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Analysis of fuel cell hybrid locomotives

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Abstract

Led by Vehicle Projects LLC, an international industry–government consortium is developing a 109 t, 1.2 MW road-switcher locomotive for commercial and military railway applications. As part of the feasibility and conceptual-design analysis, a study has been made of the potential benefits of a hybrid power plant in which fuel cells comprise the prime mover and a battery or flywheel provides auxiliary power. The potential benefits of a hybrid power plant are: (i) enhancement of transient power and hence tractive effort; (ii) regenerative braking; (iii) reduction of capital cost.

Generally, the 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 assist applications that require high acceleration, e.g. subway trains with all axles powered.

In most cases, the value of regeneration in locomotives is minimal. For low-speed applications such as switchers, the available kinetic energy and the effectiveness of traction motors as generators are both minimal. 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 power plant suffers a double efficiency penalty, namely, 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 present battery technology.

Capital cost in some applications may be reduced. Based on an observed locomotive duty cycle, a cost model shows that a hybrid power plant for a switcher may indeed reduce capital cost. Offsetting this potential benefit are the increased complexity, weight and volume of the power plant, as well as 20–40% increased fuel consumption that results from lower efficiency.

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

Keywords: Fuel cell; Hybrid; Locomotive; Road-switcher; Power-plant efficiency; Capital cost

1. Introduction

Led by Vehicle Projects LLC, an international industry–government consortium is developing a 109 t, 1.2 MW road-switcher locomotive for commercial and military railway applications (see Fig. 1) [1]. As part of the feasibility and conceptual-design analysis, an assessment has been made of the potential benefits of a hybrid power plant in which fuel cells comprise the prime mover and a battery or flywheel serves as rechargeable auxiliary power device.

Potential benefits of a hybrid power plant are: (i) enhancement of transient power and hence tractive effort; (ii) regenerative braking; (iii) reduction of capital cost. These potential advantages may, however, be less realized 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 power plant 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 gradient may require a hybrid system with an impractically large auxiliary storage capacity.

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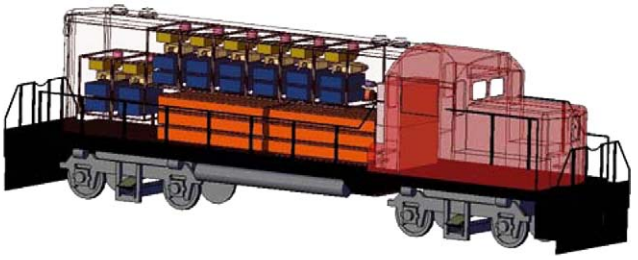

Fig. 1. Conceptual design of 1.2 MW fuel cell-powered road-switcher locomotive. Power plant design consists of eight identical 150 kW stand-alone modules. Based on analysis presented in this paper, the locomotive will not use a hybrid power plant.

This study examines the practicality of fuel cells 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. This does not apply, however, to high-speed rail and heavy freight operations because maximum power is required for extended periods and only a fraction of the large kinetic energy of the train can be absorbed by today's auxiliary storage devices. We do find that yard switchers, and possibly other rail vehicles, may have reduced capital cost (or first cost) if a hybrid power plant is used. Nevertheless, this saving is offset by increased complexity and reduced thermodynamic efficiency of the system.

A hybrid fuel cell–battery mine loader has been developed [2]. Although packaging has been challenging (see Fig. 2), the 'peaky' duty cycle of a loader [3] demanded the use of a hybrid power plant.

Nonetheless, based on the analysis below, the 1.2 MW road-switcher will not be a hybrid. Vehicle Projects LLC developed and demonstrated, during 1999–2002, a fuel cell-powered mine locomotive, which likewise was not a hybrid [4]. A feasibility analysis for that project showed that wheel adhesion was the limiting factor in performance and not fuel cell power [5]. Excellent performance of the mine locomotive has shown the analysis to be correct.

