Demonstration of a Hydrogen Fuel-Cell Locomotive

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Abstract

A North American consortium has developed a prototype hydrogen-fueled fuel-cell-battery hybrid switch locomotive for urban and military-base rail applications (see Fig. 1). This prototype is intended to lead to commercial locomotives, including freight, that will (1) reduce air and noise pollution in urban railyards, (2) increase energy security of the rail transport system by using hydrogen as fuel, (3) reduce atmospheric greenhouse-gas emissions, and (4) serve as a mobile backup power source ("vehicle-to-grid") for critical infrastructure on military bases. The locomotive successfully completed one month of operational testing in April 2010 at a BNSF railyard in the Los Angeles metro area. It will perform a power-to-grid demonstration at a United States military base in May-June 2010.

At 130 tonne, continuous net power of 240 kW from its proton-exchange membrane fuel-cell prime mover, and transient power well in excess of 1 MW, the hybrid locomotive is the heaviest and most powerful fuel-cell land vehicle yet built. Its 14 carbon-fiber composite compressed-hydrogen storage tanks, located at the roofline, have a combined storage of 70 kg at 350 bar. The system provides enough fuel for an eight to sixteen hour shift depending on the work performed during the shift. This paper focuses on the locomotive's potential to reduce air and noise pollution in the Los Angeles Basin and reports the result of initial operational testing.

Introduction

A hydrogen fuel-cell powerplant provides the advantages of its competitors, namely electric and diesel-electric power, while avoiding their disadvantages. It possesses the environmental benefits at the vehicle of an electric locomotive but the lower infrastructure cost of a diesel. Electric (catenary) locomotives – when viewed as only one component of a distributed machine that includes an electricity-generation plant, transformers, and transmission lines – are the least energy-efficient and most costly of conventional locomotive types. Elimination of high catenary-wire infrastructure costs by fuel-cell locomotives is the key to economic viability of zero-emission, low-noise electric trains in low population density regions. Diesel-electric locomotives, while collectively worse as sources of air pollution than an equal number of electric locomotives driven by a coal-fired powerplant, are more energy efficient and have a less expensive energy infrastructure. The natural fuel for a fuel-cell is hydrogen, which is manufactured like the electricity of the electric locomotive, and therefore hydrogen may be cyclically and indefinitely produced from water. If its hydrogen fuel is produced from renewable or nuclear primary energy, operation of the locomotive will not depend on imported oil and will not emit carbon in the energy cycle.

Fuel-cell locomotives can help resolve the joined international issues of urban air quality and energy security affecting the rail industry and transportation sector as a whole. The issues are related by the fact that about 97% of the energy for the transport sector (in the US) is based on oil, and more than 60% is imported. Because its primary energy is based largely on combustion of fossil fuels, the transportation sector is one of the largest sources of air pollution. Beyond local air quality, a consensus has been reached that the burning of fossil fuels is a significant factor in global climate change. Energy security is low because world oil reserves are diminishing, demand is increasing, and political instability threatens supply disruptions.

Furthermore, a need exists for large vehicles that serve, in addition to conveyance, as mobile backup power sources ("vehicle-to-grid") for critical infrastructure. Vehicle-to-grid applications include military bases and civilian disaster-relief operations.

A North American public-private project partnership comprised of our sister company, Vehicle Projects Inc, BNSF Railway Company, and the U.S. Army Corps of Engineers (through the Engineer Research and Development Center Construction Engineering Research Laboratory, ERDC-CERL) has developed a prototype fuel-cell-powered switch locomotive (see Fig. 1) for urban rail applications. This prototype is intended to lead to commercial locomotives that will (1) reduce air and noise pollution in urban railyards, including seaports, (2) increase energy security of the rail transport system by using a fuel independent of imported oil, (3) reduce atmospheric greenhouse-gas emissions, and (4) serve as a mobile backup power source (“vehicle-to-grid” or “power-to-grid”) for critical infrastructure on military bases and for civilian disaster relief efforts.

This paper focuses on the locomotive’s potential to reduce chemical (primarily diesel particulates and nitrogen oxides) and acoustic noise emissions in the Los Angeles Basin and reports the result of initial operational testing.

Figure 1. Fuel-cell switch locomotive: This is the largest fuel-cell land vehicle, photographed at a press conference in completed form on 29 June 2009

Technical Overview

This project commenced in May 2006, and the vehicle has now successfully completed one month of operational testing at a BNSF railyard in the Los Angeles metro area during the months of March and April 2010. It will perform a power-to-grid demonstration at a United States military base in May-June 2010.

