ENVIRONMENTAL PERFORMANCE OF HEAVY DUTY VEHICLES

Dr. Herbert Fox, Professor
New York Institute of Technology
Old Westbury, NY 11568
herb@nyit.edu

Dr. Pasquale M. Sforza, Professor
University of Florida
Gainesville, FL
sforzapm@ufl.edu

1. INTRODUCTION

There are many studies looking into the possible environmental and economic impacts of a shift to an alternative economy broadly based on hydrogen fuel for transportation; representative studies are available in [1] - [5]. We are not as convinced as others might be that this is an appropriate direction for all energy consumers. Heavy commercial vehicles are often targeted for a change to hydrogen using a fuel cell as the power train, but our recent studies suggest neither greenhouse gas emissions nor fuel economy are improved so dramatically to warrant such a change. More, attendant problems with hydrogen use (like storage and infrastructure) may obviate the benefits. On the other hand, continued improvements in existing power train performance can lead to decreases in emissions for these types of vehicles. The purpose of this paper is to show results from recent work on hybrid buses in New York City, as an example supporting this point of view.

In the last year, critiques of hydrogen use have become commonplace (see, for example, [6], [7] and [8]). Our focus will be on specific comparisons of diesels, diesel hybrid electrics and (projected) hydrogen fueled buses. We will address the most critical issues for hydrogen use: fuel economy, emissions, energy density and infrastructure.

In order to assess the use of hydrogen in the context of bus operations, we set the stage first with a review of the literature evaluating bus performance and hydrogen as a fuel. Then we relate these two areas and report the potential and problems for buses employing hydrogen.

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2. SETTING THE STAGE — BUS PERFORMANCE; HYDROGEN PERFORMANCE

In order to understand the results we will show in Section 3 of this paper, it is necessary to provide some background information from hybrid bus operations and from recent studies looking at the production of hydrogen in "well-to-wheel" (WTW) scenarios. Detailed hybrid bus data is available from the extensive program carried out by New York City Transit (NYCT). We summarize these first with results derived from [9] and [10]. Well-to-wheel data are taken from [1] and [2].

2.1 Bus performance

NYCT, part of the Metropolitan Transportation Authority in New York, began operating the first of 10 heavy-duty diesel hybrid-electric transit bus prototypes from Orion Bus Industries (Model VI) in 1998. All 10 buses were in revenue service by mid-2000. The hybrid buses are intended to provide NYCT with increased fuel economy and lower levels of harmful exhaust emissions, compared with NYCT's standard diesel transit bus fleet.

Between 1999 and 2001 (over various predefined fuel and maintenance evaluation periods), these first 10 hybrid buses were part of a data collection and analysis project sponsored by the U.S. Department of Energy (DOE). The operating costs, efficiency, emissions, and overall performance of these low-floor hybrid buses were compared against those of 14 conventional high-floor diesel transit buses (7 each from NovaBUS Corporation and Orion) operated by NYCT in similar service. Toward the end of the test period Orion VII buses became available and some results are presented for it as well.

Results indicate that the hybrid buses operate with greater fuel efficiency and much lower emissions, compared with the diesel buses. These are summarized in Exhibits 1 and 2[1]. The hybrid buses had 10% better in-service fuel economy on average for the entire evaluation period compared to the NovaBUS RTS diesel buses. Looking at fuel economy per month, the fuel economy advantage of the hybrid buses went as high as 22% during one month of the evaluation period. The hybrid bus fuel economy improved during the evaluation period. No external charging was required for the hybrid buses. The hybrid buses had a fuel cost per mile 9% lower than the NovaBUS RTS diesel buses.

Chassis dynamometer emission test results with and without regenerative braking on the hybrid buses showed that the fuel economy increase from the hybrid configuration alone is about 6%. Fuel economy is improved even further, (23%–64% higher depending on test cycle) through regenerative braking, which stores energy that would otherwise be heat energy wasted in the brakes.

Emission testing for NYCT was conducted by West Virginia University on their mobile chassis

[1] All exhibits are grouped at the end of the paper.

dynamometer for the Northeast Advanced Vehicle Consortium. On the Commercial Business District (CBD) test cycle, for the hybrid buses compared with the diesel buses, carbon monoxide (CO) was 97% lower, NOx were 36% lower, unburned hydrocarbons (HC) were 43% lower, particulate matter (PM) was 50% lower, and carbon dioxide (CO_2) was 19% lower.

