

Analysis of Fuelcell Hybrid Locomotives

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ABSTRACT

Led by Vehicle Projects LLC, an international industry-government consortium is developing a 109-tonne, 1.2-MW road-switcher locomotive for commercial and military railway applications. As part of the feasibility and conceptual-design analysis, we have analyzed the potential benefits of a hybrid powerplant in which fuelcells comprise the prime mover, and a rechargeable auxiliary power device, such as a battery or flywheel, supplements peak power. Potential benefits of a hybrid powerplant are (1) enhancement of transient power and hence tractive effort, (2) regenerative braking, and (3) reduction of capital cost.

Generally, tractive effort of a locomotive at low speed is limited by wheel adhesion and not by available power. Enhanced transient power is therefore unlikely to benefit a switcher locomotive but could benefit applications, such as subway trains with all axles powered, requiring high acceleration.

In most cases, the benefits of regeneration in locomotives are minimal. For low-speed applications such as switchers, the available kinetic energy and the effectiveness of traction motors as generators are low. For high-speed heavy applications such as freight, the ability of the auxiliary power device to absorb a significant portion of the available kinetic energy is low. Moreover, the hybrid powerplant suffers a double efficiency penalty: Losses occur in both absorbing and then releasing energy from the auxiliary device, which result in a net storage efficiency of no more than 50% for current battery technology.

Capital cost in some applications may be reduced. Based on an observed locomotive duty cycle, a cost model utilized in this project shows that a hybrid powerplant for a switcher may indeed reduce capital cost. However, offsetting this potential benefit are increased complexity, weight, and volume of the powerplant and 20 - 40% increased fuel consumption resulting from lower efficiency.

Based on this analysis, the consortium has decided to develop a pure fuelcell road-switcher locomotive, that is, not a hybrid.

Keywords: Fuel cell, hybrid, locomotive, train

INTRODUCTION

Led by Vehicle Projects LLC, an international industry-government consortium is developing a 109-tonne, 1.2-MW road-switcher locomotive for commercial and military railway applications (see Figure 1) [Miller, et al, 2004 A]. As part of the feasibility and conceptual-design analysis, we have analyzed the potential benefits of a hybrid powerplant in which fuelcells comprise the prime mover and a rechargeable auxiliary power device, such as a battery or flywheel, supplements peak power.

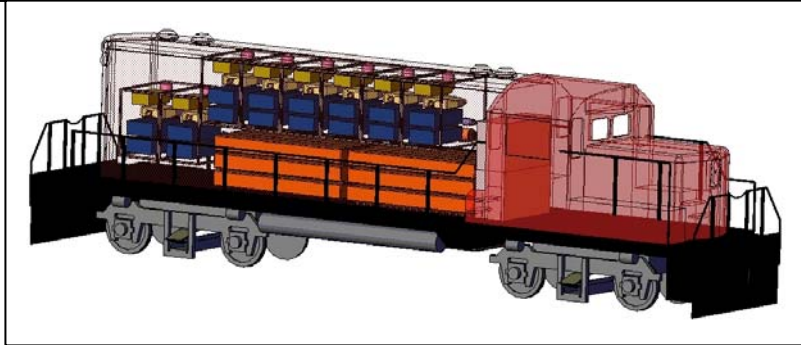


Figure 1: Conceptual design of the 1.2 MW fuelcell-powered road-switcher locomotive. Powerplant design consists of eight identical 150-kW stand-alone modules. Based on the analysis presented in this paper, the locomotive will not use a hybrid powerplant.

Potential benefits of a hybrid powerplant are (1) enhancement of transient power and hence tractive effort, (2) regenerative braking, and (3) reduction of capital cost. However, these potential benefits may be weak in locomotives and other forms of railway motive power because of the characteristics of steel wheels on steel rails and the large kinetic energy of trains. The effectiveness of a hybrid powerplant in exploiting these benefits depends

heavily on the duty cycle and the characteristics of the operating route. There are also a number of fixed operating requirements, propulsion system design issues, and fundamental operating constraints that will determine the feasibility of applying hybrid power systems. For example, the time required for a train to negotiate a long grade may require a hybrid system with an impractically large auxiliary storage capacity.

