

Hydrogen Fueled Hybrid Electric Transit Buses

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ABSTRACT:

This paper describes three hydrogen fueled city transit bus designs which use hybrid electric drive. Experience with the first hybrid electric fuel cell bus, and the prototype HHICE (Hydrogen fueled Hybrid Internal Combustion Engine) bus is described, and early experience with the new generation hybrid electric fuel cell buses is presented.

The HHICE bus has been subjected to winter and summer testing, respectively in Winnipeg, Manitoba and in the Palm Springs area. With the exception of tours such as for winter testing it has been in service with SunLine Transit in the Coachella Valley. The new hybrid electric fuel cell buses were delivered in late 2005 and have entered service early in 2006. The HHICE bus has accumulated over 25,000 miles, the four fuel cell buses in aggregate are at similar mileage.

Keywords: hydrogen, hybrid electric, fuel cell bus, HHICE

1. Introduction

The hybrid electric drive, incorporating regenerative braking which saves energy and brake wear, is well suited to the stop and go service of transit buses. ISE Corporation has developed hybrid electric drive buses for transit service fueled (at the choice of the facility) with diesel, gasoline, LPG, or hydrogen. The ISE gasoline fueled hybrid electric is certified in California as an alternative fueled bus, and over a hundred have been delivered and are operating in California.

Transit buses are recognized as a premier platform for demonstration of hydrogen fueled powerplant technology, in part due to the exposure to many riders while operating up to sixteen hours per day, and in part due to the important role of the clean vehicle technology in the city center. Fuel cell engines tend to be expensive, heavy and bulky. Hybrid electric drive technology allows use of a smaller, less expensive fuel cell and using battery (or ultra-capacitor sourced power to satisfy the transient acceleration and hill climb needs of the bus. Further, hybrid electric drive system architecture allows recapture of braking energy and hence allows higher efficiency, of critical importance for vehicles operating on hydrogen. Finally, the roof of the bus allows storage of massive amounts of hydrogen, thus providing the range demands – often 400-500km – of transit agencies.

Hydrogen as a fuel for heavy vehicles has been a focal point of ISE technology development for nearly ten years. As will be described in more detail, the first hybrid electric fuel cell bus, the Thor/ISE bus, was in revenue service at SunLine Transit (Palm Springs area) and at AC Transit (Oakland – Berkeley area) during 2002-2004. Fuel consumption was less than 50% of that of conventional buses, and the bus range was in excess of 300 km.

Unfortunately, the price of fuel cells only increased. Looking to the internal combustion engine as an interim “surrogate fuel cell”, ISE developed the prototype HHICE (Hydrogen fueled Hybrid Internal Combustion Engine) bus. This bus was introduced into service late in 2004 and likewise has range in excess of 300 km, with in service km/kg near double that of conventional natural gas fueled buses. The HHICE bus uses a turbocharged Ford V10 engine and ultra-capacitor energy storage. The HHICE bus is also (like the fuel cell bus) much quieter and offers better performance than conventional buses. Recently a new design bus which uses a 120 kW fuel cell and hybrid electric drive incorporating advanced technology batteries integrated into a modern Van Hool chassis has been introduced into service by AC Transit and by SunLine Corporation.

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The body of this paper describes these buses in more detail, including presenting the results of test and demonstration programs.

These modern hydrogen fueled buses are very attractive to transit properties, as riders are pleased with the quiet and clean ride. The HHICE bus is particularly attractive, as it is only marginally more expensive than hybrid electrics. Where hydrogen is supplied at prices at or below US\$4/kg, this bus is near price competitive with liquid fueled or natural gas fueled buses, while offering the quiet, clean and safety advantages of hybrid electric hydrogen fueled vehicles.

2. The Thor-ISE Hybrid Electric Fuel Cell Bus

The thirty foot long „Low Rider“ bus platform (manufactured by El Dorado, a Division of Thor Industries) is identical to that used for the city DASH buses in Los Angeles and other major cities. In this early bus hydrogen was stored at up to 250 bar (3600 psi) in Type 4 (composite plastic) tanks mounted above the bus. The Siemens „Elfa“ drive train uses electricity sourced from a 60 kW fuel cell by UTC Fuel Cells and stored in lead-acid batteries. The UTC PEM fuel cell system design operates at ambient pressure. This not only eliminates the need for a compressor, it also eliminates the need to develop power to run a compressor, thereby increasing the efficiency of the fuel cell system. The fuel cell system has efficiency of over 50% for most of the operating range.

