Submitted for the 2013 Second World Sustainability Forum
Section D: Energy Efficiency and Renewable Energy Sources

THE ECONOMICS OF ELECTRIFYING NORTH AMERICAN RAILWAYS

Ellen Morrison, BASc, MASc Student

Dr Gord Lovegrove, P.Eng., MBA, PhD
Associate Professor, Civil Engineering
gord.lovegrove@ubc.ca, 250-807-8717

School of Engineering, Faculty of Applied Science
The University of British Columbia | Okanagan Campus

Word Count: 5,225 + 4 tables = 6,225
Tables 4 @ 250 = 1,000 words

October 22, 2012

ABSTRACT

As fuel costs increase, transportation modes are looking to railways as a cheaper, more efficient and environmentally friendly alternative. Because of railway transportation's immense advantages over road and air transportation, its use is expected to increase two-fold or more over the next 10 years in the US and Canada, and likely all of North America (NA). However, NA railways are still dependent on diesel-electric locomotives, while other countries in Europe and Asia have long ago switched to more efficient electric locomotive technology. Electric locomotives have significant benefits over diesel-electrics, such as increased efficiency and traction, a lower probability of failure, reduced noise and vibrations, potential for brake regeneration, and an overall reduced carbon footprint. Despite these advantages, electric locomotives can cost significantly more than diesel-electrics and require expensive infrastructure, such as catenary lines and electric substations.

In 2008, the U.S. Environmental Protection Agency implemented new regulations on diesel-electric locomotives to reduce emission toxins such as particulate matter and NO_X. These new regulations create i health benefits, but come at a cost to railway organizations for more stringent manufacturing and remanufacturing requirements. This paper explored the potential costs associated with electrifying the railway network in NA rather than focusing on improving diesel-electrics. A Monte Carlo Simulation was conducted to compare these costs with converting current railway lines to catenary, or partial catenary with on-board storage systems. Factors such as research costs, noise reduction benefits, health benefits, fuel usage, and productivity were taken into consideration to determine the most suitable alternative for the future of NA's railway organizations, environment, and society. Results suggest that implementing ultracapacitor or battery hybrid locomotive technology would create significant positive net present worth between 2012 and 2040, estimated at $411 Billion for passenger rail and $15.7 Trillion for freight rail, due mainly to less overhead catenary infrastructure and energy costs required, while still gaining the social benefits of reduced noise and improved health. They would also be the quickest electrification technology options to implement in terms of manageable construction and business disruption logistics, which were not considered in this analysis and should be research if and when business case development occurs in pursuit of electrifying railways. Moreover, over 80% of this significant NPW would accrue to railway organizations, suggesting that business case development and investment planning should proceed post haste to electrify, and to phase out diesel electric locomotives at the end of their economic life.

Regardless of which route is taken, electrification would have immense benefits to both railway organizations and society. Increased productivity, reduced energy requirements, decreased noise and improved health would all significantly contribute to cost savings and an improved quality of life for residents of North America. As such, there appears to be a strong business case for research into development of hybrid electric locomotives that can operate on- and off-grid.

Keywords: Rail, electrification, diesel-electric, ultracapacitor

INTRODUCTION

Freight by rail is a significantly efficient transportation mode in terms of energy consumption and costs when compared to truck and air transportation. Rail efficiency has improved 106% between 1980 and 2010, and today, one tonne of freight can travel 484 miles per gallon of fuel (AAR 2011). If just 10% of freight currently moved by truck was transferred to rail transportation, one billion gallons of fuel would be saved per year, which is equivalent to reducing greenhouse gases (GHG) by 12 million tons (AAR 2011). The majority of locomotives utilized in the United States (US) today are powered by diesel locomotives, which were found to be 50 – 94% less polluting than freight transportation by road, depending on the pollutant analyzed (Horvath and Facanha 2006). Despite the excellent efficiency of diesel locomotive freight compared to other transportation modes, diesel fuel emissions can be significantly detrimental to the environment. Since freight activity is expected to grow by 100-200% in the south of the US and by 79% in the northeast of the US between 2000 and 2020 (Horvath and Facanha 2006), it is essential to examine more environmentally friendly alternatives. The US Environmental Protection Agency (EPA) has already set forth new regulations for diesel locomotives which will positively impact the environment, but will also cost railway organizations millions of dollars.

Diesel locomotives emit significant particulate matter (PM) and oxides from nitrogen (NO_X), which can contribute negatively to health problems such as asthma and respiratory disease. Consequently, the US EPA has become more stringent regarding locomotive regulations. In 2008 the EPA implemented a three part regulation to decrease PM and NO_X from locomotives by up to 90% and 80%, respectively (EPA 2008). The EPA originally had three tiers of regulations for locomotives, where Tier 0 was applied to locomotives manufactured between 1973 and 2001, Tier 1 for locomotives manufactured between 2002 and 2005, and finally, Tier 2 for locomotives manufactured between 2005 and 2009. However, with the new regulations, Tier 3 and Tier 4 have been introduced, which are much more stringent. Overall, the 2008 EPA regulations aim to (EPA 2008):

1. Tighten locomotive emission standards when they are remanufactured,
2. Set short term standards (Tier 3) for remanufacturing of locomotives, starting in 2010,
3. Set long term standards (Tier 4) for manufacturing of locomotives, starting in 2015.

