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Hybrids in Transit

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Introduction

Transit operators face extraordinary challenges. They have to respond to public dissatisfaction while their vehicles fight the gridlock in mixed traffic. They must respond to regulatory pressures to eliminate the tailpipe emissions. And they, somehow, need to find ways to maintain the level of service despite steep increases in salaries and fuel costs. The solutions seem to be technological. Ultimately, in order to reach Zero Emissions, the bus technology will enter the hydrogen highway but this is 15-20 years away. In the meantime hybrid-drive technology is attempting to solve some problems and mitigate others.

This report addresses the opportunities and challenges posed by the introduction of hybrid-drive buses in transit.

Background

A vehicle must be capable to transition from stationary to mobile state and reach the desired speed in a reasonable period of time. Therefore, a considerable amount of energy must be spent in the process. If several vehicles of equal weight move from point A to point B the energy needed to move them will be the same regardless of the propulsion system or fuel used. However, this energy is only 30-35% of the total energy stored in the fuel used. The remaining 65-70% of the total energy used is lost in form of heat, noise, vibrations, and emissions. It is the magnitude of those losses that differentiate the various propulsion schemes used in today vehicles.

Once in motion a vehicle needs energy to keep moving and power to be able to accelerate and climb gradients. Both the power density and energy density[1], see Figure 1, of the combined engine/energy-storage[2] system must be high.

[1] Power density and energy density are respectively the power and energy provided by the fuel and/or storage device divided by the weight of the fuel and/or of the storage device. Power density and energy density allow a direct, normalized comparison among diverse propulsion systems.

[2] The energy is stored either as fuel or chemicals in a battery or mechanically in a flywheel or as electricity in ultracapacitors.

Specific energy is important because it determines the mass (and weight) of the energy storage system. Specific power, in the units of power per mass, is perhaps the most important parameter measuring electrical energy storage requirements for hybrid-drive vehicles. Because hybrids normally depend on the electric energy stored on-board to provide the power for accelerations and hill climbs, the higher the power for less mass, the better. The data presented in Figure 1 allows a quick, visual comparison of the relative merits (and penalties) of the various propulsion schemes. For example, it evident that the internal combustion engines burning gasoline or diesel have the best specific power and specific density combination. If and ICE burning CNG is used a weight penalty of about 10% is expected. Other observations derived from Figure 1 are:

- The size and weight of the vehicle will increase with the decrease in power and energy density with the undesirable result of increases in fuel consumption.

- The vehicle operating range (i.e. the distance the vehicle operates before the energy-storage device must be refilled/recharged) is a function of energy-storage density, power requirements, and weight.

- The drive and energy-storage configuration for a specific application determines the relationship between power/energy-storage density and operating time as well as being a major factor on the shape of the torque curve. A transmission unit is necessary for both the transfer and the conversion of torque.

The significance of Figure 1 is that allows immediate visual comparison among various propulsion schemes. It represents the inevitable trade-offs between performance and weight and by extension between performance and fuel consumption as well as an indication of the amount of wear and tear to be expected with increased weight.

Transit buses must achieve, simultaneously, long service life, minimal fuel consumption, low maintenance costs and conformity with increasingly demanding emissions regulations. The current propulsion system, internal combustion engine (ICE) with petroleum-based fuels, has reached its upper limit in meeting the above requirements. Of the new and experimental propulsion systems (electric, hybrid, fuel cell) the hybrids are the best option.

What Are Hybrids

In terms of performance and range the ICE is vastly superior to all other propulsion systems. However its main disadvantage, produces emissions, has become socially and politically unacceptable.

The hybrid-drive developments attempt to combine several (usually two) different drive components in such a way that each element provides an advantage under varying operating conditions and hence, overall will minimize the performance and range gap with ICE while reducing fuel consumption and emissions. Most hybrids use an ICE designed for average-power operation, with the difference between the ICE generated power and the power required at any given time being compensated by additional energy-storage devices. The ICE and the additional energy-storage device can operate either in series or in parallel.

Series Drivetrains

In the series arrangement the electric motor is the only means of driving the vehicle. The motor obtains electricity either from a battery pack or a generator powdered by an ICE. The batteries are recharged from the ICE/generator set and by capturing some of the breaking energy (regenerative breaking). Because the electric motor alone drives the wheels, no clutch or multiplexed transmission are needed.

The ICE is mechanically decoupled from the drive train and, thus, it can be operated at constant speed in the vicinity of the optimum efficiency and emissions. The major disadvantage is that energy must be converted several times resulting in mechanical efficiency between ICE and drive axle below 55%.

