

ZEV and Near-ZEV Heavy Duty Hydrogen Hybrid Electrics

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Abstract

The Thor/ISE hybrid-electric drive fuel cell bus has completed a “Development and Demonstration Phase”, including revenue service, at SunLine Transit in Palm Desert, CA. This in-service experience is very encouraging, as the availability has been in excess of 70% and the very efficient fuel cell hybrid electric drive configuration has been shown to improve fuel milage to in excess of 11 miles/eq. gallon diesel. Succeeding demonstrations are following, first at Chula Vista Transit (near San Diego).

Unfortunately, the price and availability of fuel cells does not support commercial introduction of large numbers of fuel cell buses at this time. However, the hydrogen fueled internal combustion engine can be combined with hybrid electric drive (the HHICE bus) to make a very desirable alternative to the fuel cell powered bus. HHICE likely will be the hydrogen bus most suitable for extreme cold climates, and for the foreseeable future it will most certainly have a price advantage over the FC bus. This presentation includes description of the unique features of hydrogen as used in internal combustion engines, discussion of the exhaust emission properties and possibilities for the use of catalytic processes to eliminate criteria gas emissions.

Keywords: hybrid electric, bus, hydrogen, ICE

Introduction

Urban transit buses have become a focal point for introduction of hydrogen fueled vehicle technologies for several reasons:

- They operate in a city environment which is most in need of clean vehicles,
- Transit buses are manufactured in limited numbers to meet high standards, including 12 year service life, at a unit cost ten times that of automotive vehicles,
- Being wholly public sector funded, they are uniquely accessible to public agencies interested in test and demonstration of clean technologies.

In January 2000 the California Air Resources Board committed to an urban fuel cell bus technology program, at which time only one North American manufacturer appeared capable of supplying the vehicles. In response, Thor Industries, the largest mid-sized bus producer in the United States, in conjunction with ISE Research, committed over \$1M in seed capital to developing a hybrid electric fuel cell bus.¹ The new low-floor Eldorado National EZ Rider 2 was chosen as the vehicle chassis.

¹ The Sacramento Municipal Utility District, Calstart/Westart, the US Department of Transportation and the South Coast Air Quality Management District have contributed funding in support of this Thor and ISE Research development program.

Hybrid electric vehicles are well suited to “stop-and-go” city operation. The hybrid-electric design allows considerable increase in efficiency (compared to conventional drive vehicles) due to energy recovery by use of regenerative braking. As the average speed of a city transit bus is seldom over 25 mph the average power demand is comparatively small, typically some 20-40 kW. While the traction motors in this bus may intermittently develop upwards of 150 kW for initial acceleration or hill climb, the average demand is but a small fraction of this peak. Hence a much smaller engine running steadily, in combination with a powerful electric drive with battery storage, can provide motive power with good performance.

The capability of using a *small* fuel cell engine is very attractive, as it can reduce the fuel cell cost.

Further, the hybrid-electric vehicle concept allows energy recovery by regenerative braking action, which reduces brake wear and offers improved mileage and emissions performance. As hydrogen fueled vehicles are “range challenged“, this allows an important performance advantage by reducing the amount of hydrogen storage required for a given range. The reduction of fuel cost is a notable related benefit.

1. Description of the Thor/ISE Fuel Cell Bus

The thirty foot long “EZ 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. Hydrogen is 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. The fuel cell system has efficiency of over 50% for most of the operating range.

The component arrangement is designed for easy service, with full accessibility to drive motors, power electronics and auxiliaries. For example, the entire fuel cell system can be removed in an hour, with aid of a fork lift truck.



Figure 1 The Thor/ISE fuel cell bus in a recent demonstration.

With the expected high charge/discharge rate, effective battery cooling is essential. Air from the passenger compartment (cooled by air conditioning during the summer) is ducted around the batteries to provide this cooling.

Figure 2. Showing the fuel cell at top, power electronics at bottom. Inverters and inductors for drive motor power conversion, right and left of the cables in the bottom compartment, can also be accessed from the bus sides.



2. Revenue Service Demonstration of the Thor Fuel Cell Bus

The Thor/ISE bus completed (in February 2003) a six month Development and Demonstration Program conducted by SunLine Transit.²

- 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 a similar CNG powered conventional bus, with average mileage over ten miles per equivalent gasoline gallon as compared to under five for the conventional CNG fueled bus.
- The bus was shown to operate 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.
- 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 only concession to the prototype nature of the bus is that an ISE field engineer rode on board. Remote monitoring, by wireless transmission from the bus to the internet, allows bus parameters to be remotely monitored in real time at factory locations such as in San Diego and at the fuel cell factory in Connecticut.
- In the SunLine demonstration the bus traveled 100- 140 miles per day. (The range of the bus is much more, an estimated 250 miles.)