Although there are significant health savings associated with these improvements, this does not come without costs to railway organizations for new research, engineering, certification, and more costly remanufacturing (EPA 2008). Furthermore, with international rail transport, these EPA regulations will affect the rest of North America, meaning that Canada and Mexico may also be required adopt these more stringent regulations for diesel-electric locomotives. Since a large investment must be made to develop more environmentally friendly diesel-electric locomotives, railway organizations should examine alternative solutions especially since a significant investment is already required. Therefore, this paper summarizes research to examine the economics of electrifying 100% Canada and the U.S. railways with catenary line, ultra capacitor hybrid, and battery hybrid technology as an alternative to continuing with diesel-electric locomotives. Specifically, the research objectives were to:

1. Review the literature on systems designs and costing data for railway electrification technology, including: hybrid ultra-capacitor/battery; overhead catenary/third rail; battery; and Tier 3/4 diesel locomotive propulsion railway systems.
2. Use this comparative costing data to complete a strategic level cost-benefit analysis to determine how long it would take and how much it would cost to implement the capital infrastructure to support the conversion of current freight, tourism, and commuter railway systems in North America to 100% electric.
3. Make recommendations based on the results of the literature review economic analysis.

Electric Railways

Compared to conventional carbon based railway infrastructure, electrified railways are greatly beneficial for railway organizations economically, socially, and environmentally (Boozarjomehri 2009; Regenstreif 2009). Aside from the initial capital cost required to electrify a railway, money is saved as capacity and efficiency are increased. Electric trains are quieter and create fewer vibrations which are beneficial to passengers and urban centers. Furthermore, electric energy sources create fewer GHG emissions compared to diesel fuel. There are several railway organizations throughout the world that currently have a large portion of electrified railways and are expanding their infrastructure, including the European Union, Japan, and other Asian countries (Regenstreif 2009).

About 33% of Britain's railway network is currently electrified, focused mainly on corridors. Two thirds is powered by overhead line electrification, while the remaining third is powered by third rail electrification (Britain Department for Transport 2009). Moreover, 60% of passenger rail journeys in Britain are on electric trains (Britain Department for Transport 2009). This shows how important electrified railways have become to Britain and their rail transportation network. Because they recognize its importance to CO_2 emission reduction and rail efficiency, the Britain Department for Transportation (DfT) decided to launch a program costing $1.77 billion, funded by Network Rail and the Government to electrify more of their railway system. The Britain DfT believes that this investment will pay for itself through the inherent benefits of an electrified railway system, including: 1) lower running costs, 2) lower carbon emissions and better environmental performance, 3) increased capacity and reliability, and 4) better passenger experience (Britain Department for Transport 2009).

Regenstreif (2009) looked into converting Canada's current railway network into electric rail. He found that Canada is falling behind in sustainable rail transportation, as several areas around the world have electrified networks and plan to construct and convert more. Although major public infrastructure investment would be required to electrify Canadian railways and link 80% of Canadians living and working throughout the country, he argued that such a project would (Regenstreif 2009):

1. Reduce total fossil fuels for transport by more than 10%,
2. Shift dependence on fossil fuels to more sustainable and energy efficient options,
3. Generate many work opportunities for rail transport revitalization,
4. Reduce GHG and other emissions,
5. Provide an alternative for long-haul truckers, which would increase productivity and increase driver safety, while also reducing road congestion and emissions,

6. Build important transportation connections throughout the country through an electrified railway

The U.S. Department of Transportation (DoT) has also considered the possibility of enhancing US passenger rail infrastructure to electrified high speed rail. They calculated that to build an entirely new electrified track, for example between Los Angeles and Las Vegas for speeds of 240 kph, it would cost about $13.8 million per route kilometer. In contrast, improving existing track would cost about $1.6 million per route kilometer. Incremental track improvements could cost between $2.6 million and $7.1 million per route kilometer. An upgrade to the 366 kilometer long track in the north end of the Northeast Corridor connecting Boston to New York City, which included electrifying the route and replacing a bridge, cost about $5.6 million per kilometer, reduced travel time by half just over half an hour for passengers, and increased overall capacity (Peterman, Frittelli and Mallett 2009).

The literature suggests that the electrification of Britain, Canadian, and US railways would create significant benefits to railways and society, including: improved capacity, higher speeds, lower maintenance and operation costs, decreased environmental impact, and improved passenger and resident comfort. However, estimated electrification costs have traditionally been a major barrier, making a business case difficult. An emerging mitigating circumstance may be government policy, in response to global climate change and energy shortages. As government regulations become more strict with diesel powered locomotives (e.g. Tier 3, Tier 4), and as fuel prices increase, railway organizations may see that they need to make changes sooner rather than later. The question is whether cleaner diesel locomotives or all-electric locomotives are the better long-term, sustainable railway technology and business strategy.