In this paper, we will examine the potential benefits in turn for several rail applications. In summary, the most likely applications to benefit from enhanced tractive effort and regeneration are commuter rail and possibly long distance intercity passenger trains. Because maximum power is required for extended periods and because only a fraction of the large kinetic energy of train can be absorbed in today's auxiliary storage devices, cases least likely to benefit from enhanced tractive effort or regeneration are high-speed rail and heavy freight operations. We do find that yard switchers, and possibly other rail vehicles, may have reduced capital cost (or first cost) if a hybrid powerplant is used. However, this benefit comes at the price of increased complexity and reduced thermodynamic efficiency.

In another project, we have developed a fuelcell-battery hybrid mine loader [Miller, et al, 2004 B]. Although packaging has been challenging (see Fig 2), the peaky duty cycle of a loader [Desrivieres & Betournay, 2002] made development of a hybrid powerplant compelling.

Nonetheless, based on the analysis below, the 1.2-MW road-switcher will not be a hybrid. Vehicle Projects LLC developed and demonstrated, during the period 1999-2002 a fuelcell-powered mine locomotive, which likewise was not a hybrid [Miller & Barnes, 2002]. Our feasibility analysis for that project showed that wheel adhesion was the limiting factor in performance and not

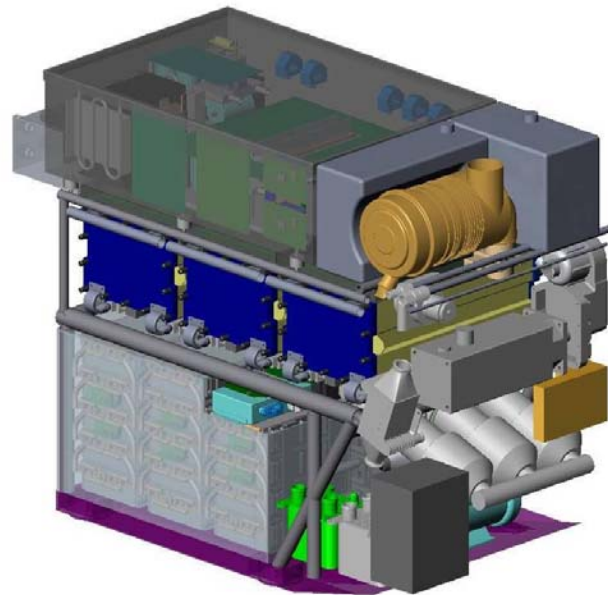


Figure 2: Fuelcell-battery hybrid powerplant of the mine loader. Fuelcell continuous power is 90 kW and the auxiliary storage unit, a nickel metal-hydride battery, can supplement this by 70 kW of transient power. Both are water-cooled.

fuelcell power [Miller, 2000]. Excellent performance of the mine locomotive has shown the analysis to be correct.

BACKGROUND

The main requirements of auxiliary energy-storage devices for railway use are that they be rugged, have a high energy density, and provide power over a relatively long period. There are currently only two viable energy storage technologies – batteries and flywheels – that meet these requirements. A typical power bus structure of a fuelcell-battery or fuelcell-flywheel hybrid system is shown in Figure 3.