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.

In April 2003 the bus was relocated to Chula Vista, a small city south of San Diego, for further demonstrations.

² The FC bus and its demonstration are described in more detail in a companion paper by J. Cannon.

3. The Future of Hydrogen Buses – Fuel Cell and HHICE

In consequence of this successful program, ISE Research presently has orders for five more hybrid electric fuel cell buses. However, delays in fuel cell programs and high costs limit the viability of the fuel cell approach at this time.

To proceed with deployment of hydrogen fueled buses, ISE Research is designing a hydrogen fueled hybrid electric bus which will use 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 will have both advantages and disadvantages as compared to the fuel cell bus. 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 will quickly drop to one percent of the present cost of the equivalent fuel cell. Based on present experience, it appears the HICE approach will have a significant cost advantage over fuel cells for at least the next five years.
2. Engine reliability is critical – it is expected that the hydrogen ICE will demonstrate reliability similar or better than that of the modern internal combustion engine.
3. Fuel cell repair is done by specialized technicians and engineers, the ICE technology is well known by thousands of automotive mechanics.
4. The HICE has about 30% higher fuel consumption and increased noise levels. (For a hybrid electric bus using the HICE, we expect approximately 250 mile range using hydrogen storage at 5000 psi.)
5. The HHICE bus will be capable of operation and storage at very low temperatures. Thus some of the funding for the HHICE bus is from Canada, and cold weather testing is planned in Winnipeg.
6. The engine has a higher specific power than the fuel cell, hence the HHICE bus will have improved highway and extended hill climb performance.

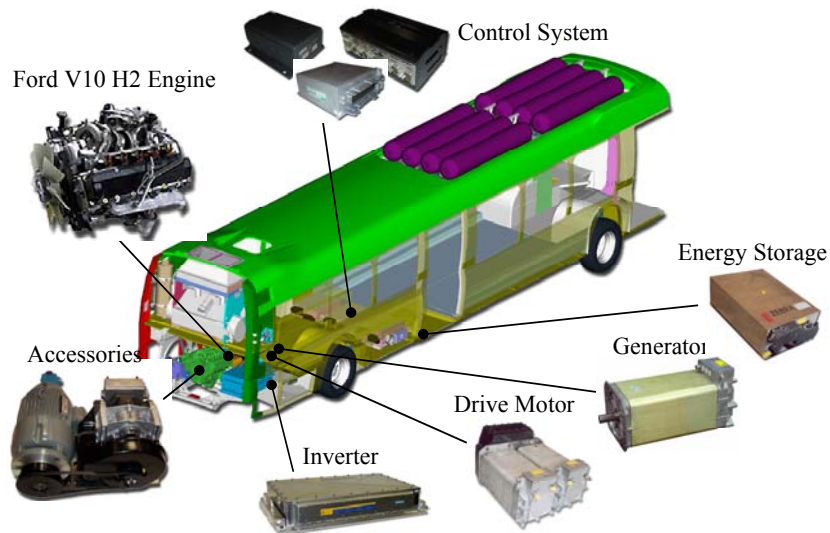


Figure 3. Illustrating the components of the HHICE bus.

Figure 3 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. The prototype HHICE will use the Ford turbocharged V10 driving a 150 kW Siemens generator. The bus will use the high temperature “Zebra” batteries, an improvement over the lead acid batteries used in the Thor/ISE fuel cell bus. The Siemens Elfa drive train will be virtually identical to that used in the fuel cell bus and also being used in other gasoline and diesel fueled hybrid electric buses presently being supplied by ISE.

It is of interest that Ford Motor Company, with the presentation of the Model U hydrogen fueled hybrid electric SUV at the 2003 Detroit Auto Show and at its Centennial celebration, has indicated its appreciation of the combination of the characteristics of the hydrogen engine with hybrid electric drive. The now well publicized efficiency advantages of the hybrid electric drive are even more important with hydrogen fueled vehicles.