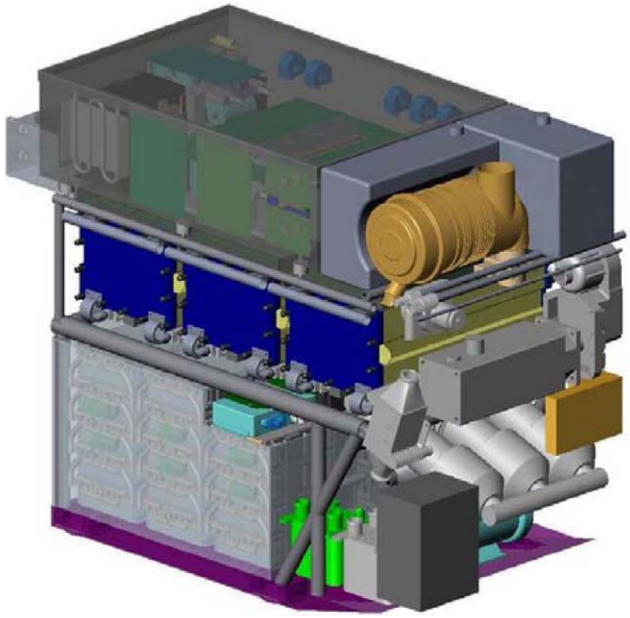

Fig. 2. Fuel cell–battery hybrid power plant for a mine loader. Fuel cell continuous power is 90 kW and an auxiliary storage unit, i.e. a nickel–metal-hydride battery, can supplement this by 70 kW of transient power. Both are water-cooled.

2. Background

Auxiliary energy-storage devices for railway use are required to be rugged, have a high energy density and provide power over relatively long periods. At present, only two viable energy-storage technologies meet these requirements—batteries and flywheels. A typical power bus structure of a fuel cell–battery or fuel cell–flywheel system is shown in Fig. 3.

Hybrid power has already been demonstrated in some rail applications. In situations 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. For examples, diesel–third-rail locomotives are used for commuter trains travelling through the approach tunnels to New York City terminals. Recently, a number of diesel–battery hybrid switcher locomotives, marketed

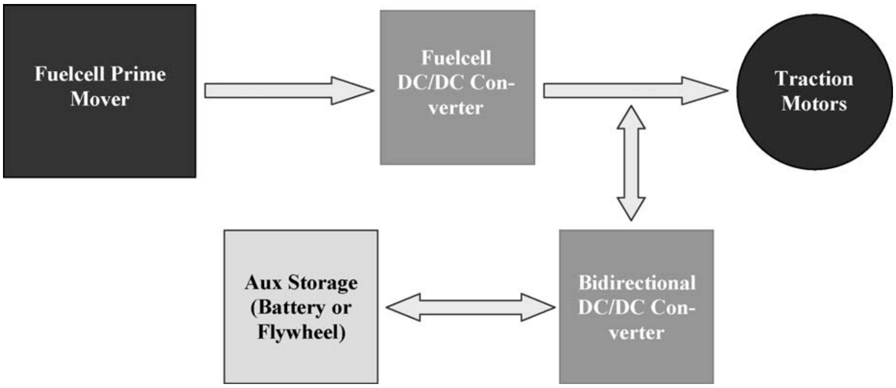

Fig. 3. Main components of fuel cell hybrid power train. 'Aux Storage' represents either battery or flywheel auxiliary energy storage. Arrows point in the direction of power flow. Traction motors are used as generators during braking. A system using a.c. traction motors would be analogous to the d.c. system shown.

as the 'Green Goat' [6], have been field tested by several North American railroads. The justification for many of these applications that involve a diesel-engine prime mover is reduction of exhaust emissions. Since fuel cells are zero-emission devices, emissions reduction is not an issue in the analysis of a fuel cell hybrid power plant.

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 [7]. The objective of the ALPS project, funded by the US Federal Railroad Administration, is to develop a fossil-fuelled locomotive for non-electrified high-speed rail services, and with the same short-term power rating as a catenary-electric locomotive. The purpose of flywheel energy-storage is to reduce the thermal cycling of the gas turbine, and thereby reduce maintenance. Power cycling, like emissions, is not an issue for fuel cells.