Emission testing was also conducted by Environment Canada on the new Orion VII diesel hybrid buses and the conventional Orion V diesel buses, with and without a catalyzed diesel particulate filter (DPF) installed. The new hybrid bus had 94% lower CO, 49% lower NOx, 120% higher HC, 93% lower PM, and 37% lower CO_2 than the Orion V diesel without the catalyzed DPF. The new hybrid bus had 38% lower CO, 49% lower NOx, 450% higher HC, 60% lower PM, and 38% lower CO_2 than the Orion V diesel with the catalyzed DPF. The only anomaly here is the result for the unburned hydrocarbons; this remains unexplained.

The hybrids make improvements in both fuel economy and emissions. We would point out that the diesel alone with a filter coupled to a low sulfur fuel does nearly as well. In any case we expect such improvements in both the diesel and the hybrid cycles to continue as technological advances are made in system performance as manufacturers address increasingly stringent environmental regulations.

Since the object of this paper is to look at fuel economy and emissions, we will not address maintenance costs. However it should be noted that these were higher for the prototype hybrid buses than those of the diesel buses during this evaluation. However, these costs are expected to decline for the next generation Orion VII buses, currently being procured by NYCT, as repair technicians become increasingly familiar with advanced hybrid propulsion systems.

2.2 Well-to-wheel analyses

Now let us turn our attention to the production and use of hydrogen in vehicles. Well-to-Wheel analysis is a systems approach to assessing the energy consumption and greenhouse gas emissions associated with different fuels and vehicle propulsion systems. A well-to-wheel analysis takes into account energy use and emissions at every stage of the process, from the moment the fuel is produced at the "well" to the moment the "wheels" are moved.

For example, using this type of analysis, a vehicle with a diesel powered internal combustion engine can be directly compared to a fuel cell vehicle that uses hydrogen made from natural gas, both in terms of emissions and energy use. This is particularly important when considering hydrogen fuel cell vehicles since there are numerous ways to produce hydrogen, some of which are clean and efficient and others which are polluting and energy intensive.

Two recent studies, [1] and [2], one North American and one European, analyze well-to-wheel energy use and greenhouse gas emissions (CO_2) for a wide range of fuels and vehicle propulsion systems. The reports analyze the whole universe of fuels, fuel pathways, and propulsion systems. They assess the most common ways to produce hydrogen (reformation of natural gas and electrolysis of water) and some variations (centralized production vs. on-site at gas stations and conventional power mix vs. wind power) and compares these scenarios with conventional gasoline, diesel, and hybrid electric vehicles.

The European study concludes that, with the exception of renewables, fuel cell hybrid vehicles (FCHV) using compressed hydrogen reformed from natural gas have the lowest greenhouse gas emissions (GHG) on a well-to-wheel basis. They also consume/require the least amount of energy on well-to-wheel basis, tying with FCHVs using hydrogen produced from electrolysis of renewable wind power. Of course, GHG emissions associated with hydrogen derived from electrolysis powered by wind energy are zero. FCHVs using hydrogen produced via electrolysis and the current EU power mix are both energy intensive and high in GHG emissions due to the fact that coal and other fossil fuels are used to produce the electricity.

Similarly, the North American study shows that the fuel cell vehicles using compressed hydrogen reformed from natural gas have lower total system energy use (Btu/mi) than conventional gasoline and diesel vehicles. Likewise, GHG emissions were lowest on a well-to-wheel basis for the FCHVs using hydrogen reformed from natural gas. FCHVs using hydrogen produced from electrolysis and the current US power mix are very energy intensive and high in GHG emissions due to the fact that much of US electrical power is derived from coal and other fossil sources.

We provide a short summary of these results in Exhibit 3. Here we compare diesel, diesel hybrids and hydrogen fuel cell automobiles in terms of fuel economy and greenhouse gas emissions. The fuel cell car clearly shows great promise in terms of both of these figures of merit. We would emphasize that even the hydrogen fueled vehicle produces greenhouse gases, here in the generation of the fuel.