At 130 tonne (287 thousand lb), continuous net power of approximately 240 kW from its PEM (proton exchange membrane) fuel-cell powerplant, and transient power well in excess of 1 MW, the hybrid locomotive is the heaviest and most powerful fuel-cell land vehicle yet. Its prime mover is a modular design based on Ballard P5TM stacks. For energy storage, fourteen lightweight carbon-fiber composite tanks are located above the traction battery. Fig. 2 shows the fuel-cell prime mover installed in the locomotive.

Based on engineering design by Vehicle Projects Inc, the BNSF Topeka System Maintenance Terminal in Topeka, Kansas, fabricated most of the fuel-cell powerplant which replaced the diesel engine-alternator and installed the prime mover in the vehicle. Subsystem and complete powerplant testing was executed by Vehicle Projects Inc. Because the combined weights of fuel-cell powerplant and carbon-fiber hydrogen storage system are substantially lighter than the diesel engine-alternator and diesel fuel tank they replace, a steel-plate ballast of approximately 9000 kg is placed in the undercarriage bay. A locomotive has a fixed operating weight in order to maintain wheel adhesion to the rails.

Previous papers have discussed the theory [2-4] and engineering design [1, 5-6] of the hybrid locomotive. While the BNSF locomotive is the largest and possibly the most sophisticated fuel-cell land vehicle to-date, it is not the first fuel-cell locomotive. The first fuel-cell-powered locomotive was an underground mine locomotive successfully completed and demonstrated in a working gold mine by Vehicle Projects Inc in 2002 [7, 8].

Locomotive Fuel-Cell Systems Design

The rational starting point for engineering design of a fuel-cell-hybrid vehicle is the duty cycle [9]. Figure 3 shows a typical duty cycle – that is, the function P(t), where P is vehicle power and t is time – recorded from an in-service yard-switching locomotive. The vehicle’s required mean power, maximum power, power response time, and power duration may be calculated from function P; its energy storage requirements are calculated from the integral of P. As shown, peak power commonly reaches 600-1000 kW for durations of no more than several minutes – usually corresponding to acceleration of train cars or uphill movement. However, between the peaks, the power requirements are minimal, as when coasting a load, or zero when idling between move operations. The idle time, varying from minutes to hours between operations, usually accounts for 50-90% of the overall operation schedule. Our analysis of multiple duty-cycle data sets from various railyards shows that the short duration of peak power and long periods of idle time result in mean power usage in the range of only 40-100 kW. The sharp peaks, low mean power, and long idle intervals of the duty cycle are ideal for a hybrid powertrain [4, 9].

For a hybrid vehicle to be self-sustaining, the prime mover, a hydrogen PEM fuel-cell in this case, must provide continuously at least the mean power of the duty cycle. The auxiliary energy storage device, lead acid batteries in this hybrid, must store sufficient energy to provide power in excess of the continuous power rating of the fuel-cell and must do so continuously under operation of the duty cycle. This energy must be available while not exceeding a rather shallow depth of discharge, which significantly increases the size of the battery. Allowable depth of discharge is a function of acceptable battery cycle life and recharge rate. In

Figure 2. Locomotive under construction: Right-rear view of the locomotive with installed fuel-cell prime mover shown in the foreground (31 July 2008)

this application, battery charge is maintained within 60% - 80% of full capacity. The Railpower lead-acid traction battery, in parallel with our fuel-cell prime mover, allows transient power well in excess of 1 MW. For the power-to-grid application, the hybrid locomotive can provide only 240 kW of net power on a continuous basis but can provide power surges in excess of 1 MW.

The fuel-cell powerplant consists of three primary subsystems; fuel-cell stack modules, air delivery, and cooling. At the heart of the power module are two Ballard Power Systems P5 TM fuel-cell stack modules. The fuel-cell stack modules contain Ballard Mk902 stacks; each rated at 150 kW gross power at 624 V, for a total of 300 kW gross power at 624 V. Each fuel-cell stack module includes the auxiliary components for air and hydrogen humidification, water recovery, hydrogen recirculation, and hydrogen purge. For the fuel-cell stack modules to produce power, they require both oxygen (cathode) and hydrogen (anode) reactants. The systems that provide these reactants as well as support operation of the stack modules are referred to as the balance of plant (BOP). The air delivery system provides air at a specified mass flow and pressure. Hydrogen is supplied to the stack modules at nominally 12 bara and is pressure-regulated and recirculated inside the stack module. The cooling system rejects waste heat from the fuel-cell stacks as well as auxiliary motors and electronics. The electrical distribution and control systems regulate power output, control various electrical devices, and monitor system parameters for faults.