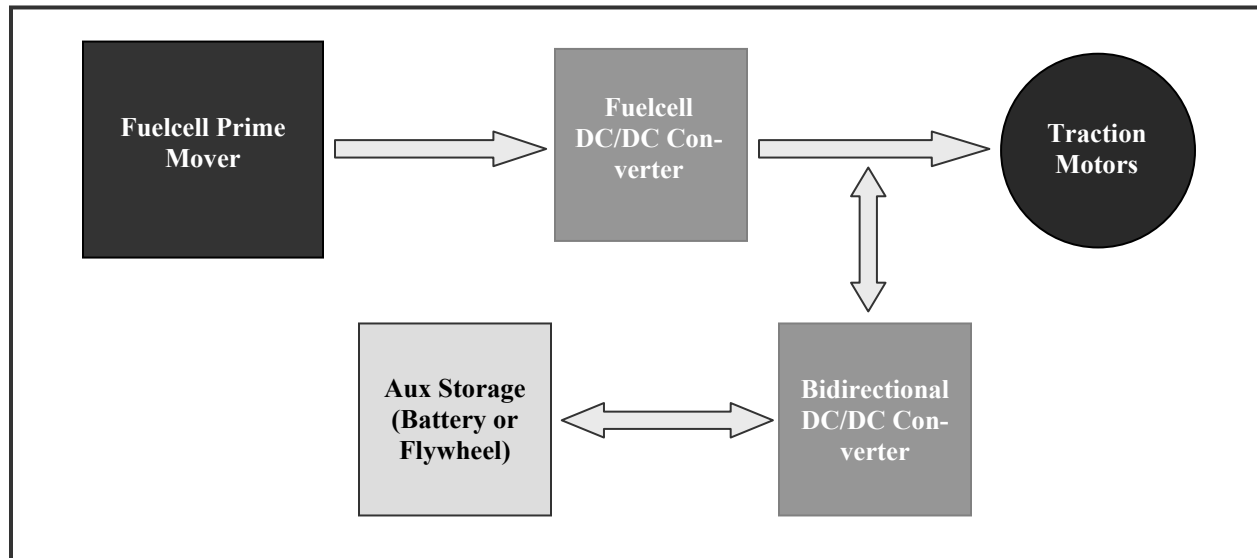


FIGURE 3: Main components of a fuelcell hybrid power train. "Aux Storage" represents either battery or flywheel auxiliary energy storage. Arrows point in the direction of power flow. The traction motors are used as generators during braking. A system using AC traction motors would be analogous to the DC system shown.

Hybrid power has already been demonstrated in some rail applications. In cases where rail tunnels have no traction power supply or when the third rail is turned off for maintenance, diesel-battery and third-rail-battery hybrid locomotives pull maintenance trains in tunnels. Diesel-third-rail locomotives are used for commuter trains traveling through the approach tunnels to New York City terminals. Recently, a number of diesel-battery hybrid switcher locomotives, marketed as the "Green Goat" [Railpower, 2003], have been trialed by several North American railroads. The justification for many of these applications involving a diesel-engine prime mover is reduction of exhaust emissions. Since fuelcells are zero emission devices, emissions reduction is not an issue in the analysis of a fuelcell hybrid powerplant.

A gas-turbine-flywheel hybrid has been under development by a consortium led by the University of Texas as part of its Advanced Locomotive Propulsion System (ALPS) project (Herbst & Hebner). The objective of the ALPS project, funded by the US Federal Railroad Administration, is to develop a fossil-fueled locomotive for non-electrified high-speed rail services having the same short-term power rating as a catenary-electric locomotive. The purpose of flywheel energy-storage is to reduce thermal cycling of the gas turbine, thereby reducing maintenance. Power cycling, like emissions, is a non-issue for fuelcells.

Regenerative braking is already used in many electrified railway systems to recover braking energy. Power generated by the electric braking system is returned to the third rail or overhead catenary system for use by other trains on the system. This is feasible for catenary-electric trains because there is little additional equipment required on the rolling stock. Also, the trackside distribution system has the capacity to distribute the power to the other trains and only make up the difference from the utility grid. Many AC overhead systems also have the ability to return power to the grid. The traction supply system can provide substantial transient-power overload. Whether a fuelcell hybrid system has the potential to be equally effective in recovering braking energy is a subject of this analysis.

An obstacle to widespread use of hybrid power in rail vehicles is onboard limitation of mass and volume. Railway vehicles, subject to severe restrictions on axle load and clearances, require efficient use of available weight and space in packaging onboard equipment. For example, the diesel-third-rail hybrid locomotives discussed above required compromising diesel-engine power in order to package both the diesel alternator and the third-rail chopper equipment. Space issues are particularly acute for multiple-unit train configurations, in which the power equipment must be mounted below the floor. Auxiliary energy storage systems are heavy and bulky and may pose a substantial problem for onboard packaging in any application.

