A Series Hybrid-Electric Drive System Optimized for Large Transit Buses

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Omnitrans is the local transit agency that provides bus and Paratransit service to the San Bernardino Valley, a 480 square mile suburban area located approximately 60 miles east of Los Angeles, California. Omnitrans secured a FTA grant in 1995 to acquire electric buses because of the need to find ways to improve air quality, since our region is ringed with mountains and all the pollutants generated in the greater LA area are carried by the prevailing winds are carried to us.

Omnitrans' intent was to advance the state of the art in electric vehicles that could be practically operated as regular service vehicles. The search for an all-electric vehicle proved futile. Trying to recharge a fleet of 150+ buses every night at one bus yard is impractical; and their need for maximum air conditioning for significant portions of the year is beyond the storage capacity of current generations of batteries.

Their search finally lead Omnitrans to hybrid-electric vehicles and ISE Research Corporation, a San Diego based firm that had successfully completed a number of related projects with the financial support of a variety of governmental agencies, including the local Air Quality Management District (AQMD). In fact, it was the AQMD that brought them to Omnitrans' attention.

ISE told Omnitrans that they were interested in developing powertrains that could be installed in buses by bus manufacturers just like they now install diesel and CNG drivetrains. Omnitrans had a contract with New Flyer to produce up to 85 low floor buses, including 10 optional units. They agreed to supply three of the optional units as gliders that could be mated to ISER's hybrid-electric powertrain.

The balance of this paper describes a series hybrid-electric drive system developed by ISE Research-ThunderVolt, in partnership with Omnitrans, which is optimized for large 40-45 foot transit buses. Series hybrid-electric drive systems have been shown, through analytical studies and testing of prototype vehicles, to offer environmental, efficiency, and performance benefits in heavy-duty vehicle applications. These benefits can be significant for vehicles that perform substantial amounts of stop-and-go driving, such as large transit buses. The "ThunderVolt" hybrid system developed by ISE Research, like other series hybrid systems, uses an internal combustion engine solely to generate electricity. For the 40-foot bus application, a Ford V-10 gasoline engine is mated to a custom-designed 200 kilowatt permanent magnet generator to supply prime power for the vehicle. Electrical power from the engine-generator unit is routed to a high power, high torque AC induction motor, also custom designed for the large bus application. The motor is linked to a standard differential in a "direct drive" configuration, eliminating the need for a separate transmission or gear reduction system. Two different types of energy storage subsystems have been developed for use with this ThunderVolt drive system, one utilizing a deep-cycle battery pack and one using ultracapacitors. Both energy storage systems are capable of providing surge electrical power to augment the output of the engine-generator set, and of absorbing braking energy through a regenerative braking process. These functions significantly enhance the operating efficiency of the ThunderVolt drive system, and enable the combustion engine to be operated at its most efficient speed. The ThunderVolt system can reduce fuel consumption in large buses by 25-50% and reduce harmful emissions by more than 90%, while offering faster acceleration and a smoother, quieter ride than conventional drive systems. Three New Flyer low floor demonstration buses using this ThunderVolt system are being deployed in San Bernardino by Omnitrans. Omnitrans will have initial operational experience to report on at the conference.

The Need

Hybrid-electric vehicle technologies are being developed at a fast pace, in response to growing concerns about the global environment and the need for more reliable, fuel-efficient transportation. Over the past few years, heavy-duty vehicles (vehicles with gross weights in excess of 8,500 lb.) have been increasingly targeted for use of hybrid-electric technology. Such vehicles produce approximately 50% of mobile source emissions, even though they constitute a much smaller percentage of the overall vehicle population. They also consume disproportionate amounts of fuel, utilizing some 20 billion gallons of fuel in the U.S. each year.[1]

Large transit buses in the 40-45 foot length range have emerged as the first type of heavy-duty vehicle to adopt hybrid-electric technology on a large scale. Most large urban diesel buses currently in service are among the worst polluting road vehicles in the world, owing to their large diesel engines and demanding, inefficient duty cycles. Nitrous oxide (NOx) emissions from diesel buses in New York City have been measured at more than 70 grams per mile, a level far higher than the emissions standards being developed by most air quality agencies.[2] A typical large diesel bus also consumes a great deal of fuel, typically achieving fuel economies in the range of 3 miles per gallon.