Battery Hybrid Locomotive Technology

A hybrid system is a system that can conduct coordinated performance between two power sources, for example 60% of power would come from a main energy source and 40% would come from a sub-energy source at a given instance (Ogasa 2010). It is also important to consider the purpose of the system and associated requirements to select an appropriate hybrid technology (Ogasa 2010). There are several types of batteries that have been developed and can be utilized for hybrid locomotives applications (Konishi, et al. 2010), including: 1) lithium ion, 2) nickel-metal hydride, and 3) lead acid batteries. Hybrid locomotives with onboard energy storage would be beneficial for an electrified railway as there would be less infrastructure cost requirements for overhead contact lines.

Lithium ion batteries have a relatively high energy density as lithium has the smallest atomic weight of metals. Energy density is especially important if charging and discharging of the battery is required in longer trip durations. Also, it does not suffer from the “memory effect”, which is the ability to meet the maximum energy capacity after repeated charging and discharging cycles. Furthermore, it requires low maintenance and has a higher durability than lead acid batteries. However, lithium ion batteries still have a high initial cost as they are a relatively new technology. The service life of lithium ion batteries has been an issue, but as technology improves, their lifetimes are increasing and are therefore becoming more feasible. (Konishi, et al. 2010).

In contrast, nickel metal hydride batteries have a lower energy density than lithium ion batteries, but have a higher power density. Power density is more important if charging and discharging is required repeatedly over short durations. Furthermore, nickel metal hydride batteries do not contain harmful materials, which is a significant benefit to the environment. Moreover, they have a longer service life than the lithium ion battery (Konishi, et al. 2010). Ogasa (2010) described several hybrid locomotive models, including the Sapporo Municipal Transport system in Japan, which implemented nickel-metal hydride battery storage units on their electrified railway line. Each battery weighed 3200 kg and provided 120 kWh. Each unit consisted of 480 battery cells. With this setup, the train was able to operate for 37.5 km without contact with the power grid at a maximum speed of 40 km/h. Another test was conducted in Metro Transportes do Sul in Portugal, with nickel-metal hydride batteries, electric double layer capacitors, and the third rail gaining energy from the power grid. This experiment showed that the prototype train could run for 2.5 km without the third rail and that 30% of energy could be saved in favourable conditions (Ogasa 2010).

Lead acid batteries have been around longer than the lithium ion and nickel metal hydride batteries, and their performance is better known. Also, since it is an older technology, lead acid batteries are much less expensive (Sisson 2011). Through several years of development, they are also very robust and more dependable (Sisson 2011). However, they have lower energy capacity compared to newer battery technologies and a heavier weight (Sisson 2011). Heavier weights can be detrimental as there is more weight for the locomotive to pull or push through the trip. Sisson (2011) examined a potential hybrid freight train that utilizes a large battery car along with a standard diesel train. The hybrid design would charge from the grid and recharge through braking during downhill portions of the trip. The train would run on electric power whenever possible, and if not, it would revert to diesel power (Sisson 2011). Sisson selected lead-acid batteries for his economic analysis as they were cheaper and more feasible for current applications. Sisson also conducted an analysis using newer, more efficient battery technology for future application once their abilities have been proven and their prices lowered.

Hybrid locomotive technologies can greatly save energy costs, reduce greenhouse gas emissions, and can improve overall quality of life, which ultimately supports the triple bottom line. However, much consideration must be placed in determining which hybrid technologies should be implemented based on the nature of the railway system, current technology and infrastructure, as well as terrain.

Ultracapacitor Hybrid Locomotive Technology

Ultracapacitors, also known as supercapacitors or electrochemical double layer capacitors (EDLCs), (Maher 2006) are a fast emerging energy storage technology, with promising applications for railways. They are called *ultra or super* capacitors mainly due to their large capacitance of several thousand farads compared to a conventional capacitor, which can only hold several microfarads. Ultracapacitors are comprised of two electrodes, an electrolyte, and a separator. Energy can be stored in the ultracapacitor if the applied voltage is lower than the minimum voltage required to electrolyze the electrolyte (Okui, et al. 2010). This great increase in capacitance in ultracapacitors is possible due to a large surface area and a small charge separation compared to conventional capacitors (Maher 2006).

Today, several areas throughout the world have begun testing of ultra capacitors on their railway lines, including South Korea, France, Japan, and Germany (www.railwaygazette.com). This is because there are several advantages to using ultracapacitors as energy storage for locomotives compared to other technology, such as:

- Quicker charging/discharging, (Zhao, et al. 2010)
- High efficiency (Zhao, et al. 2010) (Okui, et al. 2010) (Maher 2006)
- Low maintenance (Zhao, et al. 2010) (Maher 2006)
- Lower impact on the environment (Zhao, et al. 2010) (Okui, et al. 2010)
- High output power (Okui, et al. 2010)
- Low heating levels (Okui, et al. 2010)
- Can operate in a variety of temperatures (McCluer and Christin 2011)
- Long lifetime (Okui, et al. 2010) (Maher 2006)

Although there are several advantages, ultracapacitors do have only 20% the energy density (the ratio of energy output to its weight) of a battery (McCluer and Christin 2011). However, large ultracapacitors are being developed with energy densities over 20 kWh/m^3. Other disadvantages are their technology is not widely known, which could be a barrier for many railway companies (McCluer and Christin 2011).