RESULTS AND DISCUSSION

Transient Power and Tractive Effort

In rail applications, tractive effort is limited at low speeds by adhesion between the powered wheels and the rails. Wheel adhesion limits the usable power and reduces the benefit of hybrid power for low-speed, frequent-starting vehicles such as yard switchers. Adhesion is generally less of an issue in rolling stock, such as a mass-transit (subway) train, having a large proportion of its axles powered. As demonstrated by computer simulation [Peters, 2004], wheel adhesion limits tractive effort most severely in locomotive-hauled trains during startup (acceleration from rest). In a simulated commuter locomotive pulling a passenger train, due to the limits of wheel adhesion, the hybrid auxiliary source is not able to augment the prime mover until the train speed has reached a speed of 40 km/h.

In most passenger-train configurations, the minimum continuous power is defined by either a requirement to hold (balance) the maximum train speed on a specified gradient or to balance the speed at some specified margin above the maximum train operating speed on tangent (straight), level track. For locomotive-hauled freight trains, the total locomotive power is assigned on the basis of the dispatch adhesion rating of the units and the power required to reliably haul the train over the maximum grade at the minimum required operating speed. In both freight and passenger service, a clearly defined minimum continuous power must be delivered by the primary mover in a hybrid power system. On this basis, it is judged that the main benefit to be derived from hybrid enhancement of tractive effort would not be in starting the train from rest but for a service where there are a relatively large number of line-speed restrictions or short grades, where good speed recovery and maintenance is necessary to adhere to a schedule. This is unlikely to be the case in freight service but could benefit some long-distance passenger train services. Switcher locomotives, which spend most of the time operating at speeds below 20 km/h, are generally wheel-adhesion limited rather than power limited, and their tractive effort is unlikely to benefit from a hybrid powerplant.

Our analysis of rail applications with respect to their potential to benefit from enhanced tractive effort is summarized in Table 1. The entry for the switcher service illustrates the results displayed: Likely benefits are ranked "low" because wheel adhesion, rather than power, limits tractive effort during frequent startup

operations. The challenge of packaging a hybrid powerplant within the mass and volume constraints of the vehicle is termed the "packaging difficulty" in the table.

TABLE 1: Hybrid Power and Tractive Effort			
Type of Service	Qualitative Benefits	Packaging Difficulty	Comments
Switcher	Low	High	Wheel adhesion limits tractive effort
Light Rail	Medium	High	Acceleration and speed are limited by traffic in street-level operation. Power equipment must reside under floor.
Mass Transit	High	High	Similar to light rail but uses third rail, which may be coupled to hybrid powerplant. Acceleration and speed potential greater than for light rail
Commuter Rail	High	Low	Good benefits. Space is less of an issue, and tender car can be used if necessary
Intercity Passenger	High	Medium	Same as commuter rail but tender car less desirable due to platform/train-length constraints
High-speed Rail	Medium	High	Continuous power of prime mover dominated by aerodynamics. Added volume and weight are major issues
Line-haul Freight	Low	Medium	Duty cycle dominated by long periods at full power. Express freight may benefit from transient power boost

Regenerative Braking

Regenerative braking can only be implemented when the rail vehicle has the capability of using the traction motors as generators or alternators to recover potential or kinetic energy of the vehicle. Switcher locomotives, particularly the older ones, are not generally equipped with dynamic brakes because the slow-speed duty cycle does not lend itself to efficient use of electric braking. Even friction braking requirements are generally modest. Furthermore, if electric braking were to be used, the switcher duty cycle contains frequent transitions between power and braking functions, sometimes with short overlapping periods (power braking). The time taken for the traction system to transition from power to electric brake would greatly impact the operator's response time.

Almost all modern passenger trains and mainline freight locomotives are equipped with electric braking. In principle, passenger trains and freight locomotives (perhaps with tenders) have the potential to be equipped with hybrid power systems because the necessary reverse power management system is already in place. For passenger and freight applications, the value of regenerative braking hinges on how much of the available energy can be recovered.

Train braking power characteristics vary according to the type of train. Constant-rate blended braking systems are generally used on modern passenger trains and these result in an unbalanced braking power

characteristic. At high speeds, the power levels are at their highest and probably exceed the capability of being absorbed by a practical hybrid storage system. Accordingly, a substantial portion of the high-speed braking energy would necessarily still be dissipated by other means. At low speeds, the available energy is low, and the efficiency of DC traction motors (installed in most switchers) acting as generators is also low. The electric braking characteristics and efficiency of AC traction motors, fast becoming the industry standard, are substantially better at low speeds. While they have the ability to provide a constant braking force at the adhesion limit down to 5 km/h, AC traction motors add little to the overall available energy recovery.