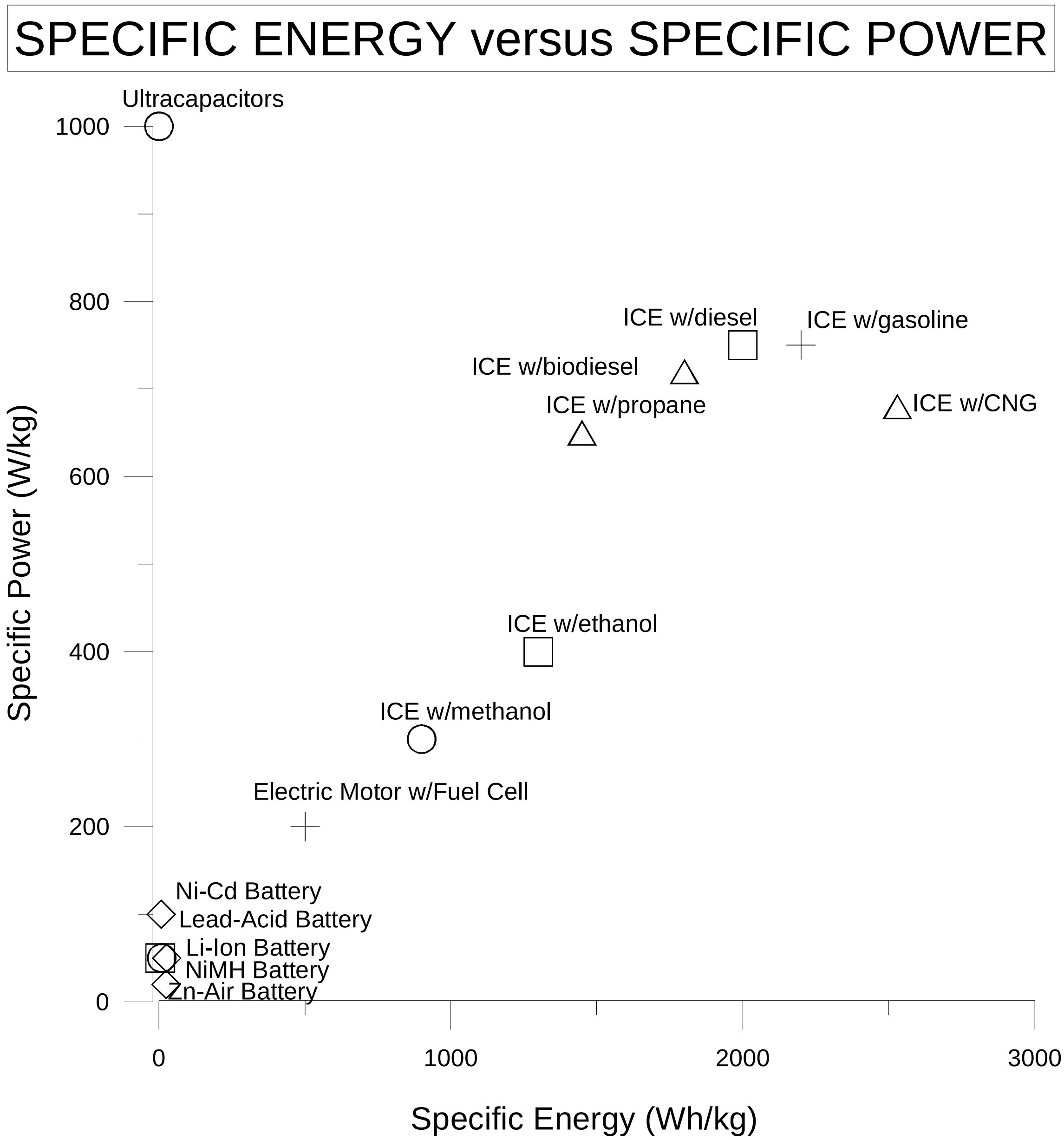

Figure 1. Power density and Energy density for various propulsion concepts

To gain the most advantage in efficiency from using a small engine, series drivetrains use relatively large battery packs. Batteries and motors cost more than engines for the same amount of power and, therefore, series drivetrains are more expensive than parallel drivetrains.

Series drivetrains are the most efficient under the CBD driving cycle and are especially appropriate for transit buses.

Parallel Drivetrains

In parallel drivetrain vehicles, both the engine and the electrical motor can drive the wheels. Here as well the batteries are recharged by using regenerative breaking and by reversing the electric motor into generator during driving. Parallel drivetrains require a transmission and means of coupling engine, motor and transmission.

In parallel configuration the ICE-drivetrain efficiency is the same as in conventional vehicles. However, the ICE operates over a large range of speeds away from the optimum operating efficiency and emissions.