The Seibu Railway in Japan installed ultracapacitors at two substations in 2007. The ultracapacitor system designs at both substations were generally the same, with both systems having 288 ultracapacitor units (8 in series, and 36 in parallel). The segment of rail between the substations was at a slope of 2.5%, which allowed for regenerative braking to add energy to the systems. The regenerative energy charged by both systems was 7.7 kWh and the discharge energy was 5.9 kWh. Overall, about 77% of regenerative energy was able to be reused effectively using the ultracapacitor systems (Okui, et al. 2010).

Siemens Transportation Systems developed an energy storage system in the early 2000's called the SITRAS SES. This system is composed of 1,344 ultracapacitors that operate at 2.3 volts and each have a capacitance of 2,600 farads. These ultracapacitors have an efficiency of 95% and provide a peak power capacity of one megawatt. The SITRAS SES system stores energy from regenerative braking to ensure that energy is not lost to the atmosphere and can be used by accelerating trains at differing times. Another benefit of the system is that it stabilizes the energy within the rail network to allow for backup when several trains require energy at one time. The SITRAS SES system has been implemented throughout Europe, and also in Portland, Oregon since 2002. (Maher 2006). The system has shown to save 30% of energy from the network. If the system were to operate 22 hours per day, this could reduce energy requirements from the grid by 500,000 kWh per year, which is the same as saving 300 tons of CO_2 per year. Each SITRAS SES system can save 320 MWh per year, which can save about $32,000 per station per year based on energy costs of $100 per MWh. The 30% energy savings, 50% reduced peak power requirements and a system lifespan of 10 years combined contributes to millions of dollars of savings. (Maher 2006)

Ultimately, ultracapacitors can lead to great economical and energy savings. They have an abundance of advantageous characteristics and are only becoming better with time.

ECONOMIC ANALYSIS

Several areas were taken into consideration when conducting the economic analysis on rail electrification in North America. Statistics from the U.S. and Canada were compiled and vetted to determine noise costs and benefits, projected energy use and costs, capital costs for electrification, research costs, health benefits, and productivity.

Noise Costs and Benefits

It was found that on average, households were willing to pay 5 – 50 Euros ($6.50 – $65 USD) per year per decibel in areas of 55 dB or more due to railways (Committee on Technology for a Quieter America National Research Council 2010). It was found that in 1981, 4.7 million households were negatively affected by railway noise in the U.S. This number was extrapolated with the number of track miles in the U.S. in 1981 to find the average population density per kilometer of railway track. This density of residents per track kilometer was then increased with each year at the same rate as the general population growth of the U.S.. The newfound population densities per track kilometer was then multiplied by the number of track miles in 2009 (the latest statistic found) to find the total number of people affected by railway noise in 2009. An average of 3 residents per household was assumed to find the number of household residing along each track kilometer. Finally, the number of households was multiplied by the willingness to pay per household and the present worth (PW) was found from 2012 – 2040 of $7.4 to $74.0 billion.

Alternatively, the average cost incurred on a railway to mitigate railway noise and vibration by 5 dB was found to be $100 - $500 per foot of track (Zapfe, Saurenman and Fidell 2009). Assuming an equal portion of the track was mitigated each year, from 2012 to 2040, it was found that the railways would need to pay a PW of $304.4 to $1,521.9 billion to decrease the noise by 30 dB.

Therefore, the cost to the railroad significantly exceeds the willingness to pay for households residing along the railway track. Therefore, it would not make financial sense for the railways to mitigate the issue, but meanwhile, they would be disturbing residents along the track. However, electrifying a railway can decrease the noise by 30 dB without the need for costly mitigation, making adjacent communities more livable and creating goodwill for expanding railway networks. This would therefore be an inherent benefit of electrified railways.

Diesel Costs

Using data from the Organization for Economic Co-Operation and Development (OECD) Infrastructure to 2030 report (OECD 2007), the projected diesel fuel consumption between 2012 to 2040 for rail in Canada and the U.S. was established. The OECD estimated the growth of passenger and freight rail traffic from 2005 to 2035. The projected future costs of diesel fuel was also found (California Energy Commission 2011), to determine the present worth in 2012 dollars of diesel fuel that would be consumed if diesel-electric locomotives were to continue operating. It was found that the present worth in 2012 dollars of projected consumption of diesel fuel between 2012 and 2040 is $11.9 to $17.5 trillion.

Electrical Energy Costs

The electrical energy requirements were calculated by finding the equivalent input energy required through projected diesel fuel requirements. The future energy costs for electric energy were estimated through projections from the U.S. Energy Information Association (EIA 2011). The 2012 present worth of electric energy costs was then determined to be $85 billion between the years 2012 and 2040, a factor 500 times less than diesel energy costs.