In response to the environmental issues posed by large transit buses, a large number of alternative fuel vehicles have been deployed over the past decade. The most widely used alternative fuel is compressed natural gas (CNG). However, many transit operators have been reluctant to adopt CNG on a large scale, due to the cost and complexity of CNG refueling infrastructure and other logistical concerns. In addition, CNG buses have been shown to produce NOx emissions equal to or higher than diesel buses when their engines aren't tuned properly, and they produce significantly higher levels of hydrocarbons than diesel buses.[3] CNG buses are also less fuel efficient, and recently concerns have been raised about the health effects of ultra-fine particles emitted by CNG engines.

Hybrid-electric vehicles are starting to be embraced by the transit industry because they offer the potential to reduce emissions and to improve fuel economy, while avoiding many of the problems associated with CNG. When used in conjunction with diesel or gasoline fuel, hybrid-electric buses can achieve emissions equal to or lower than conventional buses fueled with CNG. When used in conjunction with CNG, hybrid-electric vehicles offer greater fuel economy and lower emissions than conventional CNG vehicles. In early demonstrations of this new technology, hybrid-electric vehicles have also shown significant performance advantages over conventionally powered vehicles, as discussed in more detail later in this paper.

Principles and Benefits of Hybrid-Electric Operation

There are two basic types of hybrid-electric drive systems: parallel hybrid drive systems and series hybrid drive systems. In both versions, an electric drive motor is used to augment the internal combustion engine (ICE), enabling use of a smaller engine than required in a conventional vehicle, and enabling the ICE to be operated more efficiently.

In the parallel drive system, the electric motor provides mechanical assistance to the ICE, supplying additional power and torque for brief power surges. During such intervals, the mechanical power required to move the vehicle is essentially "shared" between the ICE and the electric motor, allowing the ICE to be "downsized" and operated at its most efficient speed. For long haul trucks that sustain high power levels for extended periods, parallel hybrids equal or exceed the efficiency of conventional vehicles by preserving the direct mechanical link between the ICE and the driveline. During sustained high speed driving, this direct mechanical link is more efficient than the series hybrid approach, which is to use the ICE to generate electricity, and then use an electric motor to reconvert this electrical power back to mechanical power.

The series hybrid drive system, depicted schematically in Figure 1, is a more radical departure from the conventional automotive drive system. In the series drive system, the electric motor is the sole means of moving the vehicle's wheels, as the ICE is mechanically decoupled from the driveline. The ICE in the series hybrid drive system is used only to generate electricity, which is in turn used to power the electric drive motor.

Series hybrid systems are not expected to be particularly efficient for long haul trucks, but they are projected to surpass the performance of parallel hybrids in vehicles that spend large amounts of time in stop-and-go driving. In locally-driven vehicles such as urban transit buses and delivery trucks, a deep-cycle battery pack can be used to augment the electrical power supplied by the ICE during brief periods of high power consumption, enabling the engine in the series hybrid drive system to be exceptionally small. During extended periods of low power usage, such as when the vehicle is stuck in traffic, the series hybrid vehicle can be sustained with extremely low amounts of power from the ICE. Depending on the size of the battery pack and the design of the vehicle's electrical system, the series hybrid vehicle can even operate with the ICE completely shut off for significant periods of time, providing even greater emissions reductions and fuel savings.

In both the parallel and series hybrid drive systems, use of an electric drive motor offers improvements in performance and efficiency. Advanced electric motors, particularly the AC induction motors used in most hybrid vehicles, generate high torque and can provide swift, smooth acceleration. In addition, use of electric drive motors enables "regenerative braking," a process wherein the kinetic energy of the vehicle can be partially recaptured during braking, and stored on board the vehicle in batteries, ultracapacitors, or some other type of energy storage device. Both of these benefits are particularly noticeable in vehicles that spend much of their time in stop-and-go driving, where acceleration is more frequent and there are more opportunities to utilize regenerative braking.