Energy Storage Devices

Regarding auxiliary energy-recovery devices, automotive batteries have been dominated by lead acid technology for over 100 years. Their main advantages are high power and low cost. Increasing demand for improved cycle life and operation over a broad temperature range has driven the development of advanced high-performance battery technologies. The market first turned to nickel metal hydride, which provides improved cycle life over lead acid and does not employ toxic heavy metals. Lithium ion systems, which are expected to enter this market in the near future, also provide improved cycle life under pulsing or under deep discharge when compared to lead acid. Moreover, lithium ion technology provides higher energy density, requires less expensive electroactive materials, and generally outperforms nickel metal hydride at high and low application temperatures. It also requires fewer cells to reach system voltage – an important factor that simplifies battery assembly, increases energy density, and improves high-power performance. However, there are still unresolved issues with safety of large cells and reliable battery-pack management.

When comparing traction batteries, key performance measures are power density, energy density, life, and cost. Table 2, based on a compilation of published performance and estimated cost data, provides a general comparison of these key factors. Considering the parameters collectively, lithium ion batteries are potentially the best performing of the three technologies for traction applications. However, because of the yet-unresolved safety and battery-management deficiencies mentioned above, lithium ion batteries are presently not as commercially mature as nickel metal hydride.

Battery Type	Specific Power (W/kg)	Specific Energy (Wh/kg)	Cycle Life	Life (y)	Cost Target (\$/kWh)
Sealed Lead Acid	600	40	500	2	150
Nickel Metal Hydride	400	65	3000	5	450
Lithium Ion	500	150	2500	5	500

Flywheels (sometimes called “mechanical batteries”) are one of the oldest methods of energy storage. Consisting of a rotating mass attached to an energy transfer system such as an electric motor-generator, the fundamental design principles of flywheels are well documented [Geocities, 2001].

Previous studies attempted to use flywheels to recover braking energy in rail vehicles. In the mid 1970s, tests were carried out by the US Department of Transportation on a New York City R-42 transit car equipped with a flywheel energy storage system [Access to Energy, 1975]. While these tests were reasonably successful from a technical perspective, onboard energy storage for braking was obviated by development of third-rail regenerative-braking technology, which is now used by many mass transit authorities worldwide. Also, the steel-rotor flywheel used in the R-42 test posed safety concerns about containment of the rotor under catastrophic failure conditions.

Recent advances in composite materials have greatly increased the energy density of flywheels, and advances in power generation technology have improved their energy-transfer efficiency. Rotors constructed from composite materials are less likely to fail, and if they do, they fail in a less severe manner than steel-rotor designs. Flywheel units, with storage capacities in the 1 – 10 kWh range and overall efficiencies (including energy transfer and average storage losses) in the 80 – 85% range, are now commonly used in uninterruptible power supply (UPS) installations. Because they are directly coupled to a motor-generator system, flywheels can handle higher power than batteries. Their main disadvantages are the structural requirements to ensure that rotor can be contained in the event of catastrophic failure at rotational rates of 10,000 – 40,000 rpm and the gyroscopic effect of a rotating mass.

The flywheel under development for the ALPS program [Herbst] has much larger energy storage, power delivery, and mass than the flywheels used in UPS installations. The ALPS design is based on extensive route simulations of existing and emerging high-speed rail corridors [Herbst, et al, 2000]. The current design parameters for the ALPS flywheel are given in Table 3.

TABLE 3: Parameters of ALPS Rail Flywheel	
Storage capacity	133 kWh (480 MJ)
Delivered capacity	100 kWh (360 MJ)
Total weight (including generator & controls)	18 tonne
Operating rotational speed range	7,500 to 15,000 rpm
Motor-generator rating	2 MW at 1200 VAC, 3-phase
Energy transfer efficiency (each way)	95%
Storage decay	2% per h

Recovery of more than 30% of the kinetic energy of a train can probably be achieved with the above flywheel. If the power capability could be increased to 3 MW, the energy recovery could exceed 40%. In this case, the added weight and volume of the flywheel and its safety containment system are more than offset by the reduced weight and size of the turbine and high-speed alternator set.