Parallel drivetrains use smaller battery packs than series drivetrains but larger and more expensive engines. Overall the parallel drivetrains costs are lower than the series drivetrains. But as the cost of electric motors and batteries will come down over time the series drivetrains will erode this cost advantage as the cost of transmissions and the need to couple everything together are almost fixed.

Why buy hybrids?

In order to make sense to buy hybrid-drive buses they have to reduce the fuel consumption dramatically while meeting the most stringent emissions requirements (excluding zero emission standard). Hybrid-drive buses must equal or exceed the performance of the conventional buses (range, speed, acceleration, payload, noise, etc.). Otherwise why pay an extra $250,000+ per bus?

In technological terms the following are the must-have in a hybrid-drive bus.

- **Idle-Off**. Hybrid-drive buses must be able to turn the engine off when the vehicle is at a stop.
- **Regenerative Breaking.** Hybrid-drive buses must have electric motors capable to take over most of the breaking duties and a

battery pack capable to capture the breaking energy that otherwise will be wasted.

- **Engine Downsizing.** Hybrid-drive buses must use a smaller engine in conjunction with an electric motor that boosts the vehicle power to meet the same performance as a larger engine while using less fuel and having lower emissions.

Currently, there are three commercial hybrid systems integrators in the North American transit market: Allison (parallel hybrids) and ISE and BAE (series hybrids), respectively. The pool of hybrids (both designs) delivered to transit agencies and on order, although close to 2,000 mark[3], is not yet large enough to allow for a rigorous cost analysis There are too many variables such as bus and hybrid system configurations, warranties demanded by the agencies, quantities delivered or to be delivered, and the manufacturer perceived risk of doing business with some transit agencies. Moreover, in certain circumstances the systems seem to have been priced to satisfy the immediate business needs of the manufacturers, i.e. building a backlog, feeling a gap in their regular delivery schedule, etc.[4] As a rule of thumb hybrid buses cost $200,000-$250,000 more than an equivalent conventional bus. As the hybrid systems are by-and-large plug-and-play systems the entire cost differential is due to the hybrid system.

Issues Related to the Use of Hybrids in Transit

Energy-Storage Devices

There are several commercially viable energy storage systems that are being developed for hybrid-drive vehicles on the market today. Major advances are being made on almost a daily basis. The reason

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[3] Although more than 70 transit agencies in the US and Canada operate hybrid-system buses, almost 75% of the hybrids are deployed (or have firm orders) in three US cities: New York, NY, Washington, DC, and Seattle, WA.

[4] Recently, a series hybrid system and a parallel hybrid system have been priced for the same basic bus configuration, e.g. the buses were identical except for the hybrid systems. Both 40’ and 60’ artics were priced. The series system was approximately 1.3 % less expensive for the 40’ bus and 1.7 % more expensive for the 60’ artic (Although 1-2 % either way seems inconsequential it represents thousands of dollars in actual cost, hardly a negligible sum). Go figure!

for this is the fact that the government is subsidizing a large amount of the alternative fuel research going on by many U.S. as well as foreign manufacturers. The types of devices that hold the most promise to solve the energy storage problems are batteries, flywheels, and ultracapacitors. As shown in the Figure 1, gasoline, diesel and CNG have a higher specific energy than the rest of these electrical storage devices. An advantage of hybrid-drive vehicles is that they can use the high specific energy of liquid or gaseous fuels to provide the vehicle with long-range capabilities. Conversely, the hybrid-drive vehicles can use the high specific power of electrical energy storage to supplement the peak power requirements.

The batteries used in hybrid-drive vehicles are of the deep-cycle type, i.e. can be discharged and recharged for thousands of cycles. Today Nickel-Metal-Hydride (NiMH) batteries are used for hybrid-drive vehicles instead of lead-acid batteries to reduce the weight and deliver more energy from a smaller package. Although an improvement NiMH batteries failed to provide the performance breakthrough and the long-term cost benefits that were expected of them. Unfortunately, the energy-density of NiMH batteries is severely constrained and the cost is very high.

Currently the hopes of performance breakthrough and the promise of lower costs have been transferred to lithium ion (Li-Ion) batteries. Although these batteries are successfully mass-manufactured for consumer products (laptops, cell phones, and other electronic applications) there are no commercially available large Li-Ion batteries that can be used in hybrid-drive buses. There are still significant doubts about the performance, cost and safety of Li-Ion batteries for hybrid-drive vehicles.

Figure 2 shows the relation between the cost and cycle life for various battery systems. There seems to be no specific correlation between life and cost. However, as it can be seen in Figure 3, we seem to be willing to pay quite a premium even for marginal improvements in performance.

