Hybrid Buses

Overview

Transit agencies are increasingly focused on making bus fleets cleaner and more efficient by incorporating new clean propulsion technologies. Hybrid technology that combines electrical and mechanical propulsion offers environmental and efficiency benefits and has moved from the demonstration stage to the implementation stage. This paper reviews the advantages and disadvantages of hybrid bus operation based on the best information currently available. It reviews types of hybrids, performance, and cost of operation.

Selected Resources

1. Analysis of Electric Drive Technologies for Transit Applications, Battery-electric, Hybrid-electric and Fuel Cells, Northeast Advanced Vehicle Consortium, Boston, MA August 2005: http://www.navc.org/Electric_Drive_Bus_Analysis.pdf
2. New York City Transit Hybrid and CNG Transit Buses: Final Evaluation Results, Barnitt, R. and Chandler, K., National Renewable Energy Laboratory, Report Number TP-540-40125, November 2006: http://www.nrel.gov/docs/fy07osti/40125.pdf

Context

Hybrid buses use electric power from batteries and mechanical power from internal combustion engines (diesel or gasoline) for propulsion. While ten years ago hybrid buses were demonstration vehicles, experience amassed through hundreds of buses in service and millions of miles travelled in all types of service conditions means hybrid buses are approaching viable consideration for urban transit agencies of all sizes. There are many reasons for acquiring hybrid buses such as cost of fuel, desired and regulated emissions reduction, and federal funding incentives.

At present, hybrid technology offers the best opportunity for electric drive technology to make significant inroads into transit operations in North America. It avoids the range and power problems of pure battery buses, and requires only minimal adjustment to transit infrastructure, and operating and maintenance procedures.

Experience over the past ten years indicates that hybrid buses have become a commercially viable choice for transit agencies. However, none have yet operated through the 15 to 20 year service life used for planning by transit agencies. This means there is not yet lifetime data for hybrid buses, so questions about durability, long-term system and subsystem reliability, and lifetime costs have only been partially answered.

Background

Hybrid-electric buses have reached the commercial viability stage. These are no longer primarily demonstration vehicles, although hybrid systems will continue to be developed and modified. There are approximately 1,250 hybrid buses in regular service by over 40 transit agencies in North America and many more are on order[1]. The majority of hybrids delivered and on order are 40-foot buses, but there are also deployments of 22-foot shuttle and 60-foot articulated buses. Most are diesel-hybrid, but there some gasoline-hybrids, particularly in California where they can be used to comply with both of the CARB Public Transit Fleet Rule bus “pathways.”

In New York, about 13% of the fleet of 6,200 buses is hybrid, and in Toronto, about 33% of the fleet of 1,700 buses is hybrid[1]. Many other Canadian municipalities have smaller fleets of hybrid buses.

Types of Hybrid Buses

Hybrid buses combine an electric generator and motor, controller, and battery packs with an internal combustion engine, which is most typically a diesel engine, and less frequently a gasoline engine. The hybrid system allows the internal combustion engine to operate in a more efficient mode, by “sharing” the energy and power demands of vehicle operations between the batteries and engine. The batteries can provide the traction motor with extra power as needed

[1] Surface Programs, Transit Projects, Transport Canada

for acceleration, allowing the engine to operate in a more "steady-state" mode, increasing the efficiency of the internal combustion engine.

The electric motor and energy storage also allows for energy recovery through regenerative braking. Regenerative braking allows the propulsion system to apply a retarding load on the drive axle during braking, thus converting the vehicle's kinetic energy into electrical energy. The vehicle stores that energy in the batteries to be used as required to provide tractive effort.

The overall efficiency of a hybrid-electric system depends on the system elements selection, how these various systems are integrated, and the electronic control strategy. There are two major configuration strategies for hybrid-electric vehicle systems:

A *parallel hybrid system* uses both an internal combustion engine and an electric motor for propulsion. Both the combustion engine and the electric motor have direct, independent connections to the transmission. Either power source – or both of them together – can be used to power the vehicle's wheels. In addition to supplementing the motive force of the engine, the electric motor also serves as a generator to recharge the battery pack while the vehicle is in motion. An electronic control unit blends power from the two energy sources. Parallel hybrids are often designed so that the combustion engine provides most power at high and prolonged constant speeds as determined by computer controls; the electric motor provides most as determined by computer controls power at low speeds; and both power sources work together during accelerations.