Capital Costs for Electrifying Track

The cost to retrofit freight rail with electric overhead lines has been conservatively estimated to be as high as $40 million per mile ($24.9 million per kilometer) (Smith, Jia and Mariappan 2008), although estimates as low as $1 million per mile were found in the literature (Boozarjomehri 2009). Furthermore, it was found that it would cost conservatively between $7 and $9 million per mile ($4.3 to $5.0 million per kilometer) to electrify passenger rail track with overhead wires (Peterman, Frittelli and Mallett 2009). Given this wide range of cost estimates, and the possibility of off-grid locomotive technology (Boozarjomehri 2009), two scenarios were analyzed for electrifying track:

1. 100% of current rail track electrified with overhead contact wires, and
2. 5% of current rail track electrified with overhead contact wires

The analysis included 5% of the current rail track becoming electrified with overhead contact wires since Flaherty (2005) estimated this was the requirement for an ultracapacitor hybrid locomotive to charge sufficiently to operate between stations. Table 1 displays the present worth of electrifying 100% or 5% of passenger and freight rail track.

TABLE 1 Present Worth (2012) of Electrifying Railways in North America ($ Billions)

		100% Electrified		5% Electrified	
		Min	Max	Min	Max
Passenger	2012 PW (complete in 2012)	84.2	96.3	4.2	4.8
	2012 PW (complete in 2022)	63.0	72.0	3.1	3.6
	2012 PW (complete in 2032)	46.3	52.9	2.3	2.6
Freight	2012 PW (complete in 2012)	8,117		406	
	2012 PW (complete in 2022)	6,071		304	
	2012 PW (complete in 2032)	4,463		223	

Locomotive Capital Costs

Capital costs for different locomotives of diesel-electric, electric, ultracapacitor hybrid and battery hybrid were estimated for conducting the analysis. The U.S. EPA stated that the average cost of a diesel-electric locomotive is $1.5 to $2.2 million (EPA 2008). The British Department for Transport suggested that an electric passenger locomotive would cost 20% less than a diesel-electric, which would mean it would cost from $1.2 to $1.76 million (Britain Department for Transport 2009). It was estimated that a freight electric locomotive would cost twice the cost of a diesel-electric.

A passenger ultracapacitor hybrid locomotive was estimated at $1.5 million (Boozarjomehri 2009). This cost was doubled to determine a suitable cost for a freight ultracapacitor hybrid locomotive, which was $3 million each. The cost for a battery hybrid passenger locomotive was assumed to be $700,000. Again, this cost was doubled for a freight battery hybrid locomotive.

Research Costs

Table 2 outlines the research cost for clean diesel, battery hybrid, and ultracapacitor locomotive technologies.

TABLE 2 Total Research costs to develop locomotive technology ($ Millions 2012)

Locomotive Type	Freight	Passenger
Diesel-Electric	6.66	1.85
Battery Hybrid	131.2	36.5
Ultracapacitor Hybrid	175.0	48.6

The U.S. EPA estimated the research costs required to develop diesel-electric locomotive engines that would meet the new diesel emission requirements. This cost was used to estimate research costs required for ultracapacitor hybrid and battery hybrid locomotives. Since battery hybrid locomotives are more presently more technically advanced, it was assumed that further research costs would be 1.5 times more than the research costs for the diesel electrics. For ultracapacitor locomotive research it was assumed to cost 2 times more than diesel-electric locomotives. This ratio increased since ultracapacitor hybrid locomotive technology is not as advanced as battery hybrid or diesel-electric locomotive technology. No research costs were assumed for electric locomotives as electric technology is used widely in other countries and the technology is fully established.

Health Benefits

The U.S. EPA (2008) estimated the health benefits associated with implementing the new Tier 3 and 4 diesel-electric locomotive regulations due to decreased toxic emissions. It was estimated that by 2030, a PW of health costs of $4.0 to $10.0 billion in 2006 dollars would be saved annually. This cost was assumed to be equally distributed over each year between 2012 and 2030, and also extended to 2040. The PW was then re-calculated from 2005 to 2012 at between $78.9 and $197.2 billion.

With all-electric locomotives, health benefits would be double that of diesel-electric, as there would be zero emissions at the locomotive, and only emissions at the electric power distribution source. Therefore, the 2012 PW of electric locomotives was calculated to be $157.7 to $394.3 billion between 2012 and 2040. It was assumed that the same health benefits would be seen by society with the implementation of either battery hybrid or ultracapacitor hybrid locomotive technologies.

Diesel-Electric versus Electric Locomotive Productivity

Electric locomotives are generally acknowledged to be much more efficient than diesel-electric locomotives and can generate 1.5 times more revenue (Thompson 2010, RITA 2010). The projected ton-kilometers and passenger-kilometers were found for 2012 to 2050 for Canada and the U.S. (Thompson 2010) along with projected revenue per ton-kilometer and revenue per passenger-kilometer (RITA 2010). Using this data, the PW in 2012 dollars was found for freight and passenger rail for both electric and diesel-electric locomotive technology, and is summarized in Table 3.