3.1 Characteristics of Hydrogen Fueled Internal Combustion Engines

Automotive piston engines have been successfully converted to operate with hydrogen fuel, using some special precautions and taking advantage of some of the special characteristics of hydrogen:

- Hydrogen combustion properties dictate that it be introduced in a very dilute form. Commonly, hydrogen engines are run extremely lean, at half of stoichiometric fuel-air ratio or less.
- Due to the lean mixture, super- or turbo-charging is used to regain lost power due to the small % of fuel.
- The lean mixture reduces combustion temperature and increases engine efficiency.
- Fuel induction must be done very close to the intake valve, and timed to avoid any back-flash from the combustion chamber. The design must assure that combustible mixtures exist only in the combustion chamber!
- No carbon in the fuel results in virtually no CO or HC in the exhaust – and very little CO₂. NO_x is present in small amounts at 0.4 of stoichiometric, and in increasing amounts for more rich mixtures.

Comparing the fuel cell used in the Thor/ISE bus with a hydrogen fueled Ford Triton V10 engine:

	<u>Fuel Cell Engine</u>	<u>Ford 6.8 L “fuel cell surrogate”</u>
Power:	rated 60 kW	140 kW shaft, est. 120 kW electric
Size	30x32x60” lg	32x37x57”lg – including generator
Weight	800 pounds	640 lb. + 270 lb generator
Peak efficiency	54% @ 15 kW, 49% @ 60 kW	estimated 35% elect.@ 120 kW
Bus range	240 mi (Thor/ISE, 3600 psi)	estimated 250 mi (HHICE equiv., 5000 psi)

Several investigators have added catalytic conversion exhaust gas treatment to reduce the engine emissions to nil, hence offering ZEV advantages at competitive cost.³ It seems clear that with a concentration of effort of even a small fraction of that presently devoted to either fuel cell development or to the improvement of liquid fueled ICEs one can expect there will be further revolutionary improvements in HICE technology.

³ Most recently, J. W. Heffel, “NO_x emission and performance data for a hydrogen fueled internal combustion engine at 1500 rpm using exhaust gas recirculation”, *International Journal of Hydrogen Energy* 28, 901-908 (August, 2003)

3.2 The Drive System

The Siemens Elfa drive system⁴ (also used in the Thor/ISE fuel cell bus) 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.

Batteries are used to obtain range improvement through regenerative braking. Further, the batteries support power demand in excess of the 60kW available from the fuel cell or the 120 kW from the HICE generator, allowing improved acceleration and hill climb capabilities. In a similar bus with hybrid electric drive combined with the Ford Triton V10 we are presently demonstrating operation of the hybrid electric drive with energy storage in an ultracapacitor system.

3.3 HHICE Bus Plans

A prototype HHICE bus using the Ford V10 engine and Siemens Elfa drive-train in a New Flyer chassis will be in test this winter. Program sponsors include SunLine Transit, the SCAQMD, CARB, CEC, Ford Power Products, the Province of Manitoba and Natural Resources Canada.. There are indications that this hydrogen bus may be ordered by other groups as well.

4.0 Gasoline Hybrid and the HHICE - a Bridge to Clean Public Transport

Figure 4 suggests the use of gasoline fueled hybrid electric buses and the HHICE buses as a bridge to lead to a fuel cell bus future.



Figure 4. The Gasoline Hybrid and the HHICE as a Bridge to the Fuel Cell Bus

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. This bus represents the first implementation of the system in a bus in the United States.

ISE Research and New Flyer are in the process of obtaining Altoona certification of a gasoline fueled hybrid electric bus which uses the same chassis and drive train as the HHICE bus. This bus has been developed in a cooperative program with Omnitrans and the SCAQMD, and has shown extremely low emissions in CARB chassis dynamometer testing. The use of these buses will reduce NOx emissions by a factor of ten compared to advanced natural gas or diesel hybrid electric buses, and virtually eliminate the emission of particulates. The City of Long Beach will be a pioneer in implementing a fleet of the first twenty-seven of these buses. It is expected that hundreds of these buses will be supplied to California transit properties in the coming years.

The HHICE prototype bus now in development is a “sister ship”, similar in many respects to the gasoline fueled hybrid electric bus, but for the substitution of the hydrogen fuel for gasoline and the turbocharged hydrogen engine for the more conventional liquid fueled engine.

The following table compares emissions from conventional and hybrid buses.