This Thor/ISE bus (completed in February 2002) was used in demonstration programs and revenue service at SunLine Transit, the Los Angeles Metropolitan Transit District, and then served over a year of operation in revenue service with AC Transit (Oakland, Berkeley CA).



Figure 1 The Thor/ISE fuel cell bus in Washington.

Results included:

- The bus initially operated in simulated service, shadowing a bus in service. This was more successful than expected, and thus the bus was put into revenue service earlier than originally planned, on November 6, 2002.
- The very low noise levels were found to be attractive to the driver as well as the riders.
- The fuel cell bus energy use was found to be well under that of similar size conventional drive CNG powered conventional bus, with SunLine service averaging 16 km/kg hydrogen, service in hilly Berkeley averaged about 11 km/kg.
- The bus was shown to operate in service successfully in the high temperatures of the Palm Desert summer environment. The fuel cell cooling system is oversized such

that even at 45°C outdoor temperature the radiator cooling fans operate only intermittently.

- In the SunLine demonstration the bus traveled 160-200 km per day. (The range of the bus is much more, an estimated 300-400 km.)
- Over the several demonstrations, the bus was available over 75% of the time. The MBTF was better than this would suggest, as any problem with the fuel cell system generally resulted in a week of down time due to UTC travel.
- Passenger reaction was favorable, the “regulars” like the smooth quiet ride, One enthusiast parked his car and rode the bus for two laps just to “ride the future”, and there was a virtual absence of concern about the nature of the fuel, perhaps partly because this community has had natural gas fueled bus service for nearly a decade.

3. The HHICE (Hydrogen fueled Hybrid Electric Internal Combustion Engine) Bus

To proceed with deployment of hydrogen fueled buses, ISE has built a prototype hydrogen fueled hybrid electric bus² which uses an internal combustion engine, rather than a fuel cell, to maintain battery charge. It is believed the Hybrid electric Hydrogen Internal Combustion Engine (HHICE) bus has both advantages and disadvantages as compared to the fuel cell buses. In brief summary:

1. The internal combustion engine as used for gasoline and natural gas fueled vehicles provides a store of parts and technology readily available for engine development. These engine parts are in mass production and thus have low cost. Thus the cost of hydrogen ICE engines is now below two percent of the present cost of the equivalent fuel cell.
2. Engine reliability is critical – it is expected that the hydrogen ICE will have reliability similar or better than that of the gasoline fueled internal combustion engine.

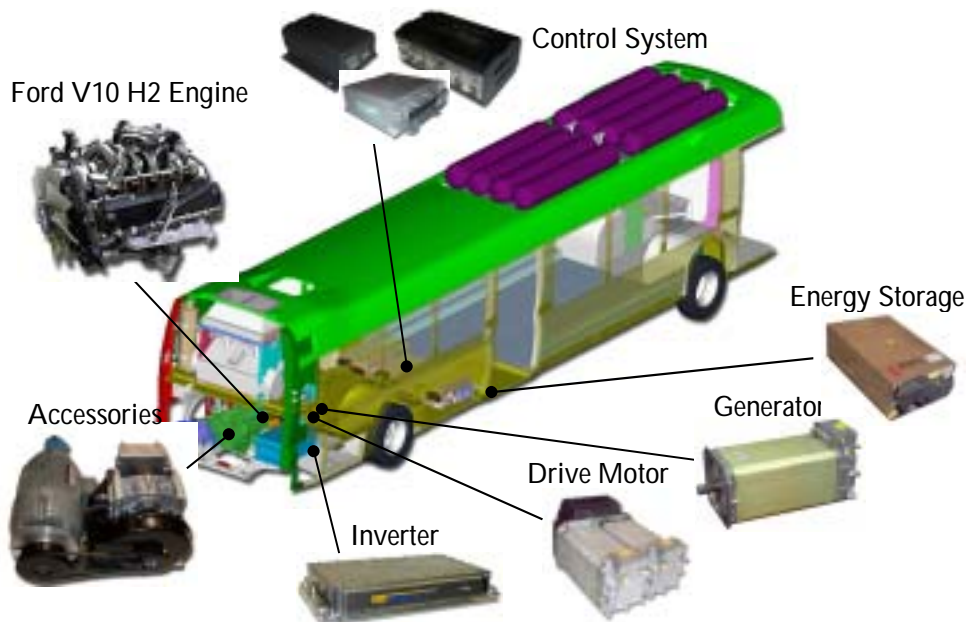


Figure 2. Illustrating the components of the HHICE bus.