In the longer term, it is projected that hybrid-electric drive systems will offer maintenance benefits, as stresses on the ICE are reduced, the transmission is eliminated (at least in some configurations), and the new components added to the system generally have few moving parts. In the series hybrid system, the down-sizing of the ICE and its decoupling from the driveline may also offer greater flexibility in packaging the drive system within the vehicle, enabling vehicles to be reshaped with more aerodynamic and fuel efficient designs. The projected benefits of series hybrid-electric drive systems, including life-cycle cost savings expected to accrue from reduced fuel consumption and maintenance costs, are summarized in Table 1 and discussed in more detail in the last section of this paper.

Description of the ThunderVolt™ Hybrid-Electric Drive System

The ThunderVolt™ hybrid-electric drive system is a modular series hybrid drive system designed to function in a wide variety of heavy duty vehicles, including trucks, buses, tractors, and construction equipment. The ThunderVolt™ philosophy is to maximize the degree of flexibility in configuring a drive system to meet the requirements of a specific vehicle. This is achieved by employing a flexible system architecture that allows components of different types to be "mixed and matched," and by drawing from a varied "menu" of components produced by numerous suppliers. In this manner, a hybrid drive system can be configured to meet specific requirements for acceleration, hill-climbing, top speed, and fuel type, as well as taking into consideration weight constraints, budgetary limitations, and other factors.

The ISE Research (ISER) ThunderVolt™ drive system is divided into five major subsystems: motive drive subsystems, auxiliary power unit (APU) subsystems, energy storage subsystems, controls and displays, and electrically-driven accessories. Within each of these subsystem areas, ISER offers a range of components so that each subsystem, and the drive system as a whole, can be tailored to the specific requirements of the targeted vehicle application. Since 1996, variants of the ThunderVolt™ series hybrid drive system have been integrated by ISER into ten different models of heavy-duty vehicles, including four different truck models, three different tractor models, and three different bus models.

The most recent variant of this family of drive systems is the ThunderVolt™ TB40H hybrid-electric drive system, which was developed by ISER between 1998 and 2001 specifically to meet the requirements of 40-45 foot transit buses. Recognizing the unique requirements of buses in this class, the TB40H is designed to the following basic requirements:

- Gross vehicle weights up to 45,000 lb.
- Maximum sustained speed of at least 75 miles per hour.
- Maximum hill-climbing grade of 17% without gear reduction, 20% or more with gear reduction.

- Periodic all-electric operation (with internal combustion engine turned completely off).
- Ultra-low emissions.

To facilitate development of the TB40H, ISER teamed up with Omnitrans, the transit agency in San Bernardino, California. Omnitrans agreed to purchase three New Flyer 40-foot low floor buses from ISER equipped with the new TB40H drive system, and is entering these vehicles into revenue service on a trial basis during 2001. The first of the three buses is equipped with the "standard" ThunderVolt TB40H drive system, whose major components are listed in Table 2. The second bus is equipped with the same drive system, with the exception of the main battery pack, which is replaced with a pack of ultracapacitors. The third bus uses the standard TB40H system, with the exception of an advanced experimental main drive motor in lieu of the motor typically offered with the TB4-0H drive system.

Several of the major TB40H components listed in Table 2 were designed specifically to meet the requirements of large transit buses. These include the following:

Main drive motor — The main drive motor in the TB40H configuration is a custom designed liquid cooled AC induction motor with a continuous power rating of 170 kW. This power rating, which can be sustained by the motor indefinitely, is the amount of motive power needed to sustain a fully loaded large transit bus at highway speeds. Liquid cooling of the motor allows the motor to be smaller and lighter than if air-cooled were employed. The motor weighs approximately 1,200 lb., as compared with air-cooled motors with equivalent power ratings that weigh 1,600 to 2,000 lb. The 170 kW motor was developed by ISER in partnership with Mawdsley, Ltd., a specialty motor manufacturer based in the United Kingdom.