A *series hybrid system* uses an internal combustion engine to power an electric generator, which can then power the electric motor to drive the wheels, or charge the battery pack. The engine is completely mechanically decoupled from the drive wheels. All of the energy produced by the engine is converted to electric power by the generator, which powers one or more electric traction motors as well as recharging the energy storage device that provides supplemental power. The electric motor system – by itself – provides torque to turn the wheels of the vehicle. Because the internal combustion engine is not directly connected to the wheels, it can operate in an optimum range.

Compared to a parallel system, a series system requires a larger electric motor and battery pack, but a smaller internal combustion engine. A series hybrid does not need a transmission because the electric motor is capable of a wide range of speeds. The system works well in frequent stop-and-go service because the electrically driven propulsion system has high torque at low speeds, providing smooth, fast acceleration regardless of the grade.

Advantages and Disadvantages of Hybrid buses

Hybrid buses offer the following advantages compared to conventional diesel buses:

- Reduced fuel consumption in the order of 10% to 40%.
- Reduced noise level due to either a smaller internal combustion engine or lower RPMs
- Extended brake life due to regenerative braking
- Potential for reduced maintenance (fewer oil changes, less engine wear-and-tear)
- Better acceleration from a stop
- Passenger acceptance due to smooth ride and environmental friendliness
- Reduced emissions

There are several disadvantages to hybrid buses:

- The capital cost for hybrid buses is 50% to 70% more than comparable diesel buses, depending on the options ordered and the order size. It remains to be seen how much the price difference will close as hybrid buses gain wider usage.
- Battery life has been a significant cost and operational factor. There are three types of batteries typically used for hybrid buses and they offer different costs, advantages, and disadvantages.
- Some changes in maintenance procedures are required. For examples, additional parts need to be inventoried and equipment is required for the servicing of roof-mounted battery packs.

Canadian Experience

Hybrid buses are in service in several Canadian cities including Toronto, Victoria, Edmonton, Hamilton and Vancouver, and other cities have tried hybrid buses on a trial basis or have orders pending. Vancouver (Translink), Gatineau (Société de transport de l'Outaouais [STO]), and Montreal (Société de transport de Montréal [STM]) have tested hybrid buses under Transport Canada's *Urban Transportation Showcase Program.*

In early 2008, STM (Montreal) obtained six new standard diesel-engine buses and eight hybrid buses to be operated on the same routes under similar service conditions to allow a direct comparison of operational and maintenance costs. Instrumentation was installed on the buses to track variables such as bus speed, number of stops, the use of air conditioning, and hybrid engine operation.

After the hybrid buses were acquired, two series of controlled tests were conducted. The first series of tests was done at Environment Canada's Environmental Technology Centre to compare the fuel consumption and green house gas characteristics of the hybrid bus propulsion technology to conventional diesel engine propulsion under laboratory conditions. Testing was done at +20 and -20^{o}C (and with and without air conditioning for the STO buses). For the engine/transmission configuration used in the STM buses (280 hp, 2007 model), the hybrid buses reduced fuel consumption by 36% (using the Manhattan Test Cycle).

In addition to the laboratory analysis, a second series of trials was made at a test track in Blainville, Quebec. Instrumentation was used to provide the hybrid buses and the standard buses the same stop/start and acceleration schedules. Passenger loads were simulated using sandbags. The buses were tested at speeds from zero to 50 km/h. Track testing indicated that, for an average speed of 10 km/h and 10 stops per kilometre, the hybrid buses consumed 28% less fuel than standard diesel buses. The higher the maximum speeds, the less advantage the hybrid bus had in relation to the standard bus, making them particularly well suited to routes with low maximum speeds and frequent stops.

As of December 2008, route testing results showed a 30% savings in fuel consumption for the STM hybrid buses. Laboratory testing showed a 36% reduction and the track testing at Blainville indicated a 28% reduction. The variability of these findings is an indication of the susceptibility of fuel economy on terrain, speed, frequency of stops and driver habits. Over the next several months, the hybrid buses will be route-tested under winter conditions and the cost of maintenance for the new hybrid and standard diesel-engine buses will continue to be tracked.