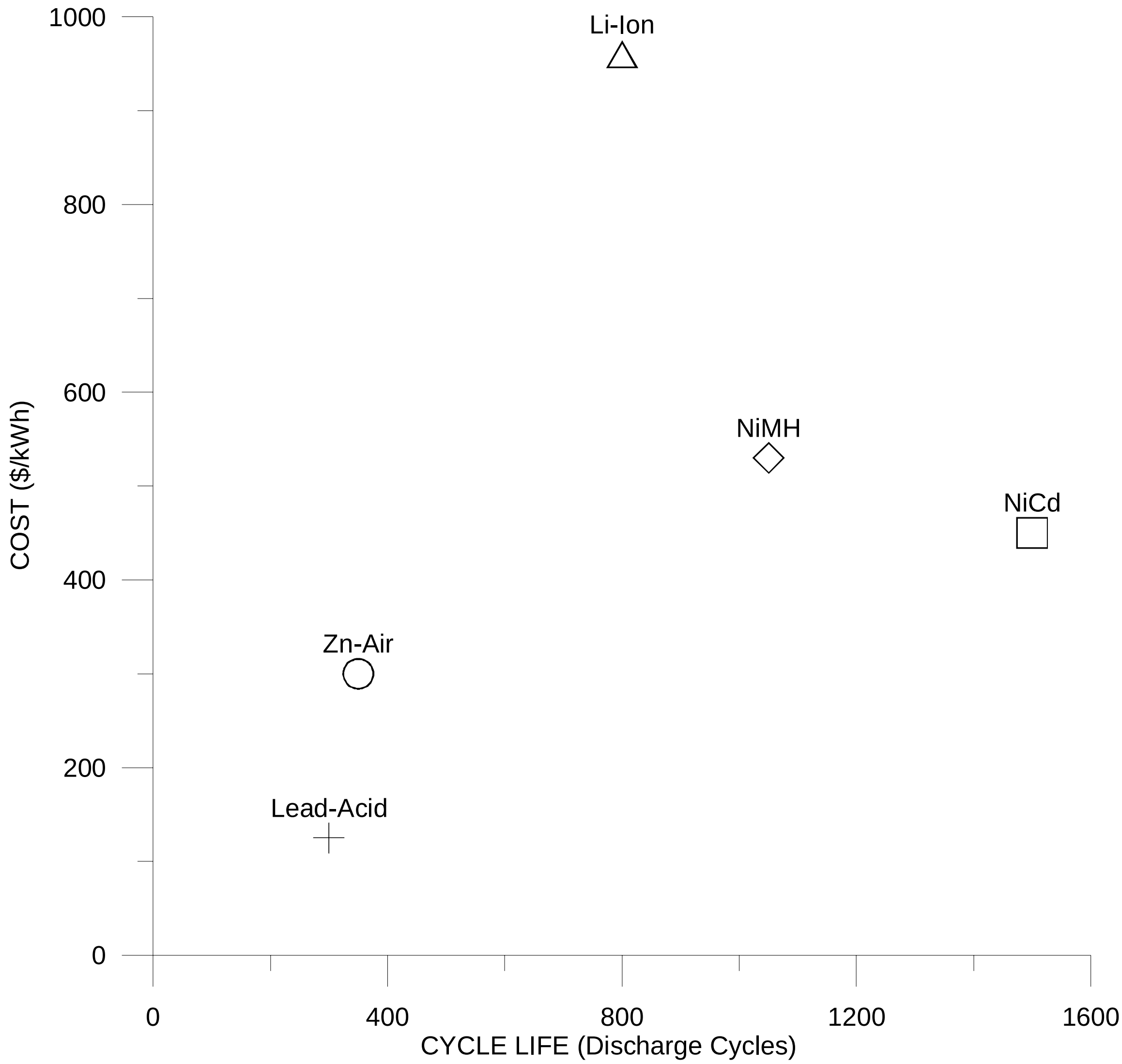

Figure 2. Cost vs. Cycle Life

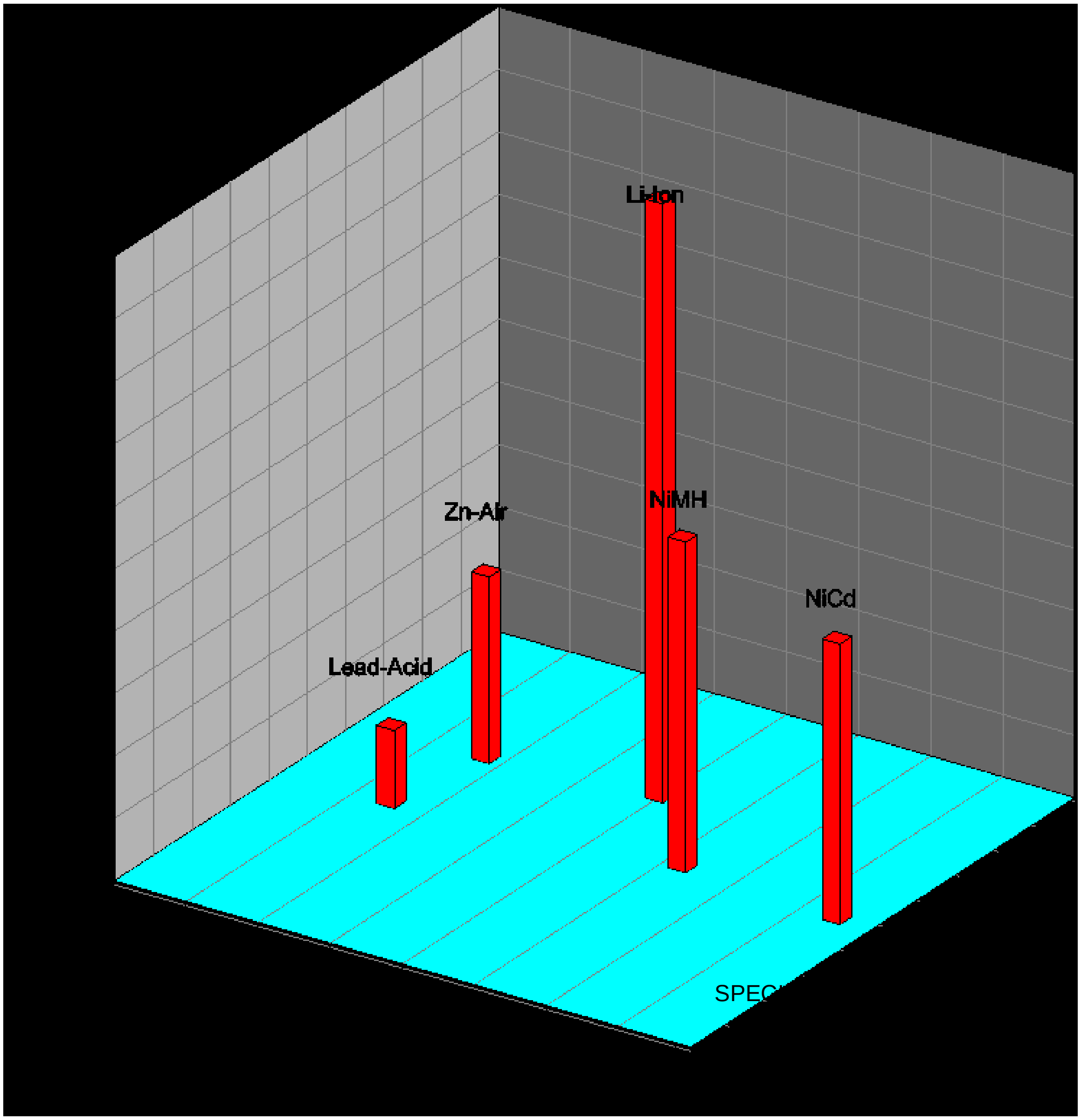

Figure 3. Cost, Cycle Life and Performance.

Flywheels store energy mechanically by turning a heavy rotor at ever-increasing revolutions per minute to store kinetic energy. Flywheels are good because they store energy very efficiently but their specific energy is very low. At this point in their development their commercial availability is almost nil. Furthermore, compared to other available products flywheels system integration ability is still very low and unproven.

The next possible technology is ultracapacitors. These devices work by accumulating and separating unlike charges. The positive abilities lie in the fact that they have no moving parts as well as the number of times that they can be cycled through their charge discharge cycle is very high. Ultracapacitors shortfalls arise from the fact that they have low specific energy in addition to the fact that those commercial versions that are available have only limited service history. Unlike the flywheels, ultracapacitors have greatly improved both price and availability. Ultracapacitors store (and release) energy in electrical form and they are capable of recovering large power spikes that can occur from heavy breaking. Ultracapacitors can also release the energy in high power bursts to accelerate the vehicles from start. This is a tremendous advantage over batteries that store energy chemically and thus cannot quickly store power. Using both batteries and ultracapacitors allows a higher percent of energy from braking to be captured and stored.

Figure 4 illustrates the reason there is an excellent reason to use both batteries and ultracapacitors in hybrids despite added cost and weight. Batteries provide the energy (as limited as it may be) and the ultracapacitors provide all the power a system might need.