TABLE 3 Railway Revenues, based on Locomotive Technology Productivity

	Freight		Passenger	
Locomotive	Electric	Diesel	Electric	Diesel
PW (2012)	$1,418 Billion	$886.2 Billion	$170.4 Billion	$109.5 Billion

Overall, it was found that electric locomotives could transport about 1.60 times more freight ton-kilometers than a diesel-electric locomotive for each kilo-watt-hour of energy. It was also found that electric locomotives could transport about 1.55 times more passenger-kilometers than a diesel locomotive per kilo-watt-hour of energy.

RESULTS & DISCUSSION

Using costing data described above, a Monte Carlo simulation (n = 1000 iterations) was conducted for the following four technology scenarios: 1) Clean diesel-electric technology following Tier 3, Tier 4 EPA regulations; 2) Overhead catenary locomotive technology; 3) Ultracapacitor hybrid technology; and, 4) Battery hybrid technology. In addition, with a view to possible future business case development, three separate social cost benefit analyses were considered, including i) railway companies, ii) society in general, and iii) the railway organization and society combined. The Net Present Worth (NPW) results using a 7% discount rate are summarized in Table 4 in terms of expected, worst case, and best case estimates.

TABLE 4 Net Present Worth (in 2012 $ Billions): Locomotive Technology

	NPW Passenger			**NPW Freight**		
Technology	**Worst Case**	**Expected**	**Best Case**	**Worst Case**	**Expected**	**Best Case**
Clean Diesel[1,2]	- 1,646	- 989.2	- 350.8	- 18,093	-11,381	- 14,681
Catenary[1]	+ 241.6	+ 321.8	+ 402.8	+ 5,135	+ 8,061	+ 10,715
Catenary[2]	+ 227.6	+ 269.1	+ 312.4	+ 5,121	+ 8,010	+ 10,625
Ultracapacitor[1]	+ 335.6	+ 411.2	+ 484.6	+ 12,886	+ 15,610	+ 18,454
Ultracapacitor[2]	+ 321.7	+ 359.2	+ 394.1	+ 12,872	+ 15,557	+ 18,363
Battery hybrid[1]	+ 335.6	+ 411.2	+ 484.6	+ 12,886	+ 15,610	+ 18,454
Battery hybrid[2]	+ 321.7	+ 359.2	+ 394.1	+ 12,872	+ 15,557	+ 18,363

Notes:

1. Adding both railway company and society costs and benefits together.
2. Considering only costs and benefits that the railway company would accrue.

The results of the Monte Carlo simulation for the diesel-electric locomotives subjected to the new U.S. EPA regulations are all negative, suggesting a net present cost of the technology, with estimates ranging from a worst case net cost of $18 Trillion for clean diesel freight, to a best case net cost of $ 0.35 Trillion for clean diesel passenger. At this magnitude of cost, the roughly $8 Billion (= $ 0.008 Trillion) PW impact of social benefits, and the roughly $110 to $888 Billion (= $0.1 to $0.9 Trillion) PW impact of revenue for passenger and freight, respectively, were not significant. This engineering economic analysis, resulting in a negative net present value even considering future revenues, demonstrates why railway companies are loathe to change to Tier 3 and 4 locomotive technology unless legislatively mandated.

The catenary line electric locomotive technology with 100% electrified track suggest a positive NPW in all cases, due mainly to four factors: 1) locomotive productivity increases improving revenue by 60%, 2) noise reduction community benefits of $74 billion, and 3) far less costly associated electrical power creating significant energy savings (e.g. $160 billion and $12,100 billion for passenger and freight, respectively). Further research into energy savings is recommended, as this analysis is most sensitive to energy costs; and, the assumption that abundant electrical energy would exist may not be reasonable without significant investments that increase costs. In any case, even assuming zero energy savings would still produce better NPW results for catenary (and still positive results for ultracapacitor and battery hybrid systems). It is estimated that passenger rail electrification completed in 2012 would, between 2012 and 2040, create a net present value (2012 dollars) of $321.8 billion. As electrification would more realistically take much longer, this was re-calculated for electrifying in 20 years. However, slowing the initial capital outlay would increase NPW by 12.8% up to an estimated $362.7 billion; therefore, the one-year construction assumption was left. The estimates are similarly positive and much higher for electrifying freight railways, with an NPW expected to be over $15 Trillion due mainly again to increased productivity, reduced power, and reduced noise benefits.

Ultracapacitor and battery hybrid locomotive technology were assumed to have very similar costs as both require further research costs, are assumed to require the same amount of overhead wire, and are assumed to use generally the same amount of energy. There were even larger cost savings through hybrid locomotive technologies as there was a reduced requirement for overhead wire infrastructure costs.