The experience of the Toronto Transit Corporation (TTC) with about 500 hybrid buses has been well publicized due to a lower than expected fuel savings of around 10% and premature replacement of lead-acid batteries after 18 months. The results from Toronto may be explained by the hybrid buses serving on routes with fewer stops and starts – which are operating conditions that are not best suited to hybrid buses. The lead-acid batteries have not lasted the expected 2 to 3 years.

Drive-train technology

There are currently three major hybrid propulsion system companies in the full-size transit bus market: Allison Transmission, British Aerospace Engineering (BAE) Systems, and ISE Corporation.

BAE Systems: BAE Systems uses a series hybrid system configuration, and its buses are equipped with lead acid battery packs and diesel engines. To date, BAE has partnered primarily with Orion Bus Industries. BAE has been involved in the production of several generations of hybrid buses, beginning with the pilot fleet of ten buses in New York City starting in 1998.

Allison: Allison produces parallel hybrid systems and today they are equipped with nickel metal hydride batteries and diesel engines.

ISE Corporation: ISE Corporation integrates hybrid and fuel cell drive systems, as well as internal combustion engine systems (hydrogen, diesel and gasoline). ISE's hybrid drive is a series configuration. ISE buses have incorporated a variety of energy storage options.

Types of batteries

A major decision facing purchasers of hybrid buses is the type of batteries to select. There are three types of batteries presently available. *Lead acid* batteries were used exclusively for early-generation hybrid buses. *Nickel metal hydride* batteries have higher upfront cost than lead acid, but are smaller and lighter, and have a shorter recharge time. *Lithium-ion batteries* became commercially available in 2007 and are the next generation of batteries for hybrid buses. They offer a service life of about six years, are fast charging, and, due to their light weight, further fuel consumption reduction compared to lead acid and nickel metal hydride batteries.

Although the purchase price of lithium ion batteries is substantially higher than the other two types, proprietary cost/benefit analysis by one bus manufacturer claims that they are the most cost effective over the 15 to 20 year service lives of buses. The analysis includes allowances for recharging time and time-out-of-service for more frequent battery replacements.

An important consideration is annual bus duty cycle. For example, the projected time to replacement for lead-acid batteries is 2-3 years based on 30,000 miles per year. The higher the mileage, the more charges and discharges imposed on the batteries. If the mileage is significantly high, the service life of batteries will be lower.

It is possible to upgrade batteries from lead acid to other types offering longer service life. However, in addition to the purchase cost, programming changes are required to ensure optimum operation of the electric motor.

About 80 hybrid buses presently in service use ultracapacitors in the place of battery packs. Ultracapacitors store energy electrostatically by polarizing an electrolytic solution.

Performance

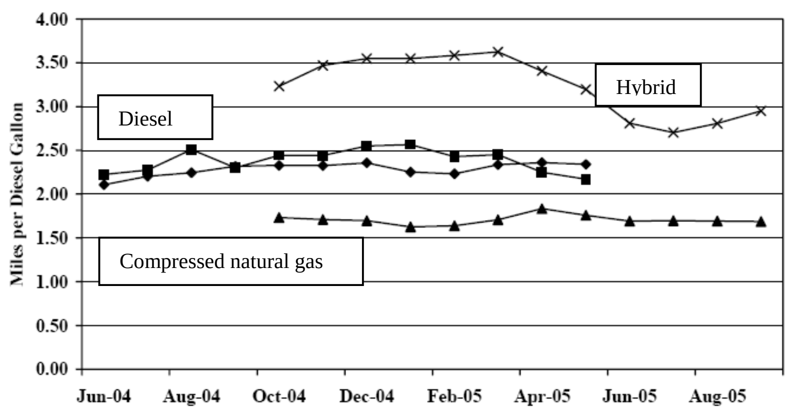
Fuel Economy

Hybrid buses provide 10% to 40% in fuel savings depending on a number of factors including:

- Hybrid system configuration;
- Duty cycle (particularly average speed and the level of stop-and-go driving);
- Whether the hybrid system is optimized for peak fuel economy results (as opposed to lower emissions or certain performance characteristics);
- Load placed on the hybrid drive by accessories;
- Driver competence.