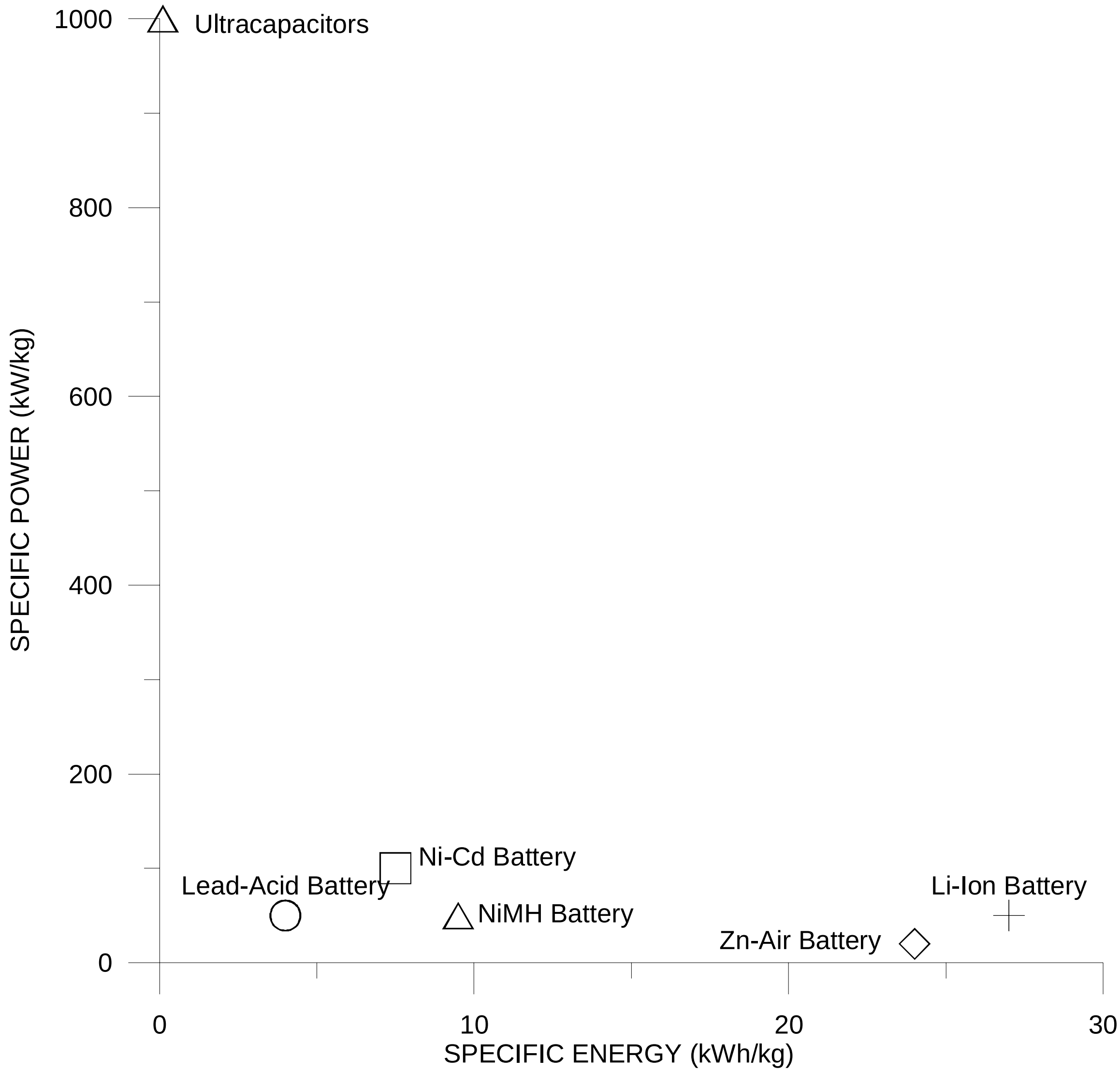

Figure 4. Specific Power vs. Specific Energy for Batteries and Ultracapacitors.

Fuel Consumption

The fuel consumption is determined by the weight of the vehicle and the distance traveled as well as by the losses due to internal factors (engine, drivetrain, and weight) and the external factors (rolling and breaking resistance and aerodynamic drag.

In the case of hybrid-drive buses the external factors do not change but the evaluation of the internal factors becomes confusing.

For series drivetrains the battery pack adds 15-20% to the weight of the vehicle. But a much smaller and lighter engine and the absence of a transmission and clutch mitigate weight gain. On the other hand the electric motor, the generator and the controller add weight back. Overall the weight gain is 14-17%. From an efficiency point of view the engine will have smaller specific fuel consumption and there will be no efficiency losses due to transmission. But the energy must be converted several times and the mechanical efficiency will be low.