DRIVE / EMISSIONS	NOx (g/mi) ⁵	PM (g/mi)	CO ₂ (g/mi)	Fuel Consmt.	Average
Conventional Diesel	30, 11	0.24, 0.13	2200	4.4 mpg ⁶	Poor
Conventional CNG	15, 10	0.02, 0.031	2500	3.3 mpgde	Poor
Hybrid Diesel	13-16, 15	0-0.03, 0.07	2500	3.8 – 6 mpg ⁶	Good
Hybrid CNG	2 (?)	0.01(?)	2100	3.9 mpgde	Very Good
Hybrid Gasoline	0.5	0	2100	5.2 mpgde	Very Good
Hybrid Hydrogen ICE	0.5(?)	0	0	7 mpgde (?)	Excellent
Conventional Fuel Cell	0	0	0	8 mpgde(?)	Excellent
Hybrid Drive Fuel Cell	0	0	0	10 mpgde	Excellent

Combining the hybrid drive with today’s very clean alternative bus fuels (CNG or gasoline) allows attaining the “very good” attributes of a factor of ten reduction in NOx and near zero particulates. Although this makes a very attractive package from the criteria emissions and the health aspects, only with the use of hydrogen as fuel does the ZEV vision become fully accessible.

It is very important to have, in the near future, commercially accessible production of hydrogen buses and to introduce these buses in quantities into revenue service with the transit fleets. Only with such implementation and with the use of increasing quantities of hydrogen as fuel will the hydrogen fuel infrastructure development progress as needed to be available for the fuel cell buses expected in coming years.

A spreadsheet model has been used to investigate the effects of such a bridging scenario on total transit bus emissions in the State of California. The model results, as presented in the following two plots, based on an assumed replacement of 1/12 of the present fleet of buses each year, plus adding 3% to account for growth of the transit property fleets year by year. Hence new orders equal 1/12 plus 3%, or 11.33% of the present bus fleet year by year. The California new orders for successive years are split between conventional diesel buses, natural gas fueled buses (shown in Figure 5 as “alt fuel”), and the gasoline, hydrogen and fuel cell hybrid electric buses.

⁵ Emissions and fuel consumption data are from CARB dynamometer testing as stated in the CARB Staff Report released Sept. 6, 2002, and from CBD cycle by Brodrick et. al. SAE 2002-01-3117. Author’s estimates are marked with (?).

⁶ The diesel number (4.4) refers to NABI buses, the 3.8 number refers to data from Orion diesel hybrid buses. It is noted in the paper that “the fuel economy of the Orion VI hybrid buses tested in this study was lower than anticipated for comparable Orion VI vehicles” and possible explanations were offered. Early on the road test experience with the diesel hybrid Nova bus recently delivered to New Jersey Transit indicated mileage in excess of 6 mpg.

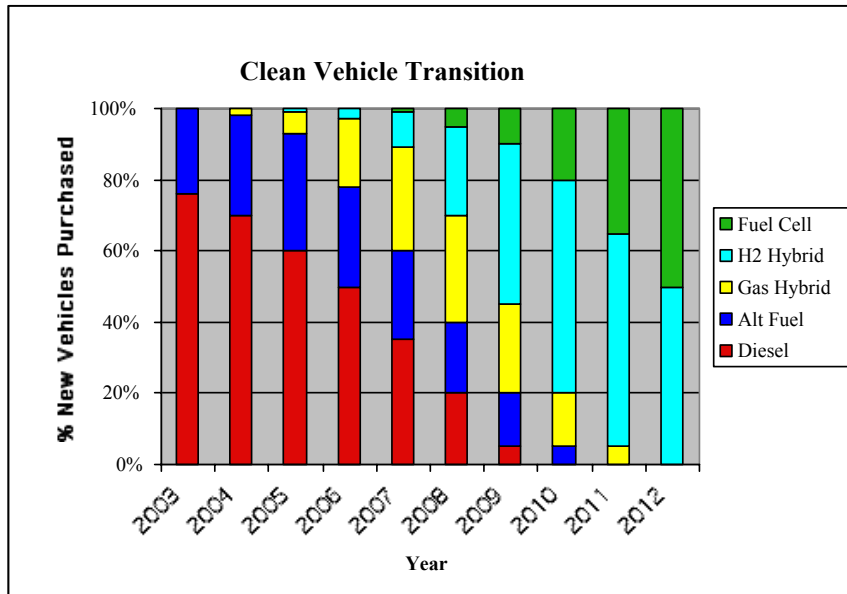


Figure 5. The assumed bus replacement scenario, whereby (for example) in the year 2005 diesel, natural gas, gasoline hybrid and HHICE comprise respectively 60%, 33%, 6% and 1% of California bus orders.

Initially the total emissions continue to increase, but about 2006 the criteria emissions peak and CO2 emissions peak only a year or so later. A dramatic reduction occurs within a decade.