Montreal hybrid buses are operated from one garage. Because any driver could be called upon to drive a hybrid bus, all 600 drivers at this garage obtained three hours of classroom and driving training. In addition, 24 maintenance personnel and technical staff received 40 hours of training. Because hybrid buses react differently compared to diesel buses in terms of acceleration and deceleration, driver training was considered essential for extracting maximum fuel efficiency from the hybrid technology.

Results of fuel economy studies in New York City are shown in Figure 1. Hybrid buses have consistently provided fuel economy between 10% and 40%. The extent of the fuel economy seems to depend most on whether the buses are used where they work best – on low-speed, high-number-of-stops routes.



Source: New York City Transit Hybrid and CNG Transit Buses: Final Evaluation Results[2]

Figure 1 Miles per gallon (US) for New York City buses

Emissions

Testing on New York City buses in 2004 (Table 1) showed that hybrid buses achieved particulate matter levels comparable to diesel buses equipped with particulate filters, and much lower NOx levels than the diesel buses. However, the hybrid advantage would have narrowed when 2007 emissions standards came into effect and will narrow further for the 2010 standards.

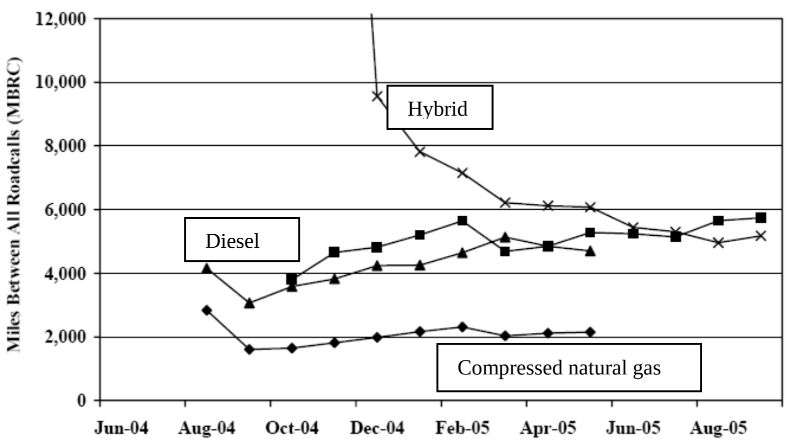
Table 1 – New York City Transit Emissions in grams per mile

Emissions (grams per mile)	Carbon monoxide (CO)	Nitrogen oxides (NOx)	PM/10	Total Hydrocarbons (HC)
Diesel (with diesel particulate filter)	0.12	2.79	0.2	0.02
Hybrid	0.03	0.94	0.2	0.2

Source: Analysis of Electric Drive Technologies for Transit Applications, Battery-electric, Hybrid-electric and Fuel Cells[1]

Reliability

Mean Distance Between Failures for hybrid buses has improved to the point where it is comparable to that of diesel buses[1] (Figure 2). After eight months of hybrid bus operation in Montreal, no above-normal maintenance issues have been reported related to the hybrid drive system.



Source: New York City Transit Hybrid and CNG Transit Buses: Final Evaluation Results[2]

Figure 2 – Average miles between recall for New York City buses

Customer and driver satisfaction

Customers, through surveys conducted in Vancouver, New York and Seattle, have indicated a positive response for the comfort and environmental benefits of hybrid buses. Hybrid drive provides smooth acceleration without shifting, a feature that drivers and passengers like. Hybrid propulsion also provides fast acceleration due to the increased low-end torque characteristics of electric motors. Most hybrid bus fleet managers reported being pleased with hybrid buses' performance and with driver and passenger response to the buses.

For example, New York City Transit conducted surveys of its drivers and passengers to gauge their reaction to the hybrid buses, with positive results. Almost 88% of the passengers surveyed preferred riding in a hybrid to a diesel. While only about 60% were initially aware they were in a hybrid bus, 70% reported that the noise and vibration levels in the hybrid were preferable to that of a diesel bus. 71% of drivers said the hybrids were not hard to get used to driving, while 25% said they had only a little difficulty getting used to the buses. Almost 93% of the drivers said the hybrid buses' acceleration was better than a diesel bus, and 61% found the braking superior.