For parallel drive trains there is little mitigation for the weight added by the battery pack although in this case the weight gain is at the lower end of the range (10-15%)[5].

Although the hybrid-drive buses have the potential of having lower fuel consumption than their conventional counterparts the actual performance depends on how well the manufacturer integrates the various technologies. The energy-storage devices make no contribution to the fuel economy as they need to be charged (and according to the 2nd law of thermodynamics the input energy will always be higher than the output energy). The idle-off and engine downsizing are clearly contributing to the fuel economy but if their contribution is enough to offset the weight gain is debatable. Regenerative braking, at this time, is underutilized and has the potential of making significant contributions to the fuel economy. How much regeneration can be achieved depends on the braking system design, the ratio of breaking between the electric motor (acting as a generator) and the foundation brakes, the energy-storage devices state of charge and how hard the electrical current from the generator can driven into the energy-storage devices.

[5] Recently, a series hybrid system and a parallel hybrid system have been weight estimated for the same basic bus configuration, e.g. the buses were identical except for the hybrid systems The weight of a set of parallel system main components (excluding the I.C. engine) is approximately 600 lbs. lighter than the weight of a complete set of series system main components (excluding the I.C. engine). Furthermore, the integration of these systems in the bus adds several additional hundred lbs. to the series system bus.

Two recent reports[6] evaluated series diesel-hybrid buses in NYC and parallel diesel-hybrid buses in King County, WA. The fuel economy of the two hybrid systems was very close, 3.17 mpg for parallel system and 3.19 mpg for series system, respectively. For comparison, the fuel economy of diesel and CNG buses were lower, 2.50 mpg for diesel buses and 1.70 mpg (diesel equivalent) for the CNG buses. However, the hybrid benefit might not be so great if the energy charged into batteries (no information available) is subtracted from the fuel economy.

The vast majority of the hybrid-system buses are fueled by diesel. Diesel engines offer extra torque, critical in applications where large payloads are present, and for this reason have long been the propulsion system of choice for transit buses. In hybrid-systems the electric motor can give a torque boost and thus leveling the playing field for the gasoline buses.

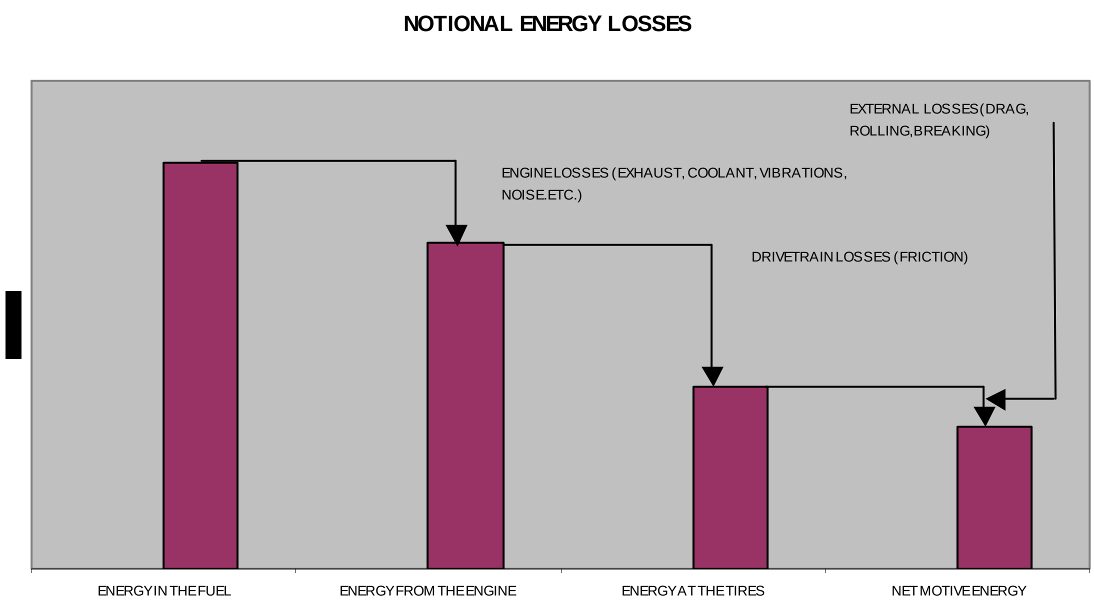

Figure 5- Energy Distribution Along the Systems in a Vehicle

[6] NREL/TP-540-40125 (November 2006) and NREL/TP-540-40585 (December 2006).

Emissions

The primary emissions advantage for the hybrid-drive buses is that they can use smaller, lighter engines that heat up fast thus reducing the start-up emissions (until the engine runs on its own the fuel burns partially leaving hydrocarbons that pollute a lot). During the running times series drive trains engines operate at or near the optimum thus producing less running emissions. Finally, at stop the idle-off feature cuts the emissions down.