The ISER-Mawdsley motor has a unique stator design that optimizes the motor's operation with the modular ISER-Siemens motor controller system. During low power driving, the motor can be operated efficiently while drawing power from just one of the two 100 kW motor control power modules installed into the Omnitrans bus. When higher power levels are required, the second power module is automatically activated and the motor efficiently converts the additional power into mechanical power for the vehicle. The main drive motor also has torque characteristics that enable it to be used in the 40-foot Omnitrans bus application without the use of a separate transmission or gear reduction system. For heavier vehicles or vehicles with unusually steep hill climbing requirements, the motor can be augmented with a two-speed transmission or gear reducer.

Internal Combustion Engine (ICE) — A variety of ICEs can be utilized in the TB40H configuration, as long as the ICE-generator combination can supply the continuous electrical power levels (approximately 200 kW) required for high speed driving with accessories such as the air conditioner running. The ICE selected for the Omnitrans bus demonstration program is a novel selection for a transit bus application — a Ford 6.8 liter V-10 gasoline engine (Figure 2). This engine — the first gasoline engine used in a large hybrid transit bus — meets drive system power requirements and produces very low emissions. In fact, the rated NOx emissions of this gasoline engine are actually lower than the NOx emissions produced by equivalent sized CNG engines such as the popular Cummins 5.9 liter CNG model.

Use of gasoline instead of CNG offers two advantages for Omnitrans: freedom from having to rely on a CNG refueling infrastructure, and smaller, lighter fuel tanks. This latter consideration is vital because it would be extremely difficult to accommodate CNG tanks and a deep cycle lead-acid battery pack within the design of a low floor bus. Even with the CNG fuel load reduced to 50% of normal, the combined weight of the CNG tanks and battery pack would be approximately 5,000 lb., which exceeds the structural weight rating of the bus roof — the only place where the CNG tanks and batteries could conveniently be located. Use of gasoline reduces the fuel system weight by more than 1,000 lb. and allows use of standard diesel tanks (modified to accommodate gasoline) mounted in front of the engine compartment. Gasoline has a slightly lower energy content than diesel fuel, but the performance advantages of the hybrid drive system are expected to more than offset this disadvantage. With a tank capacity of 120 gallons and a projected fuel economy of at least 4 to 5 miles per gallon (versus 3.2 mpg. for a typical diesel bus), the Omnitrans gasoline hybrid buses are expected to have a minimum operating range of 400 to 600 miles without refueling.

Generator — The electric generator used on the Omnitrans buses, pictured in Figure 3, is a 200 kW permanent magnet generator specifically designed to meet the power requirements of large transit buses. Earlier versions of this type of generator, with power ratings ranging from 75 kW to 120 kW, have been employed by ISER successfully in a variety of trucks, buses, and tractors since 1997. The 200 kW version was developed by ISER and Fisher Electric Technology in 2000 to meet the sustained high power requirements of large buses and trucks operating for extended periods at high speeds. The 200 kW unit can supply up to 170 kW to the main drive motor, with enough power to spare for heavy air conditioning loads, without relying on the energy stored in the main battery pack. A large transit bus may exceed this 200 kW power requirement for brief periods, such as when accelerating to pass a vehicle or attempting to climb a steep hill at high speeds, but the battery pack can typically supply the surge power required during these short intervals. The ISER-Fisher generator is a relatively compact, lightweight unit that can be mated with most conventional ICEs. It is an air-cooled unit, which simplifies its operation and maintenance.

Vehicle Controls and Displays — The Omnitrans demonstration vehicles are the first hybrid buses to use ISER's advanced APU and energy management control architecture, which relies on several new components to optimize the performance of the APU and maximize the overall energy efficiency of the vehicle. A customized electronic engine controller varies the engine speed in accordance with vehicle power requirements. The "state of voltage" of the battery pack is factored into the determination of vehicle power needs by continuously monitoring each individual battery and feeding this information to a central processor. When state of voltage is low, additional power is drawn from the APU to make up for the difference and to gradually recharge the batteries. When state of voltage is high, the APU is commanded to generate less power. If stage of voltage remains high and vehicle power requirements are low for an extended period, the control system will turn the engine-generator combination off completely, and the vehicle will operate on battery power alone until APU power is once again required. When stuck in traffic in a heavily congested urban area, the Omnitrans buses will produce zero emissions and will operate extremely quietly.