The largest of the fuel-cell system modules are the two hydrogen storage modules. Each module consists of seven carbon-fiber composite cylinders that collectively store approximately 35 kg (70 kg for the vehicle as a whole) of compressed hydrogen at 350 bar (5,100 psi). Given the physical space required for the cylinders, the only packaging options were to mount the hydrogen modules (1) under the chassis or (2) above the existing traction battery. A thorough safety analysis highlighted two factors that led to packaging of the hydrogen system above the battery. First, because of the buoyancy of hydrogen, storing hydrogen below void volumes in the locomotive platform, battery rack, and rear hood could lead to confinement of leaked hydrogen and increase the possibility of detonation. In contrast, roof-line storage allows for harmless upward dissipation of hydrogen in the event of a leak. Second, locating the hydrogen tanks at the roofline minimizes the likelihood of damage from common events such as derailment, track debris, and impact from yard traffic such as fueling trucks. Because of the relatively light weight of the hydrogen storage tanks (empty, 95 kg each), the roof location has minimal effect on vehicle center of gravity. Indeed, after conversion to hydrogen-fuel-cell power, a ballast of approximately 9000 kg was placed in the undercarriage to bring the locomotive weight to its specified value of 130 t.

Impact and Operational Testing

Extensive impact testing was performed to validate shock isolation design. The new equipment isolation systems were designed with low natural frequencies, in the range of 3-7 Hz. This minimizes the potential of resonance with on-board equipment and track input frequencies. Relatively "soft" mounts provide dynamic deflections up to 25 mm which enables maximum energy dissipation.

Coupling typically takes place at 1-3 mph, however on occasion harder couplings do occur resulting in extreme forces. Impact tests up to 5.1 mph were performed repeatedly to measure shock loads at critical equipment, as well as validate robustness of the system hardware and connections when experiencing dynamic motion. The maximum allowable acceleration in longitudinal, lateral, and vertical directions for the fuel-cell hardware is 3 G. This 3 G maximum limit applies at or below the system natural frequency. At the maximum impact speed of 5.1 mph into a braked consist weighing approximately 364 t, the maximum measured acceleration of any of the isolated fuel-cell equipment was 2.5 G, filtered at 10 Hz. The corresponding structures that were directly mounted to the locomotive frame exceeded 7 G, filtered at 30 Hz. As expected, maximum accelerations were dominant in the longitudinal direction. The actual measured coupler force was 270 t, slightly greater than 2 G at the coupler input.

At the time of this writing, the fuel-cell locomotive has undergone several weeks of operational testing at the BNSF Commerce City and Hobart yards in the Los Angeles, California, metro area. The locomotive work schedule involves the movement and assembly of flat cars, tankers, hoppers, etc. within the Commerce yard as well as a three mile movement of short consists of 10 – 30 cars between the Commerce and Hobart yards. The fuel-cell locomotive performed all operational testing as a single unit, thus all work energy was provided solely from the fuel-cell locomotive. Typical loads pushed and pulled by the

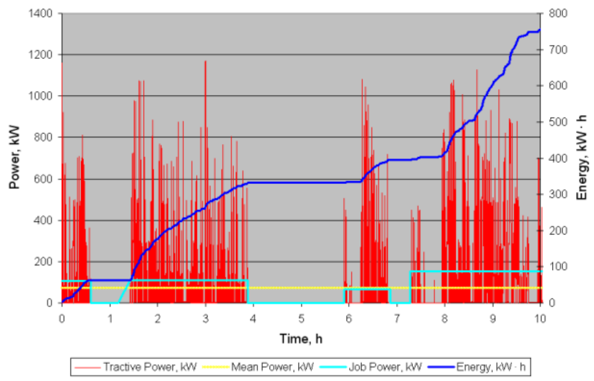

Figure 3 – Duty Cycle: Example switch locomotive duty cycle. Computed 75 kW mean power is based on a 20-h operating shift.

locomotive ranged from 200 – 1800 tons of equipment, plus additional resistance due to partially applied air brakes on the entire consist. The operation shift duration varied greatly depending on the day-to-day work load.

From a functional perspective, the locomotive performed the work well in all respects. The fuel-cell powerplant and associated cooling and fuel systems performed without issue during the repeated couplings to other rail equipment. During all work shifts the powerplant and traction battery were able to provide power to the traction motors and or provide a charging current to the traction battery. Conversely, an undersized powerplant or traction battery would have not been able to provide the required traction power when needed or the battery would have reached a state of charge too low to continue operation.