Flywheels of the size and capacity required for a fuelcell hybrid powerplant are still in the early commercialization stage and are likely to be more expensive than chemical batteries.

Freight-train braking tends to be less severe for normal speed control and stops than for passenger trains. Since freight trains tend to operate in the speed range where dynamic braking is most effective, crews will often use electric braking in preference to air braking to control the train. Thus, under normal circumstances, the braking rates are within the energy dissipation capability of the dynamic brake system, and a large proportion of the brake energy is available for recovery. Train performance modeling by Transpor-

tation Technology Center, Inc, in the mid-1990s showed that regenerative braking recovery in excess of 60% could be achieved with flywheel storage tenders attached to locomotives. The main drawback is that the storage capacity of the tender units had to exceed 3MWh to make the system practical. That is well beyond the technical and economic capability of existing or projected storage technologies.

Table 4 summarizes in qualitative terms the performance benefits to be gained from regenerative braking and restates the packaging difficulty for each of the main service types. As for tractive effort, benefits of regeneration for switchers are poor because slow-speed, normal operation does not provide substantial brake-energy recovery. At the same time, implementation would be difficult because the electric braking control equipment must be added to the basic switcher traction control system and extra volume is required for the energy-storage equipment and its control system.

TABLE 4: Hybrid Power and Regenerative Braking			
Type of Service	Qualitative Benefits	Packaging Difficulty	Comments
Switcher	None	High	Speeds too low to demand high power and to store significant brake energy.
Light Rail	Low	High	Available space limited for installation of energy storage system. Low-speed operation at street level restricts available brake energy
Mass-Transit	Medium	High	Good benefits from matching third-rail system but lack of space a major issue.
Commuter Rail	Medium	Low	Good benefits. Space less of an issue (tender car can be used if necessary)
Intercity Passenger	Medium	Medium	Same as commuter rail but tender car less desirable due to platform/train-length constraints
High Speed Rail	Low	High	Continuous power rating dominated by aerodynamics. High friction braking rates reduces scope for brake energy recovery. Added space and weight a major issue.
Line-haul Freight	Medium	Medium	Duty cycle dominated by long periods spent at full power. Braking rates may yield higher stored energy potential. Express freight may benefit from added brake energy recovery.

Analysis of Cost

While performance benefits of fuelcell-hybrid powerplant are limited to a relatively small number of rail-road service types, given the current high cost per kilowatt of fuelcells, justification of a hybrid powerplant may be possible on the basis of cost. However, the cost justification cannot be made solely on a capital (or first) cost basis. Variations in operating and maintenance costs must also be considered. For a

reliable comparison of the various options to be made, all of the cost components for the alternatives have to be identified and quantified. These can then be applied to a comparison cost model.

As part of this assessment effort, a spreadsheet cost model was assembled to enable an optimized cost analysis to be carried out for the surface locomotive designs. To allow comparisons, the model predicts costs on an annual basis. The methodology used in this model was identical to that used in the model developed by Miller [Miller, 2001] to find the least cost for fuelcell-battery hybrid industrial vehicles.

Elements of the Cost Model

Input variables of the cost model include (1) equipment capital cost, (2) equipment maintenance cost, (3) equipment life, and (4) operating costs (including fuel); these input data were provided by the partners in the 1.2-MW locomotive project. As input variables, they can be revised for other service types.

The duty cycle, as a discrete function, is one of the most critical input parameters to the model. In general, the longer the time segment of data used to establish the duty cycle, the better-defined it is. Two sources of rail duty-cycle data are available.

The first method of duty-cycle definition utilizes event-recorder data. Like the airline industry "black boxes," event recorders are mandatory on all operationally active locomotives. The main purpose of the event recorder is accident investigation, but also most of the operational parameters of the locomotive and train are continuously recorded and stored. These data include "time-at-notch" (i.e., time at a discrete power setting), recorded over several days or even weeks. This "time-at-notch" data is the most useful method of defining the duty cycle for the cost model. It is also possible to use discrete segments of time-history data from an event recorder (in either full or truncated format) to define the duty cycle. However, the risk of distorted results is higher because any selected segment is less likely to be truly representative of the longer term duty cycle.