Benefits of the ThunderVolt Hybrid-Electric Drive System

As mentioned earlier in this paper, series hybrid-electric drive systems are postulated to offer a variety of environmental, performance, and economic benefits. The design of the ThunderVolt TB40H drive system was selected to maximize these benefits. Following is a summary of specific benefits that the Omnitrans demonstration program is hoped to validate.

Environmental Benefits — As discussed in the preceding section, the Ford V-10 engine used in the Omnitrans hybrid buses, when used in normal operation, produces very low emissions. In the ThunderVolt hybrid configuration, these emissions reductions are expected to be even greater, since the hybrid drive system enables optimal use of the engine. The hybrid system, by relying on the battery pack to supply surge power, will minimize cycling of the engine. The engine will also be turned off when its power is not required. In earlier hybrid vehicles integrated by ISER, these factors have been shown to reduce emissions significantly, even as compared with other alternative fueled vehicles. Table 3 summarizes the results of emissions tests performed by ISER on one of four propane fueled 30-foot hybrid-electric buses delivered to the City of Los Angeles in 1999. As indicated, the hybrid-electric propane bus produced up to 89% less NOx, 93% less carbon monoxide, and 99% less hydrocarbons than an identical 30-foot bus equipped with a conventional propane drive system. These data show that a hybrid-electric system can take a fuel that is already fairly clean, and make its use even cleaner. If similar percent reductions are achieved with the low emission Ford engine used in the Omnitrans buses, these will be among the cleanest burning, low emission 40-foot transit buses in the world.

Performance Benefits — The Omnitrans buses are projected to show several key performance benefits that have been exhibited by all vehicles using the ThunderVolt hybrid-electric drive system, along with some new benefits unique to the TB40H configuration. As mentioned earlier in this paper, use of AC induction motors provides fast, smooth acceleration. The vehicle produces less noise and vibrations than a conventional bus because it uses a smaller engine which does less cycling, and because diesel engines are noisier than gasoline engines. The Omnitrans hybrid-electric buses are simple to operate because there is no shifting, and control of the APU is fully automatic. The vehicle's operation has been likened to that of a "20 ton golf cart."

However, the single greatest performance benefit of hybrid-electric buses is increased energy efficiency. For buses that operate in local areas with large amounts of stop and go driving, regenerative braking is a major contributor to energy efficiency.

The hybrid buses deployed in Los Angeles by ISER in 1999 and 2000 have shown that they can recapture as much as 25% of their energy through regenerative braking. Operating the engine closer to its most efficient speed is another factor that enhances efficiency, as well as the ability to turn the engine off completely when it is not needed. Figure 4 illustrates, in a general way, the potential energy efficiency benefits of hybrid vehicles, as estimated by ISER during an early feasibility study in 1996.[4] As indicated, a typical locally driven heavy duty vehicle can be expected to produce about 56% more energy than it actually requires to meet its operating requirements. Hybrid vehicles are projected to reduce the amount of wasted energy inefficiency by as much as 64%, bringing the energy consumption of such vehicles to within 20% of their ideal energy usage.

This is actually a conservative analysis, as it relates only to engine and driveline-related losses, and does not consider losses due to operation of accessories such as heating and air conditioning. A more recent study coordinated by the U.S. Department of Energy suggests that in a 40-foot bus application, hybrid drive systems could reduce total energy consumption by as much as 61%, while increasing fuel economy from 3.2 miles per gallon to more than 8 mpg.[5] These are substantially more ambitious targets than those established for the Omnitrans demonstration vehicles, which are expected to yield an average fuel economy of 5 to 6 mpg. However, even if only these lower targets are met, the economic implications for bus fleet operators and the public as a whole could be substantial, as discussed below.