3. COMPARATIVE RESULTS — BUSES ON DIESEL, HYBRIDS OR HYDROGEN

Unfortunately, the well-to-wheel results do not extend directly to those for hybrid buses. In order to do so for our purposes, we compared WTW fuel economy and greenhouse gas emissions from diesel and diesel hybrid automobiles to those from the NYCT testing[2], see Exhibit 4. The ratios of both these quantities --- diesel hybrid to diesel --- are close enough to suggest that they scale comparably. Thus such an approach for deriving a hydrogen fuel cell bus is possible and plausible between the two sets of data and the two types of vehicles.

We show the results of this scaling also in Exhibit 4. First we develop the fuel-cell-to-hybrid ratios and then use these to estimate the performance of a hydrogen fuel cell transit bus. While

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[2] We use the central business district (CBD) bus cycle since that has the most data available for comparison purposes.

this technique is imperfect it does provide a reasonable estimate of what might be expected from such a vehicle. We note that the fuel economy is approximately 46% better than the hybrid diesel bus and about 80% better than the standard diesel. In terms of CO_2 emissions we would estimate that the hydrogen vehicle would produce about 61% less CO_2 than the standard diesel and about 23% less CO_2 than the hybrid diesel bus. Both these would represent significant improvements over the existing fleet of diesel only buses.

With performance projected, we must address some additional issues relative to hydrogen use. These critical areas were cited in Section 1; we repeat them here so that we do not lose sight of their importance:

- The hydrogen infrastructure needed to deliver the fuel to, say, a central bus depot, is not in place and will require significant investment to realize.
- Hydrogen energy density is very low compared to other fuels. As a consequence fuel tank requirements for reasonable travel distances may be a problem.

The first of these issues we address in Section 4. Let us translate the second into quantitative terms. We can look at the results from both the WTW and NYCT data in vehicle terms only — that is in terms of tank-to-wheels energy consumption — and as a function of energy use. We translate fuel economy into energy terms and estimate diesel bus energy requirements at about 40,000 Btu/mile (at 3.5 miles/gallon) and hydrogen fuel cell energy requirements at about 22,200 Btu/mile (at 6.3 miles/gallon). To realize energy storage on the hydrogen fueled bus equivalent to that on the standard diesel bus would require approximate tank pressures on the order of 1,900 atm[3]. This suggests that the hydrogen energy density makes such use highly impractical unless alternative means for storage can be developed.

4. FINAL REMARKS

The hydrogen infrastructure issue coupled to the on-board pressure requirements perhaps suggests another alternative for a hydrogen fueled bus. We might consider implementing the fuel cell with a reformer on the vehicle and carrying along a traditional amount of liquid fuel [11]. This provides a work around for the large tank pressure indicated above. However this in turn leads to other issues: First, there is the obvious maintenance issue. We do not believe that most bus operators would be pleased to maintain such a vehicle with all their attendant problems. According to their staffs this would be tantamount to maintaining a chemical plant along with the traditional maintenance problems. Second, the bus then becomes a vehicle not producing just

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[3] This should be compared to pressure requirements for compressed natural gas buses of about 250 atm.

water vapor emissions but greenhouse gases as well during its route operations[4].

In summary we offer the following conclusions:

< Hydrogen can work as fuel for transportation but with various attendant problems; these reside mainly in the storage of the fuel.

< Reforming a hydrocarbon does not alleviate the problem but rather changes the vehicle from zero emissions during operations to one producing greenhouse gases.

< Bus operators need to be careful to look at maintenance issues.

< Diesels and diesel hybrid-electrics with their continued improvements will likely remain the mainstay of bus operations for the foreseeable future.

None of this is to say that hydrogen fuel cells will not work; it just points up the issues with use of such an engine for transportation. It is our contention that hydrogen use will likely reside in stationary energy production for both distributed and central station applications.

5. REFERENCES

[1] General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell, "Well-to-wheel energy use and greenhouse gas emissions of advanced fuel/vehicle systems, North American Analysis," Executive Summary, Volume 1 and Volume 2, June 2001.

[2] European Commission, Joint Research Centre, "Well-to-wheels analysis of future automotive fuels and powertrains in the European context," Version 1b, January 2004.

[3] Energy Independence Now, "How do hydrogen fuel cell vehicles compare in terms of emissions and energy use? A well-to-wheels analysis," Fact sheet, 2204.