It is important to note that in all electrification cases – catenary, ultracapacitor, and hybrid battery - social benefits were significant but still not a major factor. For passenger railways, social benefits of electrification impact final figures by less than 20%. For freight railways, social benefits were still an insignificant factor. This suggests that the costs and benefits of rail catenary electrification would accrue mainly to railway firms, and, together with these strongly positive electrification results, warrants a business case level analysis to decide if and when it might be pursued. Moreover, a hybrid locomotives that could function with only 5% of current track requiring electrification with catenary wire for recharging would be provide not only the highest net present worth, but also be the shortest option to implement in terms of manageable construction and business disruption logistics, which were not considered in this analysis. Furthermore in the event of a power grid failure, hybrid locomotives would be the most forgiving. Should there be no power available from catenary wires, the diesel back-up in the hybrid system could allow the train to continue travel. Although this was not looked into specifically in this research, this would be an excellent subject for future research, along with a risk analysis and associated costs. If and when business case development occurs in pursuit of electrifying railways in NA, future research that future analysis would need to incorporate considerations of business disruptions and construction logistics.

CONCLUSIONS

This paper researched the literature to identify current and future costs and benefits related to technology and infrastructure of railways in North America. Based on the literature review, assumptions were made regarding research costs to develop ultracapacitor and battery hybrid locomotive technology, future diesel and electrical energy costs, railway noise mitigation costs, infrastructure costs, and community health benefits. Next, using standard engineering economic analysis techniques, we performed a comparative Net Present Worth analysis of continuing to use diesel electric locomotives until 2040 versus converting the entire passenger and freight network in North America to electricity in 2012 via overhead catenary, ultracapacitor, or battery hybrid technology. To address possible errors in assumptions, and the risk of over or underestimating costs and benefits, Monte Carlo simulation was used to check the sensitivity of results to variances in analysis inputs. Results suggest that implementing ultracapacitor or battery hybrid locomotive technology would create significant positive net present worth between 2012 and 2040, estimated at $411 Billion for passenger rail and $15.6 Trillion for freight rail, due mainly to less overhead catenary infrastructure and energy costs required, while still gaining the social benefits of reduced noise and improved health. They would also be the quickest electrification technology options to implement in terms of manageable construction and business disruption logistics, which were not considered in this analysis and should be researched if and when business case development occurs in pursuit of electrifying railways. Moreover, over 80% of this significant NPW would accrue to railway organizations, suggesting that business case development and investment planning should proceed post haste to electrify, and to phase out diesel electric locomotives at the end of their economic life.

Regardless of which route is taken, electrification would have immense benefits to both railway organizations and society. Increased productivity, reduced energy requirements, decreased noise and improved health would all significantly contribute to cost savings and an improved quality of life for residents of North America.

REFERENCES

AAR. *The Environmental Benefits of Moving Freight by Rail.* Association of American Railroads, 2011.

Boozarjomehri, Elham. *Sustainable Road Safety Improvement through the Promotion of an Alternative Mode: Okanagan Valley Electric Rail.* Master of Applied Science Thesis, Kelowna: University of British Columbia, 2009.

Britain Department for Transport. *Britain's Transport Infrastructure: Rail Electrification.* London: DfT Publications, 2009.

Britain Department for Transport. *Britain's Transport Infrastructure: Rail Electrification.* London: DfT Publications, 2009.

California Energy Commission. *Transportation Fuel Price Cases Demand Scenarios: Inputs and Methods for the 2011 Integrated Energy Policy Report.* California: California Energy Commission, 2011.

Committee on Technology for a Quieter America National Research Council. *Technology for a Quieter America.* Washington, DC: National Academies Press, 2010.

Conte, M., F. Vellucci, and M. Pasquali. "Design Procedures of Lithium-ion Battery Systems: The Application to a Cable Railway." *IEEE*, 2011: 257-264.

Daniels, Laurence E. *Track Maintenance Costs on Rail Transit Properties.* Transit Cooperative Research Program Web-Only Document, Fair Oaks, CA: Transportation Research Board, 2008.

Duque, O., A.L. Zorita, L.A. Garcia-Escudero, and M.A. Fernandez. "Criticality determination based on failure redocrds for decision-making in the overhead contact line system." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.* SAGE Publications, 2009. 485-494.

EIA. *U.S. Energy Information Administration Annual Energy Outlook 2011.* Washington, DC: U.S. Energy Information Administration, 2011.

EPA. *EPA Finalizes More Stringent Emissions Standards for Locomotives and Marine Compression-Ignition Engines.* Regulatory Announcement, Environmental Protection Agency, 2008.

EPA. *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Litrers per Cylinder.* United States Environmental Protection Agency, 2008.

Flaherty, Paul A. "MULTI-STAGE HYBRID DRIVES FOR TRACTION APPLICATIONS." *Proceedings of Joint Rail Conference.* Pueblo, Colorado, 2005. 171-175.

Hondius, Harry. "RNV adopts energy saving: supercapacitors Rhein Neckar Verkehr is putting into service its latest build of Bombardier Variobahn low-floor trams, which have been equipped with supercapacitor energy storage." *Railway Gazette*, April 2010: 64-65.

Hooper, P.W.C., and L.M. McCormack. "Mainline Electrification as Part of the Railway System." *IEEE*, 2010: 1-5.

Horvath, Arpad, and Cristiano Facanha. "Environmental Assessment of Freight Transportation in the U.S." *The International Journal of Life Cycle Assessment*, 2006: 229-239.