The second method of duty-cycle definition data utilizes route-simulation data. However route simulation is only useful where the service is highly repeatable (e.g. commuter rail services).

Modeling Results

The results of a preliminary cost comparison analysis for a switcher locomotive are shown in Table 5. This comparison was based on a 1500 kW diesel-equivalent switcher locomotive working on a yard switching duty cycle derived from the analysis of time-at-notch event-recorder data for a railroad switcher unit [Peters, 2004]. The results are presented for a 1200 kW pure fuelcell (non-hybrid) powerplant and for a range of hybrid configurations, with fuelcell prime movers ranging from 200 kW to 700 kW. The data for the hybrid cost includes the projected total annual cost, the fuel-cost component of the total, and the fuel-cost penalty resulting from the double efficiency penalty – losses occur both in and out of the auxiliary storage device.

TABLE 5: Cost Analysis Results

Hybrid Configuration			Hybrid Cost Data (Annualized)			
Fuelcell Rated Power (kW)	Battery Capacity (kWh)	Battery Weight (Tonne)	Total Cost	Hybrid Fuel Cost	Fuel Cost Penalty	Fuel Capacity Penalty (%)
200	1863	28.7	\$345,001	\$106,829	\$36,904	53
250	1105	17.0	\$276,578	\$102,442	\$32,517	47
300	870	13.4	\$261,006	\$98,091	\$28,166	40
350	824	12.7	\$267,075	\$94,558	\$24,633	35
400	752	11.6	\$260,033	\$90,474	\$20,549	29
450	683	10.5	\$266,299	\$87,753	\$17,828	25
500	624	9.6	\$269,961	\$85,793	\$15,868	23
550	559	8.6	\$281,328	\$83,458	\$13,533	19
600	497	7.6	\$271,644	\$80,826	\$10,901	16
650	372	5.7	\$279,592	\$79,479	\$9,554	14
700	328	5.0	\$286,634	\$78,497	\$8,572	12
750	288	4.4	\$293,836	\$77,246	\$7,321	10
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1200	0	0	\$369,925	\$69,925	0	0

In the example shown, the model predicts that the total annual cost, capital plus recurring costs, for the pure fuelcell configuration is approximately \$370 thousand, including a fuel cost of \$70 thousand. The least-cost fuelcell hybrid configuration – utilizing a 400 kW fuelcell and a 752 kWh battery – predicts that total cost can be reduced by approximately 30% to \$260 thousand, even though the fuel-cost component has increased by over 60%.

CONCLUSIONS

Although they cannot fully reach their potential for enhanced performance, the most likely applications to benefit from enhanced tractive effort and regeneration are commuter rail and long-distance intercity passenger trains. Packaging of the bulky hybrid powerplant is relatively easy because it is in a separate locomotive. In contrast, for light rail and mass-transit, packaging is difficult because power equipment is distributed over a multiple-unit vehicle and must be mounted under the floor. Because maximum power is required for extended periods and because only a fraction of the large kinetic energy of train can be absorbed in today's auxiliary storage devices, cases least likely to benefit from enhanced transient power or regeneration are high-speed rail and heavy freight. We do find that yard switchers, and possibly other rail vehicles, may benefit from reduced capital cost (or first cost) of a hybrid powerplant. However, this benefit comes at the price of increased complexity and reduced thermodynamic efficiency.

With regard to the design of a hybrid switcher locomotive, the only current practical auxiliary storage device is a nickel metal-hydride battery. Due to wheel-adhesion limitations of locomotives operating at low

speeds, there are no likely performance benefits to be derived from potentially increased tractive effort available from hybrid power. Brake energy recovery is not practical for switcher locomotives because of the lack of available energy and the relatively poor performance of traction motors in generation mode at low operating speeds. Based on current cost data, significant cost benefits should be available from the use of a fuelcell hybrid configuration in a yard switcher locomotive. Weight and space limitations constrain available hybrid configurations and prevent the use of the cost-optimized solution. A hybrid locomotive will require either a 20 - 40% increase in fuel capacity or a 20 – 40% reduction in operating time for the same duty cycle. As future fuelcell production and operating costs are reduced, the cost advantage of a hybrid will dissipate.