[4] Ponticel, Patrick, "GM hybrid story on SAE Congress agenda," Automobile Engineering International, February 2004.

[5] Carney, Don, "High performance hybrids," Automobile Engineering International, March 2004.

[6] Wicker, Ken, "Are fuel cells ready for prime time?", Power, 148, 1, January/February 2004.

[7] Wald, Matthew, "Questions about a hydrogen economy," Scientific American, May 2004.

[4] We would be remiss if we did not note that any hydrogen-fueled system is not a zero emissions vehicle. It is just that the emissions are not realized at the point of operations, but are rather displaced to the point of fuel generation.

[8] Barbir, Franco, "Hydrogen economy: real possibility or utopia," paper presented at GlobalTech 2004, Farmingdale, New York, April 2004.

[9] Battelle, "New York City Transit diesel hybrid-electric bus site, final data report," February 2002.

[10] Chandler, Kevin, et al, “New York City Transit diesel hybrid-electric buses: Final results,” DOE/NREL Transit Bus Evaluation Project, July 2002.

[11] Shipley, Anna Monis and Elliot, R. Neal, “Stationary fuel cells: future promise, current hype,” American Council for an Energy-Efficient Economy, Washington, D.C., Report IE041, March 2004.

6. EXHIBITS

Exhibit 1
Fuel economy for various buses
Dynamometer tests and actual operations

Cycle	Bus	Fuel economy (mpg)
	Dynamometer tests	
CBD	Orion VII Hybrid*	5.4
	Orion V Diesel*	3.5
	Orion V Diesel with filter*	3.4
	Orion VI Hybrid**	4.3
	NovaBus RTS Diesel**	3.5
NY Bus	Orion VI Hybrid**	2.3
	NovaBus RTS Diesel**	1.4
Manhattan	Orion VI Hybrid**	3.4
	NovaBus RTS Diesel**	2.3
	Actual operations	
	Orion VI Hybrid	2.66
	Orion Diesel	2.17
	NovaBus Diesel	2.42

* Environmental Canada Chassis Dynamometer;** West Virginia University Dynamometer; Source: [9] and [10]

Exhibit 2

Emissions for various buses

Dynamometer tests and actual operations

Cycle	**Bus**	**CO (g/mi)**	**NOx (g/mi)**	**HC (g/mi)**	**PM (g/mi)**	**CO_2 (g/mi)**
CBD	Orion VII Hybrid*	0.08	12.9	0.11	0.012	1,848
	Orion V Diesel*	1.4	25.4	0.05	0.17	2,916
	Orion V Diesel with filter*	0.13	25.1	0.02	0.03	2,958
	Orion VI Hybrid**	0.1	19.2	0.08	0.12	2,262
	NovaBus RTS Diesel**	3.0	30.1	0.14	0.24	2,779
NY Bus	Orion VI Hybrid**	5.0	40.5	1.13	0.16	4,251
	NovaBus RTS Diesel**	11.3	72.0	0.60	0.70	7,076
Manhattan	Orion VI Hybrid**	0.1	22.6	0.18	<0.0005	2,841
	NovaBus RTS Diesel**	6.0	40.3	0.25	0.48	4,268

* Environmental Canada Chassis Dynamometer; ** West Virginia University Dynamometer; Source: [9] and [10]

Exhibit 3

Summary of well-to-wheel analysis

Vehicle type	**Fuel economy (mpg)**	**Green house gases (g/mile)**
Diesel	23.8	480
Diesel hybrid	29.4	390
Hydrogen fuel cell vehicle	43.2	300

Source [3]

Exhibit 4
Scaling of the results — extrapolation to fuel cell buses

	Fuel economy (mpg)	Greenhouse gases (g/mi)
1. WTW results		
Diesel (D)	23.8	480
Diesel hybrid (DH)	29.4	390
Ratio (DH/D)	1.24	0.81
2. NYCT results (CBD cycle)		
Diesel (D)	3.5	2916
Diesel hybrid (DH)	4.3	2262
Ratio (DH/D)	1.23	0.78
3. Fuel cell scaling compared to diesel hybrid automobile		
G H2 Fuel cell vehicle (FC)	43.2	300
Ratio (FC/DH)	1.47	0.77
3. Estimates for fuel cell buses		
Fuel cell bus performance	6.3	1740