Economic Benefits — The energy efficiency benefits just described can translate into significant economic benefits for operators of hybrid vehicles. A typical 40-foot transit bus travels approximately 60,000 miles per year. With an average fuel economy of 3.2 mpg, such a vehicle can be expected to consume 18,750 gallons of diesel fuel each year. At a price of $1.70 per gallon, this represents an annual fuel cost of nearly $32,000. If a hybrid vehicle can achieve 5 mpg, fuel consumption would be reduced to 12,000 gallons/year, for a net savings of 6,750 gallons/year, or $11,475 in fuel cost savings at the $1.70/gallon price level. At 6 mpg, the annual cost savings would increase to nearly $15,000/year. If fuel prices double over the next ten years (or if prices prevalent in Europe today are used as the standard), annual savings at the 6 mpg. level would increase to $30,000/year.

Engine and transmission maintenance are other areas where hybrid vehicles offer potential economic benefits. A typical large diesel bus requires at least one major engine overhaul over the course of its 12-year life, at a cost of about $20,000. The Ford engine in the Omnitrans hybrid drive system can be completely replaced for less than half this amount. On a day-to-day basis, the gasoline engine, operated near its optimal point, should require less maintenance than the much larger diesel engines in typical 40-foot buses. The hybrid system also eliminates the transmission entirely, which is another major maintenance item on conventional buses. Hybrid vehicles also reduce the cost of brake maintenance, as regenerative braking significantly reduces the wear on brake linings. A 50-75% reduction in brake maintenance costs could save $1,000 to $2,000 a year for a typical large transit bus.

In hybrid vehicles, these cost savings are partially offset by the cost of replacing battery packs. However, the TB40H uses inexpensive lead-acid batteries that can be replaced for a total cost of about $7,500, including the cost of labor to replace and rewire the batteries. With an expected battery life of 2-3 years, the effective annual cost of battery replacement is $2,500 to $3,750 — a small fraction of the savings accrued from fuel savings alone. Early demonstration vehicles such as the Omnitrans buses can also be expected to suffer from reliability and maintenance problems due to the newness of the technology. However, as hybrid technology matures and mass produced, high quality hybrid components become available, the inherently high reliability of electric motors and solid state electronics should minimize the cost of maintaining the core elements of such systems. All factors considered, the life-cycle operating cost of a hybrid-electric 40-foot bus should be at least $100,000 less than the cost of operating a conventional bus, and potentially as much as $200,000 to $300,000 less, depending on the key variables of fuel economy and fuel costs.

In the near term, the benefits of hybrid-electric vehicles can be secured only at the cost of paying significantly higher acquisition costs. Depending on the bus model, drive system, and specific options selected, the price of a 40-foot hybrid-electric bus today can be expected to start at about $400,000 and run to more than $500,000. This compares with prices at or less than $300,000 for conventional diesel buses and $350,000 for CNG buses. However, as hybrid-electric drive system components are produced in larger quantities, their costs are expected to decline significantly. Additional cost reductions will occur as major bus manufacturers reorganize their production processes to facilitate integration of hybrid-electric drive systems. In the long term, there is no inherent reason for hybrid-electric buses to remain any more costly than equivalent CNG buses today. Once such vehicles become available at more competitive prices, the projected environmental, performance, and economic benefits of hybrid-electric transit buses can be expected to make them an attractive option for many bus fleet operators.

ENDNOTES

1. U.S. Department of Energy, *Technology Roadmap for the 21st Century Truck Program,* Report No. 21CT-001, December 2000.
2. Northeast Advanced Vehicle Consortium and M.J. Bradley & Associates, Inc., *Hybrid-Electric Drive Heavy Duty Vehicle Testing Project, Final Emissions Testing Report,* prepared under Agreement No. NAVC1098-PG009837.
3. Ibid.
4. ISE Research Corp., *Medium and Heavy Duty Hybrid Truck Feasibility Study,* prepared for South Coast Air Quality Management District under Contract No. AB2766/C95002, May 1996.
5. See reference #1.