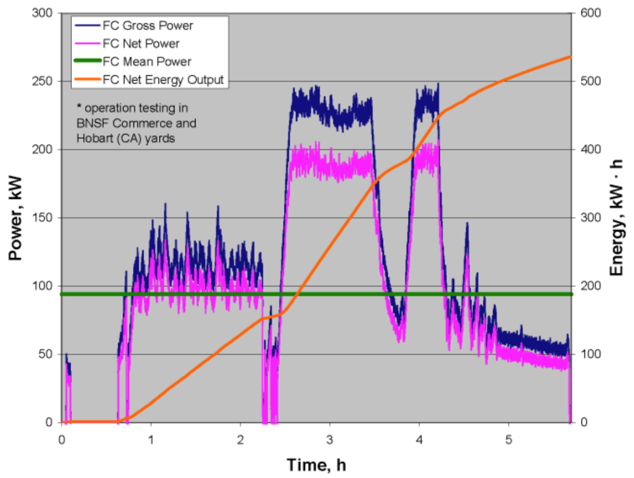

Figure 4: Sample of the fuel-cell powerplant power and energy during a 5.7 hour shift of work in the Commerce, CA rail yard. Fuel-cell, and hence vehicle mean power requirement was 94 kW.

The latter would thus require the locomotive to stop work and charge the battery via the fuel-cell.

As with most new technology operator acceptance of the locomotive was understandably mixed at the onset of the demonstration. Interface between the train engineer and the locomotive are nearly identical to a typical locomotive. Training of new operators took only a few minutes which included an overview of unique breakers, information screens, and safety systems in place as well as appropriate reactions to possible events. Over five different train engineers have operated the fuel-cell locomotive and all left with an overall positive impression as well as general agreement that it was pleasant to operate the fuel-cell locomotive due to the lack of diesel noise, vibration, and exhaust. Several train engineers commented on the quick throttle response and lack of "load up" time they were typically accustomed to with a typical diesel locomotive.

Operation of the fuel-cell powerplant is closely monitored, and data for key parameters are logged at a one-second rate during operation. Of particular interest is the mean operating gross and net power levels, associated fuel consumption, and the resulting overall fuel-cell powerplant thermal efficiency. Figure 4 shows a typical duty cycle for the fuel-cell powerplant. The fuel-cell operating power level is determined by the hybrid system controller which determines the power set-point based on throttle position and battery state of charge. Due to an unplanned thermal limitation of the DC to DC power converter, actual maximum gross power was limited to 250 kW, although the fuel-cell modules are capable of 300 kW gross. Based on data thus far, the overall thermal efficiency of the fuel-cell powerplant is between 41 % and 49 %, based on the higher and lower heating value of hydrogen, respectively. In this case, efficiency is defined as fuelcell gross power less all balance of plant and power converter losses between the fuel-cell and battery bus, divided by the heating value of hydrogen.

Table 1 summarizes overall performance data based on preliminary operating data. The mean net power requirement of the locomotive is about 96 kW. To maintain this power, actual mean fuel consumption was measured at 5.73 kg/hr. Total usable tank capacity is 63.5 kg at 20C, which yields an average mean shift duration of 11.1 hours. Considering the two weeks of operational data sampled, minimum and maximum shift times based on minimum and maximum energy requirements ranged from 8.5 to 16.2 hours. Therefore, for this application daily refueling would likely be required. With the proper fueling equipment, refueling of the system would take 15-20 minutes. Note that the quantity of processed data at the time of this writing is limited to a small sample of operational data. As more data is processed, these values will be refined.

Emissions and the Los Angeles Basin

Population of the Los Angeles metro area is 13 million, and the city measures about 130 km from east to west and 60 km north to south. Because of the low population density, and consequent reliance on the automobile for transportation, and location in a basin partly surrounded by mountains, it has historically had air-quality problems. It is also the site of the adjacent ports of Long Beach and Los Angeles, the largest seaports in the United States, which contribute to air pollution from trucks, trains, and ships. In part, because the economy of the State of California exceeds that of many nations, the state has substantial national influence and has taken a leadership role in setting US Government air-quality regulations.

The driving force of the fuel-cell-hybrid switch locomotive project is to demonstrate that fuel-cell locomotives are practical solutions to reducing chemical and noise emissions in the LA Basin. Switch locomotives, which assemble and disassemble trains in railyards, account for about five percent of all rail emissions, but they have a disproportionate impact on air quality and health risks in the communities surrounding large urban railyards. The California Air Resource Board's (CARB) 2004 assessment of diesel particulate matter (PM) risk levels near the Roseville, California railyard revealed localized risks in excess of 500 potential cancer cases per million people exposed and that over 155 thousand people living in the vicinity of the railyard faced an elevated cancer risk due to rail operations [10]. In contrast, line-haul locomotives, which travel throughout California, emit over 95 percent of rail emissions but distribute their emissions over a much larger area.