Jaafar, A, B. Sareni, X. Roboam, and M. Thiounn-Guermeur. "Sizing of a hybrid locomotive based on accumulators and ultracapacitors." *Vehicle Power and Propulsion Converence.* Lille, France, 2010. 1-6.

Konishi, Takeshi, Hiroaki Morimoto, Toru Aihara, and Masaru Tsutakawa. "Fixed Energy Storage Technology Applied for DC Electrified Railway." *IEEJ TRANSACTIONS ON ELECTRICAL AND ELECTRONIC ENGINEERING*, 2010: 270-277.

Maher, Bobby. "Ultracapacitors Provide Cost and Energy Savings for Public Transportation Applications." *Battery Power Products & Technology*, November 2006.

McCluer, Stephen, and Jean-Francois Christin. *Comparing Data Center Batteries, Flywheels and Ultracapacitors.* Schneider Electric Data Center Science Center, 2011.

North American Transportation Statistics Database. November 17, 2011. http://nats.sct.gob.mx/nats/sys/tables.jsp?id=24&i=3 (accessed December 17, 2011).

North American Transportation Statistics Database. *North American Transportation Statistics Database.* November 17, 2011. http://nats.sct.gob.mx/nats/sys/tables.jsp?id=15&i=3 (accessed December 17, 2011).

OECD. *Infrastructure to 2030.* Mapping Policy for Electricity, Water, and Transport, Organisation for Economic Co-Operation and Development, 2007.

Ogasa, Masamichi. "Application of Energy Storage Technologies for Electric Railway Vehicles - Examples with Hybrid Electric Railway Vehicles." *IEEJ TRANSACTIONS ON ELECTRICAL AND ELECTRONIC ENGINEERING*, 2010: 304-311.

Okui, A., S. Hase, H. Shigeeda, T. Konishi, and T. Yosh. "Application of Energy Storage System for Railway Transportation in Japan." *The 2010 International Power Electronics Conference.* 2010. 3117-3113.

Peterman, David Randall, John Frittelli, and William J. Mallett. *High Speed Rail (HSR) in the United States.* Report for Congress, Congressional Research Service, 2009.

Regenstreif, Avrum. "Canada needs an electrified railway." *CCPA Monitor*, 2009: 28-30.

RITA. "Research and Innovative Technology Administration Bureau of Transportation Statistics." *Table 3-17: Average Freight Revenue Per Ton-mile.* 2010. http://www.bts.gov/publications/national_transportation_statistics/2010/html/table_03_17.html (accessed December 18, 2011).

—. "Reserach and Innovative Technology Administration Bureau of Transportation Statistics." *Table 3-20: Average Passenger Revenue per Passenger-Mile.* 2010. http://www.bts.gov/publications/national_transportation_statistics/html/table_03_20.html (accessed December 10, 2011).

Sisson, Mark. "Hybrid freight train economics: hybrid streetcars, aided by batteries, are now being marketed to North American operators. Can such a concept work for rail freight transport?" *Railway Age*, June 2011: 23-25.

Smith, Richard F., Xudong Jia, and Jawaharial Mariappan. *Electrification of the Freight Train Network from the Ports of Los Angeles and Long Beach to the Inland Empire.* Pomona, California: California State Polytechnic University, 2008.

Statistics Canada. "Statistics Canada." *CANSIM - Summary of Table 051-0001.* March 23, 2011. http://estat.statcan.gc.ca/cgi-win/CNSMCGI.EXE (accessed December 17, 2011).

—. "Statistics Canada." *Railway transport survey, diesel fuel consumption, annual (litres unless otherwise noted).* February 23, 2011. http://estat.statcan.gc.ca/cgi-win/cnsmcgi.pgm?regtkt=&C2Sub=&ARRAYID=4040012&C2DB=EST&VEC=&HILITE=RAIL+PROJECTION&LANG=E&SrchVer=&ChunkSize=50&SDDSLOC=//www.statcan.gc.ca/imdb-bmdi/*-eng.htm&ROOTDIR=ESTAT/&RESULTTEMPLATE=ESTAT/CII_PICK&ARRAY_PICK=1&SDDSI (accessed December 17, 2011).

Thompson, Louis. *A Vision for Railways in 2050.* International Transport Forum Paper, Leipzeg, Germany: Oganisation for Economic Co-operation and Development, 2010.

U.S. Census Bureau. "U.S. Census Bureau." *Monthly Estimates of the United States Population: April 1, 1980 to July 1, 1999.* January 2, 2001.

http://www.census.gov/population/estimates/nation/intfile1-1.txt (accessed December 17, 2011).

—. "U.S. Census Bureau." *National Population Projections.* 2009. http://www.census.gov/population/www/projections/2009summarytables.html (accessed December 17, 2011).

Zapfe, Jeffrey A., Hugh Saurenman, and Sanford Fidell. *Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit.* Transit Cooperative Research Program Web-Only Document, Transportation Research Board, 2009.

Zhao, Kun, Xun Wang, Zhongping Yang, and Xiaojie You. "Study and Simulation of on-board Energy Saving System with Electric Double Layer Capacitor with Railway Vehicle." *International Conforence on Computer Application and System Modeling.* IEEE, 2010. 336-339.