ACKNOWLEDGEMENTS

We thank the following for their generous support of the projects described in this paper: US Department of Energy (contracts DE-FC36-99GO10458, DE-FC26-01NT41052, DE-FC36-01GO11095, and DE-FC36-05GO85049); Natural Resources Canada (Emerging Technologies Program contracts 23440-991022-001 and EA9730-F01-01); Government of Canada (Action Plan 2000 on Climate Change contract 23440-0310202-001); US Department of Defense (contracts F42620-00-D0036 and F42620-00-D0028); subcontractors to Vehicle Projects LLC who contributed project cost-share; and the Fuelcell Propulsion Institute. We are grateful to the consortium members who made contributions to the results of this paper. *Disclaimer:* Funding support from the US Department of Energy, US Department of Defense, Natural Resources Canada, or Government of Canada does not constitute an endorsement by same of the views expressed in this article.

REFERENCES

- [Access to Energy, 1975] Is That A Way To Run A Railroad?, Access to Energy Newsletter Archive, Vol. 2, No. 12, August 01, 1975, Web reference: <http://www.accesstoenergy.com/view/atearchive/s76a3842.htm>
- [Desrivieres & Betournay] G. Desrivieres and M. Betournay, Duty Cycle Evaluation Project. Final report MMSL 02-036(CR), CANMET Mining and Mineral Sciences Laboratories, prepared under contract to Vehicle Projects LLC, Denver, USA, 22 July 2002
- [Geocities, 2002] Regenerative Power and Motion, Flywheel Basics Tutorial, December 2001, (website reference: <http://www.geocities.com/dfracella/basics.html>)
- [Herbst] J. Herbst, ALPS Locomotive Propulsion System – Technology Prospectus, Center for Electro-mechanics-The University of Texas at Austin (website reference: http://www.utexas.edu/research/cem/technology_prospectus.html)
- [Herbst & Hebner] J. Herbst and R. Hebner, ALPS Locomotive Propulsion System (Description), Center for Electromechanics-The University of Texas at Austin (website reference: http://www.utexas.edu/research/cem/alps_description.html)
- [Herbst, et al, 2000] J. D. Herbst, R. F. Thelen and W. A. Walls, Status of Advanced Locomotive Propulsion System (ALPS) Project, Center for Electromechanics-The University of Texas at Austin (website reference: <http://www.utexas.edu/research/cem/publications/PDF/PN249.pdf>), May 2000

[Miller, 2000] A. R. Miller, Tunneling and Mining Applications of Fuelcell Vehicles, *Fuel Cells Bulletin*, May 2000

[Miller, 2001] A. R. Miller, Least-cost Hybridity Analysis of Industrial Vehicles. *European Fuel Cell News*, Vol 7, January 2001, pp. 15-17

[Miller & Barnes, 2002] A. R. Miller and D. L. Barnes, Fuel Cell Locomotives. *Proceedings of Fuel Cell World*, Lucerne, Switzerland, 1-5 July 2002

[Miller, et al, 2004 A] A. R. Miller, D. L. Barnes, O. Velev, L. Sheppard, P. Chintawar, A. Delfrate, M. Golben, and T. Vencill, Fuelcell Locomotive for Commercial and Military Railways. *Proceedings of 2004 Fuel Cell Seminar*, San Antonio, USA, 1-5 November 2004

[Miller & Barnes, 2004 B] A. R. Miller, D. L. Barnes, Brian D. Hoff, Omourtag Velev, Lindsay Sheppard, Prashant Chintawar, and Mark Golben, Fuelcell-Battery Hybrid Mine Loader. *Proceedings of 2004 Fuel Cell Seminar*, San Antonio, USA, 1-5 November 2004

[Peters, 2004] A. J. Peters, The Performance of Railroad Motive Power, Fuelcell Locomotive Project Report, June 2004

[Railpower, 2003] Railpower Technologies Corporation, The Green Goat – Hybrid yard Switcher, Technical Specification Sheet, April 2003