Regenerative braking is already used in many electrified railway systems to recover braking energy. The power generated 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 little additional equipment is required on the rolling stock. Also, the trackside distribution system has the capacity to direct the power to other trains and only make up the difference from the utility grid. Many a.c. overhead systems also have the ability to return power to the grid. The traction supply system can provide substantial transient-power overload. Whether a fuel cell hybrid system can be equally effective in recovering braking energy is a subject of this analysis.

An obstacle to the widespread use of hybrid power in rail vehicles is on-board limitation of mass and volume. Railway vehicles, which are subject to severe restrictions on axle load and clearances, require efficient use of available weight and space in the packaging of on-board equipment. For example, the design of the diesel–third-rail hybrid locomotives discussed above involved a compromise in 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 on-board packaging in any application.

3. Results and discussion

3.1. 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 with rolling stock, such as a mass-transit (subway) train, that have a large proportion of the axles powered. As demonstrated by computer simulation [8], wheel adhesion limits tractive effort most severely in locomotive-hauled trains during start-up (acceleration from rest). For example, simulation of a commuter locomotive pulling a passenger train, showed that the hybrid auxiliary source is not able to augment the prime mover until the train speed has reached a speed of 40 km h^{-1}.

In most passenger-train configurations, the minimum continuous power is defined by 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 a 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 haul reliably 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 prime 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 rather for a service where there are a relatively large number of line-speed restrictions or short grades, and where good speed recovery and maintenance are 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^{-1}, are generally wheel-adhesion limited rather than power limited, and their tractive effort is unlikely to benefit from a hybrid power plant.

An analysis of rail applications with respect to their possible enhancement of tractive effort is summarized in Table 1. The entry for the switcher service illustrates the results

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 power plant. Acceleration and speed potential greater than for light rail
Commuter rail	High	Low	Good benefits. Space is less of an issue (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

displayed—likely benefits are ranked ‘low’ because wheel adhesion, rather than power, limits tractive effort during frequent start-up operations. The challenge of packaging a hybrid power plant within the mass and volume constraints of the vehicle is termed the ‘packaging difficulty’.

3.2. 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 cannot be absorbed by practical hybrid storage systems. 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 d.c. traction motors (installed in most switchers) when acting as generators is also low. The electric braking characteristics and efficiency of a.c. 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^{-1}, a.c. traction motors add little to the overall available energy recovery.

3.3. Energy-storage devices

Regarding auxiliary energy-recovery devices, automotive batteries have been dominated by lead–acid technology for over 100 years. The main advantages of these batteries are high power and low cost. Increasing demand for improved cycle life and operation over a broad temperature range has, however, driven the development of alternative (so-called ‘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 with lead–acid. Moreover, lithium-ion technology provides higher specific energy, uses 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 specific energy and improves high-power performance. There are, however, unresolved issues with the safety of large cells and reliable battery-pack management.

When comparing traction batteries, key performance measures are specific power, specific energy, life and cost. Table 2, based on a compilation of published performance and estimated cost data, provides a general comparison of these important factors. Considering the parameters collectively, lithium-ion batteries are potentially the best performing of the three technologies for traction applications. Nevertheless, 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.

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 [9]. Previous studies have 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 that was equipped with a flywheel energy-storage system [10]. While these tests were reasonably successful from a technical perspective, on-board energy storage for braking was obviated by the development of third-rail regenerative-braking technology, which is now used by many mass transit authorities world-wide. 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 specific energy 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

Table 2
Battery parameters

Battery type	Specific power (W kg^{-1})	Specific energy (W h kg^{-1})	Cycle life	Life (years)	Cost target ($ per kW h)
Sealed-lead–acid	600	40	500	2	150
Nickel–metal-hydride	400	65	3000	5	450
Lithium-ion	500	150	2500	5	500

Table 3
Parameters of ALPS rail flywheel

Storage capacity	133 kW h (480 MJ)
Delivered capacity	100 kW h (360 MJ)
Total weight (including generator and controls)	18 t
Operating rotational speed range	7500–15,000 rpm
Motor-generator rating	2 MW at 1200 VAC, three-phase
Energy transfer efficiency (each way)	95%
Storage decay	2% per h

severe manner than steel-rotor designs. Flywheel units, with storage capacities between 1 and 10 kW h 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 the 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 [11] 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 [12]. The present design parameters for the ALPS flywheel are listed in Table 3.