Table 1: Fuel-cell Powerplant Performance *

Gross power operating range	0 – 250 kW
Mean gross power	115 kW
Mean net power	95.7 kW
Mean fuel usage	5.73 kg / hour
Vehicle fuel capacity @ 20C	67.0 kg
Mean required refueling interval	11.1 hours
Balance of plant parasitic losses	~ 17 %
Mean operating thermal efficiency (efficiency = Net Power/ hydrogen heating value)	41 % (HHV) 49 % (LHV)

* Power data based on 4 days of operation; fuel data based on 8 days of operation. Mean net power of approximately 95 kW and mean refueling interval of approximately 11 h.

It is apparent – through increasing regulation, public demand for cleaner transportation, concerns over national energy security, energy independence, and global environment and health concerns – that fuel-cell rail technology has a potentially significant role in the future of the rail industry.

The "real-world" operational data collected during the demonstration in the LA Basin will be invaluable in the development of future fuel-cell hybrid locomotives. It will assist in modeling their performance in order to optimize their hybridization and maximize fuel economy. In addition, this data will be useful in modeling subsequent fuel-cell powerplants for use in line haul and commuter locomotives.

Potential Future Applications

The switcher locomotive demonstration project has provided a foundation for continued development of fuel-cell powerplants as prime movers in rail applications. Albeit implementation of a fuel-cell prime mover is not without challenges, the state of the art technology is to a point where commercialization is reasonable given the proper applications. Fuel-cell stack hardware costs, on-board fuel storage, and fuel infrastructure / resulting fuel costs continue to be challenges for commercial implementation. Vehicle duty cycles that favor hybridization as well as the ability to purchase hydrogen fuel at a price competitive with fossil fuels will provide the most favorable business case for near term applications.

Hybrid applications have the potential to minimize fuel-cell capital costs as well as reduce the required space for on-board hydrogen fuel – currently both challenges for near term commercialization. The switcher locomotive is an application that lends itself well to a fuel-cell hybrid configuration. This includes relatively short periods of intense work coupled with some steady low power work as well as some idle time. Similarly, commuter locomotive applications have some appealing characteristics that merit consideration of hybrid fuel-cell powerplants. As with a switcher engine, commuter locomotives tend to have periods of intense power demands as they pull away from a station, periods of lower power demands once cruising speed is reached, followed by a relatively quick deceleration and short idle period at the next stop. This repeatable schedule, potential to recover braking energy, and ability to charge during stops provides opportunity for a hybrid system.

Each potential commuter locomotive application has its unique set of challenges that deserve consideration. The route, number of stops and grade play a significant role in power and fuel capacity requirements. On-board hydrogen fuel storage is a challenge. Compressed hydrogen provides the simplest solution, however it is volumetrically inefficient and can require a great deal of packaging space. Depending on capacity requirements, it may not be feasible to package compressed hydrogen on-board the locomotive. Other hydrogen storage options include reversible metal hydrides or liquid hydrogen. Metal hydride and liquid hydrogen can provide approximately 2.0 and 2.5 times the practical volumetric storage of compressed hydrogen, respectively. [12]. The most notable technical attribute of metal hydride is its ability to store hydrogen at relatively low pressure, easily in the 15-20 bar range, which lends itself to underground / tunnel applications. Ultimately, given the range of potential commuter applications, a case by case analysis will reveal if a hydrogen fuel-cell application is feasible.

Conclusions

The fuel-cell-hybrid switch locomotive for operation in the LA metro area combines the environmental advantages of an electric locomotive with the lower infrastructure costs of a diesel-electric locomotive. Its energy source is hydrogen, which can be produced from many renewable energies and nuclear energy and thus does not depend on imported oil. Depending on the primary energy source, it can be a totally zero-emissions vehicle, that is, with zero carbon in the energy cycle. Based on real world utilization of the fuel-cell hybrid switcher locomotive, use of hydrogen fuel-cells in the harsh rail environment has been proven technically v. Utilization of fuel-cell switch locomotives in urban railyards can prevent many cases of diesel emissions-based illnesses because such yards are frequently surrounded by residential housing that receives a high concentration of diesel particulates and nitrogen oxides; line-haul locomotives, in contrast, tend to disperse their emissions over much broader geographic areas.

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