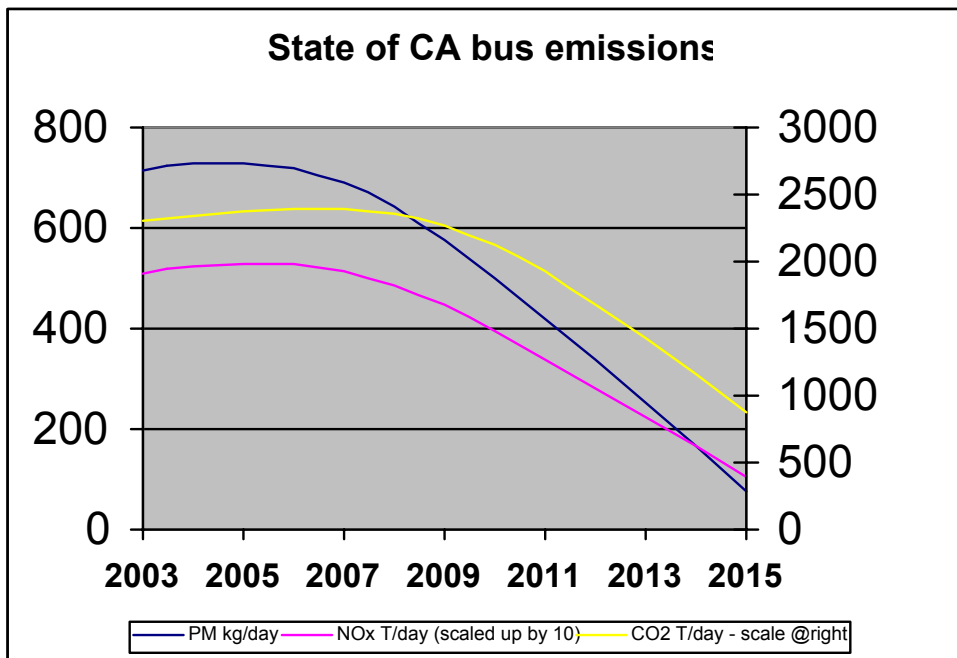


Figure 6. Illustrating the reduction of criteria pollutants and CO2 that results from the assumed introduction of advanced technology buses.

There are critical steps in achieving this vision of a very large reduction in emissions in the coming decade:

- The continuing success in implementing very low emission hybrid electric buses, using gasoline and then hydrogen as fuel. Although the same emissions advantages could be achieved with natural gas fueled hybrid electric drives, we presently expect gasoline to be increasingly favored by those transit properties which cannot yet afford a hydrogen fuel transition due to the lower cost of a gasoline fueling infrastructure combined with the present outlook on natural gas prices.
- Substantial investment in hydrogen fueling infrastructure with a consequent reduction in the cost of the hydrogen fuel is a second critical step. The HHICE bus implementation aids this as fuel quality for the ICE does not have to meet the stringent requirements that the fuel cell demands.

Figure 7 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.



Conclusions:

Initial operational experience with the Thor/ISE hybrid electric fuel cell bus is encouraging in several respects:

1. The hybrid electric technology operates meeting all expectations, offering high efficiency quiet transport in a ZEV package.
2. Passenger acceptance has made it clear that ridership can be substantially increased by offering a quiet and clean product. There has been no indication of any “fear factor“ related to the fuel, once a transit firm has offered its “stamp of approval“ by putting the bus in service the customers easily accept it as being safe transport.
3. Bus reliability in revenue service has exceeded expectations.

As a consequence of the prototype fuel cell bus, ISE Research now has orders for five more fuel cell buses. However, the high price of fuel cells limits, at this time, the general applicability of the technology to public transit.

The introduction of HHICE technology offers a hydrogen fueled technology which can serve as a bridge leading to the commercial introduction of fuel cell buses. The hydrogen hybrid ICE option appears, prior to having a demonstratable product, to offer increased reliability, lower cost and ease of maintainability. The prototype HHICE bus will be in test in early 2004, and is similar to the improved hybrid electric fuel cell buses which follow the introduction of the Thor/ISE bus but that the electrical generator is a rotating shaft combustion engine coupled to an advanced electrical generator.

Also in 2004 ISE and New Flyer will begin delivery of the gasoline fueled „sister ship“ of the HHICE. Together, the gasoline fueled hybrid electric bus and the HHICE form a powerful bridging

strategy for allowing transit properties to operate with emissions an order of magnitude below those of conventional (diesel and natural gas) fueled buses. Analysis of this bridging strategy indicates that a 50% reduction of *fleet* emissions is possible within the decade without early retirement of operating buses.

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.