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 fuel cell hybrid power plant are still in the early commercialization stage and are likely to be more expensive than 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. In the mid-1990s train performance modeling by the Transportation Technology Center Inc. 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 3 MW h to render the system practical. This 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 recovery of braking energy. 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.

3.4. Analysis of cost

While performance benefits of fuel cell-hybrid power plants are limited to a relatively small number of railroad service types, given the current high cost per kilowatt of fuel cells, justification of a hybrid power plant may be possible on the basis of cost. The cost justification cannot, however, 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, 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 [13] to find the least cost for fuel cell–battery hybrid industrial vehicles.

3.5. Elements of cost model

Input variables of the cost model include: (i) equipment capital cost; (ii) equipment maintenance cost; (iii) equipment life;

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

(iv) 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 is it defined. Two sources of rail duty-cycle data are available. The first method utilizes event-recorder data. As in the airline industry, event recorders (‘black boxes’) are mandatory on all controlling 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’ measurements (i.e. time at a discrete power setting), which are 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. The risk of distorted results is, however, 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. This is only useful where the service is highly repeatable (e.g. commuter rail services).

3.6. Modeling results

The results of a preliminary cost comparison analysis for a switcher locomotive are given in Table 5. This comparison is based on a 1500 kW diesel-equivalent switcher locomotive that is working on a yard switching duty cycle derived from analysis of time-at-notch event-recorder data for a railroad switcher unit [8]. The results are presented for a 1200 kW pure fuel cell (non-hybrid) power plant and for a range of hybrid configurations, with fuel cell prime movers that range from 200 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 that results from the double efficiency penalty, i.e. losses that occur both in and out of the auxiliary storage device. In the example shown, the model predicts that the total annual cost, i.e. capital plus recurring costs, for the pure fuel cell configuration is approximately US$ 370,000, which includes a fuel cost of US$ 70,000. The least-cost hybrid configuration—utilizing a 400 kW fuel cell and a 752 kW h battery—predicts that the total cost can be reduced by approximately 30% to US$ 260,000, even though the fuel-cost component has increased by over 60%.

Table 5
Cost analysis results

Hybrid configuration			Hybrid cost data (annualized)			
Fuel cell rated power (kW)	Battery capacity (kW h)	Battery weight (t)	Total cost (US$)	Hybrid fuel cost (US$)	Fuel cost penalty (US$)	Fuel capacity penalty (%)
200	1863	28.7	345001	106829	36904	53
250	1105	17.0	276578	102442	32517	47
300	870	13.4	261006	98091	28166	40
350	824	12.7	267075	94558	24633	35
400	752	11.6	260033	90474	20549	29
450	683	10.5	266299	87753	17828	25
500	624	9.6	269961	85793	15868	23
550	559	8.6	281328	83458	13533	19
600	497	7.6	271644	80826	10901	16
650	372	5.7	279592	79479	9554	14
700	328	5.0	286634	78497	8572	12
750	288	4.4	293836	77246	7321	10
⋮	⋮	⋮	⋮	⋮	⋮	⋮
1200	0	0	369925	69925	0	0

4. 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 power plant is relatively easy because it is in a separate locomotive. For light rail and mass-transit, however, packaging is difficult as the 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 only a fraction of the large kinetic energy of the 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. On the other hand, it is found that yard switchers, and possibly other rail vehicles, may benefit from reduced capital cost (or first cost) of a hybrid power plant. Unfortunately, this benefit is accompanied by 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 the wheel-adhesion limitations of locomotives operating at low speeds, there are no likely performance advantages to be derived from the potentially increased tractive effort that is available from hybrid power. Recovery of brake energy 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 data, significant cost benefits should be available from the use of a fuel cell 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 fuel cell production and operating costs are reduced, the cost advantage of a hybrid will dissipate.

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