The idle-off feature also creates two problems of its own. The problems are due to the fact that because of the idle-off feature there are more engine restarts than in a conventional vehicle. By itself, this problem can be managed by effective control of the engine cooling system that will keep the engine warm longer during the cool-off.

The second problem is the evaporative canister purging[7]. Because hybrid-drive buses have shorter running times between engine restart and engine shut-off and engine restarts are more frequent if the canister is not fully purged by the time the engine shuts off again the canister might not have the capacity to hold all the unburned fuel and will release the excess in the air. Eventually, a fully sealed fuel system will take care of the problem.

Several studies (mostly performed by manufacturers) have shown lower emissions of NO_x from diesel hybrid (series or parallel) buses than from conventional diesel buses in full chassis dynamometer. The series gasoline hybrid buses are certified at lower emissions standards for NO_x and particulate matter than diesel hybrid (series or parallel) buses.

Testing

Hybrid-drive buses are undergoing testing at Altoona and, in California, their engines must be certified by CARB.

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[7] When an engine turns off, unburned vapors are left in the fuel system. Instead of releasing the vapors in atmosphere (as pollutants) they are captured in special canisters. When the engine turns on the canister is purged and the fuel is burned in the engine.

At this time, CARB certifies only heavy-duty engines that have no place in a hybrid-drive bus. CARB refuses to certify medium-duty engines or smaller invoking budget constraints. But the idea of certifying engines for hybrid-drive buses is asinine. Hybrid-drive buses achieve emissions reductions as a system where the engine is just one component. As an interim solution CARB credits diesel hybrid buses with NO_x emissions 25% lower than the engine certification value.

The solution is to work with CARB, EPA, FTA and APTA to develop a protocol for emission testing buses and not just engines.

Reliability and Maintenability

Hybrid –drive buses recover much of the energy required to stop through regenerative breaking. Thus its mechanical breaks will see less wear than those of a conventional vehicle and will need less service and replacement. NREL/TP-540-40125 reports that the cost of brakes maintenance was $ 0.18/mile for the CNG buses whereas the cost of brakes maintenance for the series diesel-hybrid buses was only $ 0.04/mile.

There is not enough information to achieve a definite opinion regarding the reliability and maintenability of hybrid-drive buses. The battery packs are the most worrisome factor.

The NREL reports quoted above give us a glimpse into some maintenance costs (see Table 1). These costs can be misleading as they cover only the first two years of the twelve years buses when most of the components are still covered by warranties.

BUS TYPE	***DIESEL***	***CNG***	***PARALLEL DIESEL-HYBRID***	***SERIES DIESEL-HYBRID***
Propulsion-Related Maintenance Costs ($/mile)	0.120	0.349	0.130	0.367
Miles Between Road Calls (MBRC)	~6,000	~6,000	~5,000	~5,000
Miles Between Propulsion Road Calls (MBRC)	~12,000	~9,000	~10,500	~8,000

Table 1- Maintenance and Reliability Data

Conclusions

To date there is only spotty and sketchy information available about the performance of series and parallel hybrid system buses. We know that hybrid buses are more expensive than conventional buses. They are also heavier (1.5% for 40' buses-series hybrid vs. CNG; and, 2.5% for 60' articulated buses-parallel hybrid vs.diesel). Heavier buses are more prone to wear and tear over long runs. Fuel economy is reported as being much higher for hybrids but the energy used by the batteries is ignored. So, maybe we do not get better fuel consumption after all. Emissions, again, are reported as being much lower for the hybrids but the data is largely anecdotal. Propulsion-related mentainance costs are higher for the hybrids. There is a dire need for a test program that will separate the various variables and determine the benefits (or lack of) resulting from the use of hybrids in transit.

There is not a single magic solution to the problems created by energy costs, emissions regulations and traffic gridlock. Metro as the manager of the regional mobility must invest now in a variety of solutions from near to long term. Conventional buses with improved engines, transmissions, better aerodynamics and tires are the best short-term investment. Hybrid-drive buses can fill the midterm gap between the conventional buses and the hoped for hydrogen technology.

Metro has ordered six series gasoline hybrid buses for testing purposes. These buses will be the most integrated hybrid buses to date with small engines (with low specific fuel consumption) that will result in better fuel economy and lower emissions (in California gasoline is an alternative fuel). The buses are equipped with ultracapacitors, in addition to the battery pack, and will be able to capture and re-use much more of the braking energy that would otherwise be wasted. These buses will be deployed in the first quarter of 2008.