² The HHICE bus prototype has been supported in part by the Ford Motor Company, the California Energy Commission, the South Coast Air Quality Management District, Natural Resources Canada, the USDOT Federal Transit Administration and SunLine Transit.

3. Fuel cell repair is done by specialized technicians and engineers, whereas the ICE technology is well known by thousands of automotive mechanics.
4. The HICE has higher fuel consumption and increased noise levels – but the noise levels are much less than common for natural gas or diesel conventional drive vehicles.. (For the prototype HHICE bus the range is 300-400 km using 58 kg hydrogen storage at 350 bar.)
5. The HHICE bus is capable of operation at very low temperatures. Cold weather testing in the Winnipeg winter, completed March in 2005, indicated that the HHICE bus is fully capable of operation in winter temperatures below -25°C .
6. The engine is capable of higher specific power than a fuel cell, hence it can be expected that the HHICE bus will have improved highway and extended hill climb performance as compared to an otherwise equivalent fuel cell bus.

Figure 2 illustrates the components of the HHICE bus. Basically, the HHICE bus is a fuel cell bus with the FC power-plant replaced with the engine-generator.³ The prototype HHICE uses a hydrogen fueled Ford turbocharged V10 driving a liquid cooled Siemens generator rated at 150 kW continuous duty. This bus uses electrical energy storage in ultra-capacitors, an improvement over the lead acid batteries used in the Thor/ISE fuel cell bus offering higher efficiency and longer life. But for software changes, the Siemens Elfa drive train is identical to that used in the Thor/ISE fuel cell bus and also being used in other gasoline and diesel fueled hybrid electric buses presently being supplied by ISE.

The now well publicized efficiency advantages of the hybrid electric drive are even more important with hydrogen fueled vehicles. This is true with cars as well as buses. The HHICE bus, similar to Ford's new hybrid electric hydrogen cars, combine high performance with high efficiency – benefits of keen interest to drivers and owners. Likely they will find a ready market as the Hydrogen Highway infrastructure becomes available with fuel at competitive prices.

3.1 The Drive System

The Siemens Elfa drive system⁴ (also used in the Thor/ISE fuel cell bus and the advanced technology fuel cell buses) uses dual 75 kW motors mated through a gearbox, which is mated to the driving axle. In the Thor/ISE FC bus, motor drive electronics, inverters and inductors, are mounted in trays at both sides above and behind the motors. In the HHICE bus the inverters are mounted on the curb side of the engine cradle.

Electrical energy storage, in the form of ultra-capacitors in the HHICE bus, is used to obtain range improvement through regenerative braking. Further, the ultra-caps support instantaneous power demand not being produced by the HICE

generator, allowing improved acceleration and hill climb capabilities. ISE has done extensive testing and operation of the hybrid electric drive with energy storage in an ultra-capacitor system in similar gasoline fueled buses with hybrid electric drive.



Figure 3 – HHICE Bus in Winter Service

³ Or, the HHICE bus is even more similar to the ISE hybrid electric gasoline fueled buses, which also use a Ford 6.8 liter V10 mounted in a cradle assembly including the generator, inverters and drive motors. (See later discussion.)

⁴ The Siemens Elfa system has been utilized in Europe in over 300 hybrid buses and has accumulated millions of miles. It has also been through a 500,000 mile durability test on a major automobile manufacturer's test track including shock, vibration, salt spray, EMI/EMC and other demanding tests. The ISE hybrid electric buses represent the first implementations of the system in the United States.

3.2 HHICE Bus Operations

The prototype HHICE bus using the Ford V10 engine and Siemens Elfa drive-train in a New Flyer chassis was delivered to SunLine Transit Nov. 30, 2004. Following a public “unveiling” Dec. 16, the bus immediately went into revenue service.

Having accumulated over 3000 miles in three weeks of revenue service in the Palm Springs area, the bus was shipped to Winnipeg, Manitoba on January 10, 2005 for winter testing. The winter testing program consisted of revenue service (by Winnipeg Transit doing their Route 19) on the streets of Winnipeg during February-March, 2005 at sub-freezing temperatures (ranging at times to -27°C).



