining healthy air quality, conducting research into the causes of, and solutions to, air pollution, and systematically attacking the problems caused by motor vehicle air pollution and emission of greenhouse gases.

In September, 2006, the California legislature passed bill no. AB 32, the Global Warming Solutions Act of 2006, in an attempt to reduce man-made greenhouse gas emissions in their state. CARB regulations were embraced by the federal EPA in 2004, and the CARB Tier II standard for spark-ignited engines has been incorporated into the EPA 2007 regulations, making them federally-enforced for the entire U.S.

Forced by CARB and organizations in other states to comply with regulations on NOx in particular, IC trucks (particularly LPG) are becoming more environmentally-friendly than they were in the past, via cleaner running engines and use of 3-way catalytic converters. One could say this compliance is helping to prop up the internal combustion forklift industry. Electric trucks, AC or DC, have never been a focus for the EPA because they create essentially no emissions, while IC truck manufacturers have to scramble to make their vehicles cleaner. Electric trucks are already clean with regard to exhaust emissions.

To encourage emissions reduction, a few states offer inducements – state monetary grants as opposed to tax incentives – although not many do this yet. California, Texas, and North Carolina are examples of those that do. These states pay user companies incentives for replacing older IC trucks with cleaner vehicles (such as an electric truck), or a certain portion of the cost difference between an electric truck and battery and an internal combustion vehicle they might be considering. When replacing trucks, up to 80% of the cost of new trucks (and battery) can be reimbursed, vs up to 100% of the difference between a 'cleaner' vehicle and a new vehicle with higher emissions (assuming the user's application is accepted). Companies buying the electric vehicle receive their up-front grant as a cash refund – and, of course, go on to save substantially in terms of the total cost of ownership over time.

Why Two Companies Converted to AC Technology Forklift Trucks

Electronic Recyclers in Fresno, California

An electronic waste collector and recycler with over 70,000 square feet of enclosed warehouse space

Electronic Recyclers had many reasons for transitioning its forklift truck fleet from liquid propane-powered trucks to AC technology, including the following:

- Its employees were falling ill from propane fumes.
- Electric AC technology trucks are environmentally friendly and the company's chairman and CEO, John Shegarian, had mandated the use of "green" business practices company-wide.
- The California Air Resources Board (ARB) is requiring that operators of existing forklifts reduce emissions by engine retrofit or replacement – or through the purchase of new equipment – by 2009.
- The San Joaquin Valley Unified Air Pollution Control District offers incentives to companies who participate in the Heavy Duty Motor Vehicle Emission Reduction Program. This program provides cash incentives toward the purchase of reduced emission forklifts and/or retrofits.

Electronic Recyclers "green" fleet now includes 13 Jungheinrich EFG 430 electric counterbalance trucks which are the only electric trucks that are able to be used both inside and outside of the warehouse. These counterbalance trucks unload trucks at the dock and move these loads to the back warehouse where they are stored before sorting and dismantling; they move palletized stacks of televisions, monitors, electronic waste, bins of shredded hard drives and bales of aluminum and plastic both within and outside of the facility; and they are used to rotate bins in the production areas from the dismantling lines and to outside areas.

According to Plant Manager Anthony Borges, "the improvement in air quality, heat suppression and noise pollution are amazing and the reduction in maintenance costs is large [through use of the Jungheinrich trucks]." With the battery-powered EFG 430s our scheduled maintenance is once a month. We've eliminated the costs and headaches of radiators, fans and constant fan replacement." In addition to all of the other benefits AC technology provides, Electronic Recyclers expects that over the life of the trucks the total cost of ownership will be far less than operating IC trucks.

Although an AC truck costs more and requires the investment in a battery station, the cost to recharge each day is only pennies compared to about $25 per day in propane.

Electronic Recyclers has also reaped some exceptional safety benefits, i.e.:

- The truck's Curve Speed Reduction System which helps prevent accidents from happening since the operator cannot drive too fast around corners and curves
- The truck's automatic parking brake which prevents the truck from rolling when situated on a ramp if the operator should fail to initiate the parking brake

Alpine Pacific Nut Company in Hughson, California

A company that processes, packages and supplies English walnuts to grocery store chains, food manufacturers, bakery supply distributors, candy manufacturers and cereal makers via a 250,000 square foot walnut processing facility

To move bins and pallets of walnuts around its yard, warehouse, processing facility and shipping and receiving areas, Alpine Pacific has begun a transition to an all electric fleet, i.e., Jungheinrich EFG 425 electric counterbalance trucks and an EFG 216 3-wheel stacker (which is outfitted with a slip sheet attachment and is especially effective in confined spaces because of its exceptional maneuverability.

Jungheinrich's 3-phase AC technology allows Alpine Pacific to run two 10-hour shifts between charges. According to Plant Manager Kenny Dickens, the LP trucks typically require one to two tank fills per day, but "they battery life on the Jungheinrich trucks is excellent and we are enjoying significant savings… it costs us pennies per day to charge the truck batteries compared to at least $25 per day for LP on the IC trucks."

Emissions laws for the California Central Valley were also a consideration, since "the AC trucks are a problem and we need to comply with emissions standards. The AC trucks are clean, quiet, require far less maintenance than our IC trucks and eliminate our worries about contributing to poor air quality," adds Dickens. That said, Alpine Nut expects to transition its entire fleet to AC technology in the next three years.