Maintenance

One major benefit for hybrid buses is extended brake life, as the electric drive system and regenerative braking mean less wear-and-tear on the brakes. Some transit agencies with hybrids are reporting that the hybrid buses extend brake life by 50% to 100% (or more). Hybrid buses also may put less "stress" on the engine, as the engine is operating in a more efficient range. It is possible that this could reduce the engine repower or rebuild costs, although this is only speculative at this point. Finally, based on early experience in New York City[2], the electric drive components may require less maintenance and last longer than the transmission and its related parts.

While transit agencies need to make some operational changes to adopt hybrid buses into fleets, these are manageable. Overall, hybrid buses have demonstrated that they can be incorporated successfully into regular revenue service operations, with some issues that would be expected with a new technology.

Durability

The long-term durability of hybrid buses remains a question because no transit agency has operated them through their entire service lives. Even results from early hybrid deployments, such as the fleet introduced in New York City in 1998, may not yield applicable estimates of durability as the hybrid technology and integration, as well as the bus design, has changed since this first generation pilot fleet. A big concern for transit agencies is the durability of battery packs.

Cost/benefit of hybrid buses

Until definitive Canadian cost/benefit information is available from Transport Canada's Urban Transportation Showcase Program project in Gatineau and Montreal, a good source of information for the methodology of conducting a cost/benefit analysis for hybrid buses is *Additional Transit Bus Life Cycle Cost Scenarios Based on Current and Future Fuel Prices*[5]. Although this study was based on US data, it provides some insight into the potential costs of running a hybrid bus in Canada. The study looked at a 100-bus fleet and examined purchase costs and projected costs for maintenance, and operations on a projected bus life of 12 years – less than the 15 to 20 years typically used by Canadian transit agencies.

For the assumptions made in the US, the capital cost premium of hybrid buses could not be recovered over 12 years despite demonstrated fuel economy. However, it seems likely that with some moderation in purchase prices due to volume, ever-improving battery technology and amortization periods longer than 12 years, hybrid buses will prove to be cost effective compared to standard diesel buses. Cost/benefit information specific to Canadian conditions is expected in May 2009 when the hybrid bus testing being done in Gatineau and Montreal is concluded.

Conclusions

Hybrid buses have moved from the demonstration stage to commercial use with transit agencies in cities like New York and Toronto having hundreds in service. Some buses have been operating for over a decade but this is still not long enough to ascertain reliability through the full 15-20 year planned service life used by transit agencies in Canada. Also, newer model hybrids have been introduced that have different performance than earlier models, further delaying definitive conclusions. However, several major analyses have been completed (see references) that transit agencies can use to become well informed.

Hybrid buses offer many advantages. They provide a high level of customer and driver satisfaction due to smooth acceleration and quietness. They reduce emissions and transit agencies can deploy them with very little adjustment to maintenance infrastructure and procedures.

Their disadvantages are mostly due to purchase cost and the cost of battery replacement. This Showed itself in a life cycle analysis completed in the US in 2008 that indicated that hybrid buses are more expensive to operate over their life cycle than standard diesel buses based on expected fuel costs and other assumptions. Decreases in purchase cost due to mass production, improving battery performance and economics, or steep, sustained increases in fuel prices could improve the life cycle cost of hybrid buses and provide lower emissions.

Overall, transit agencies like Seattle and New York City that have operated large hybrid bus fleets for several years are reporting fuel conservation and resulting emission reductions in the order of 30%. The major operational concern is the cost of battery replacement. Although none of these buses have yet to be in use though their entire service lives, it is projected that the cost premium for hybrid buses can be recovered through fuel savings if the buses are operated on routes tailored to hybrids (frequent stops and starts) and the buses are amortized over a period of 15-20 years.

References

Reports

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Information

1. Hybrid Center: http://www.hybridcenter.org/hybrid-transit-buses.html
2. Hybrid buses, Canadian Urban Transit Association: http://www.cutaactu.ca/en/node/528