Figure 4 – Winter Refueling with electrolytic hydrogen

The winter testing program was done in Manitoba as a joint program between ISE, SunLine Transit, the Province of Manitoba, Winnipeg Transit, the University of Manitoba Vehicle Technology Centre, and Winnipeg’s Red River College. Manitoba’s winter climate, with temperatures commonly dipping to -40°C during the night, is an ideal location for seeing if vehicles can withstand the winter conditions. Winnipeg Transit has indoors storage for its diesel vehicles, and the HHICE bus was likewise stored overnight at a temperature of approximately 15°C , but then was taken to the refueling station⁵ and refueled at morning outside temperatures. It then served on the route from the Notre Dame campus of Red River College to downtown for a half day, limited by fuel availability.

It is estimated that over 1000 passengers rode the bus during the winter testing. It operated well, and was warm despite the lack of the usual diesel fueled auxiliary heater. The University of Manitoba used a questionnaire, which inquired as to the riders impressions of hydrogen fuel and of the bus, to study the passenger reaction. The HHICE bus returned to regular service at SunLine in April 2005 and has accumulated over 25,000 miles in revenue service.



Figure 5 – The HHICE bus fueled by wind generated hydrogen (North Palm Springs)

⁵ Which featured a Stuart Energy electrolyser, storage to 6000 psi, and a Kraus dispenser.

4. New and Improved Hybrid Electric Fuel Cell Buses

Vastly improved hybrid electric fuel cell buses, incorporating the high temperature “Zebra” batteries⁶ and 120 kW UTC fuel cells in a VanHool chassis (below), and have entered service at AC Transit (Oakland, CA, three buses) and at SunLine Transit.

These buses feature 48 kg hydrogen stored at 350 bar and have range in excess of 500 km. The 120 kW fuel cell combined with the Zebra batteries allow freeway cruise at over 100 km/hr and extended hill climb capability.

The SunLine bus has accumulated over 13,000 miles in revenue service over the first four months of service, the AC Transit buses were officially entered into service in early March and have accumulated in aggregate a similar number of miles.

Earth day (22 April, 2005) the President toured one of these AC Transit buses at the Fuel Cell Partnership Facility – and immediately appeared as an advocate of fuel cell buses!



Figure 6 – The Prototype New Technology Hybrid Electric FCB at the UN World Environment Day, San Francisco, June 2, 2005

5. The Vision: Vehicle Fuel from “Home Grown”, Renewably Sourced Hydrogen

Clearly, hydrogen fueled buses are available and they have operational advantages for the user as well as for the surrounding community. Further, considering health and environmental aspects, the HHICE bus is cost competitive with not only advanced technology buses but with the older diesel technology. The remaining concern with hydrogen fueled

⁶ Sodium chloride-nickel

Figure 8 - Wind generation of hydrogen fuel offers the possibility of fully achieving the emissions and economic security advantages made possible with the introduction of hydrogen as an alternative to imported hydrocarbons.

vehicles stems from the hydrocarbon source of much of the hydrogen now used. Thus the added value of renewable sourced hydrogen is clear, it both cleans the air of toxic chemicals and reduces the release of global warming gases.



As shown in Figure 5, where the HHICE bus is positioned for fueling at the wind farm, ISE and partners pioneered in installing wind generated hydrogen capability, located about 16 km from the SunLine facility. Wind generated - carbon free hydrogen is available for refueling the HHICE and the new fuel cell buses.

Projections suggest that large utility sized wind turbines combined with electrolysis and pipeline delivery from suitable wind sites will be competitive in future years with fuel now imported from afar.

6. Conclusions:

Initial operational experience with the hybrid electric fuel cell and HHICE buses is encouraging in several respects:

1. The hybrid electric hydrogen technology offers high efficiency and quiet, clean transport.
2. Passenger acceptance has made it clear that rider-ship can be substantially increased by offering a quiet and clean product. There has been no indication of any "fear factor" related to hydrogen as fuel, once a transit firm has the bus in service the customers easily accept it as being safe transport.
3. The new class of hybrid electric fuel cell buses features improved performance and range as well as carrying capacity, combined with multi-year warranty.
4. There is a clear choice of hydrogen vehicles, both the HHICE piston engine and the fuel cell buses are available and have attractive advantages.
5. As competitively priced hydrogen buses become available in the next couple years, attention may be focused on the need for making fuel hydrogen conveniently available at competitively attractive prices and from renewable resources. Wind sourced hydrogen is one of several sustainable approaches.